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**Through Drying of Machine Formed Paper
and
Drying Nonuniformity**

by

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**A thesis submitted to the Faculty of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of
Doctor of Philosophy**

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Abstract

Transport phenomena characteristics were determined for the through air drying of machine-produced printing and heavier papers. The momentum transport is strongly affected by the specifications of machine-formed papers, but of the drying rate characteristics only the critical moisture content varied between the types of paper tested. To determine the impact of individual parameters of commercial papermaking these experiments with machine-formed paper were supplemented by the use of handsheets. The papermaking parameters of beating, wet pressing, formation and pulp blending all strongly affect the momentum transport through the paper but only the quality of sheet formation and composition of TMP-kraft pulp blends influences drying rates measurably.

The general phenomenon of nonuniformity in through drying was examined, including its association with nonuniformity of paper structure, with process conditions affecting drying nonuniformity, and implications for minimizing the cost of providing the flow of drying air through semi-permeable grades of paper. The development and decay of nonuniformity during drying was demonstrated through two techniques, one based on the measurement of local sheet moisture content, the other with continuous monitoring of the local air exhaust temperature from the sheet. Drying nonuniformity is quite sensitive to the quality of formation and to drying intensity, and is less severe at both the higher and lower end of the basis weight range. The biggest effect on drying nonuniformity is the improvement possible by reduction in the initial moisture content. In-plane moisture diffusivity was determined to be a very strong function of sheet moisture content, and is not fast enough to reduce the sheet moisture nonuniformity during drying.

The study provides guidance in the possible future use of through air drying for application to grades of paper heavier than those for which it is now used.

Résumé

Nous avons étudié les caractéristiques des phénomènes de transfert pour le séchage percolé de papier-machine pour imprimantes et de papier à poids plus élevé. Ces expériences ont été menées avec des formettes, pour déterminer l'influence de chaque paramètre intervenant dans la fabrication industrielle. Bien que la quantité de mouvement de l'air soit fortement influencée par les caractéristiques des papiers-machine, nous n'avons pas trouvé de différence significative pour le taux de séchage. Les paramètres de la fabrication du papier, c.-à-d. le raffinage, la presse coucheuse, la formation et le mélange de pâtes affectent tous la quantité de mouvement à travers le papier mais seule la formation exerce une influence mesurable sur le taux de séchage.

Nous avons examiné les phénomènes généraux régissant les non-uniformités en séchage percolé, notamment en association avec la non-uniformité de la structure du papier, ainsi que les conditions de séchage influençant la non-uniformité, et les implications en vue de réduire au maximum le coût du séchage percolé des papiers semi-perméables. Le développement et la réduction des non-uniformités au cours du séchage a été évaluée par deux méthodes, l'une basée sur l'étude de l'humidité locale du papier, l'autre basée sur le suivi continu de la température du flux d'air sortant de la feuille. Les non-uniformités de séchage sont très sensibles à la qualité de la formation du papier ainsi qu'à l'intensité du séchage, et sont moins graves avec des feuilles assez lourdes ou assez légères. La plus grande réduction des non-uniformités est obtenue en diminuant la teneur en eau initiale. La diffusivité de l'humidité dans le plan de la feuille dépend beaucoup de l'humidité du papier, et n'est pas assez élevée pour réduire les non-uniformités de la teneur en eau au cours du séchage.

Cette étude fournit les bases d'un futur usage possible du séchage percolé pour des types de papier de grammage plus élevé que ceux pour lesquels cette technique est utilisée maintenant.

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Nomenclature

A	Surface area, m^2 , also a constant
a, a'	Constants, parameters
a_p , a'_p	Specific surface, m^2/m^3 and m^2/g respectively
B	Basis weight, g/m^2 , also a constant
BKP	Bleached kraft pulp
b, b'	Constants, parameters
C	Inertial constant, also a constant
CD	Cross-machine direction
c	Moisture content, kg water/kg moist paper
c, c'	Constants, parameters
D	Diffusion coefficient, m^2/s ; D_0 , base diffusion coefficient; D_1 , self diffusion coefficient; D_2 , apparent diffusion coefficient
d, d'	Constants, parameters
d_p	Characteristic dimension, μm
E_a	Activation energy, kg/m^2s^2
FSP	Fibre saturation point
f	Friction factor
G	Mass flow rate, kg/m^2s
GW	Groundwood
h	Heat transfer coefficient, W/m^2K
I_{DNU}	Index of drying nonuniformity
$\bar{I}_{DNU}$	Average index of drying nonuniformity
k	Permeability, m^2 ; k_a , permeability in Klinkenberg eqn.; k_B , permeability using Bendtsen porosimeter; k_G , permeability using Gurley method; k_k , for kraft paper; k_m , for paper of blended furnish; k_N , after N wetting-drying cycles; k_R , for research equipment; k_T , for TMP

k/L	Modified permeability, m
m	Constant, parameter
MD	Machine-direction
L	Paper thickness, m
N	Number of sheets
N_w	Number of wetting-drying cycles
n	Exponent of power law relation for fluid flow, Eqn. 2.1
n_i	Exponent of R-X relation for through drying over increasing rate period
n_f	Exponent of R-X relation for through drying over falling rate period
P	Pressure, Pa
PM	Papermachine paper
ΔP	Pressure drop, Pa
p	Parameter
q	Parameter
R	Drying rate, $\text{kg/m}^2\text{h}$; R_c , constant drying rate; R_s , with saturated exhaust; R, gas constant, $8314.34 \text{ kgm}^2/\text{s}^2$
R_t	Residence time of pulp suspension, s
Re	Reynolds number
r	Radius
SBK	Semibleached kraft
SGW	Stone groundwood
T	Temperature, $^{\circ}\text{C}$; T_0 , reference temperature; T_e exit air temperature; T_i , inlet drying air temperature; T_s , adiabatic saturation temperature; T_p , paper temperature
TMP	Thermomechanical pulp
t	Time, drying time, s; t_R , suspension retention time
Δt	Elapsed time, s
u	Velocity, m/s

X	Paper moisture content, kg water/kg dry fibre: X_o , initial moisture content: X_i , at the end of increasing rate period: X_c , critical moisture content: X_f , final moisture content: X_{icf} , at triple point: X_{FSP} , at fibre saturation point
Y	Air absolute humidity, kg H_2O /kg dry air: Y_i , Y_o at inlet and outlet of the sheet; Y_s , at saturation
w _T	Weight fraction, kg/kg; w_k , of kraft in blend; w_T , of TMP in blend
z	Coordinate: paper thickness dimension
α	Coefficient of viscous term in momentum equation, $1/m^2$
β	Coefficient of inertial term in momentum equation, $1/m$; diffusivity constant ($=D\mu$), $g\ cm/s^2$
ε	Porosity
κ	Kozeny constant
λ	Mean free path, m
μ	Dynamic viscosity, Pa s
ν	Kinematic viscosity, m^2/s
ρ	Density, kg/m^3 : ρ_a , air density; ρ_f , fibre density, ρ_p , paper density
σ	Standard deviation

CHAPTER 1:

Introduction and Objectives

1.1 Paper and the Papermachine

Paper is a porous structure formed mainly from natural polymer fibres, principally from wood, often with various additives. By choice of the types of fibres and additives and of the processing conditions a very wide range of products is made. With the annual production of nearly 300 million tonnes, papermaking is one of the world's largest process industries, and a papermachine is one of the largest units of process equipment.

The processes of papermaking can be divided into pulping and stock preparation, and then the papermachine for the steps of sheet forming, wet pressing, drying and calendering. Where the suspension of pulp fibres meets the sheet forming fabrics on the papermachine the water to solids ratio is 100 - 200 kg water/kg fibre. Figure 1.1. Huge amounts of water are removed mechanically on the forming screen and by suction. Pressing reduces the moisture content from 3-4 kg/kg to the level of about 1.3-1.5 kg water/kg fibre, with the dryer section bringing this to a final moisture content of 5-7%. Printing grades of paper are now produced at speeds to 100 km/h, with a tolerance on thickness of a very few microns across sheets up to 9m wide which must rarely break. Thinner grades of paper are produced at papermachine speeds higher yet. With paper being made from a great variety of fibres of quite different chemical composition, morphology and properties, to obtain a wide range of products of different physical and optical properties, papermaking is a process of high technology.

1.2 Drying Paper

Printing and heavier grades of paper are dried by hot surface contact heat transfer between the wet sheet and the surface of a long series of cylinders heated internally by condensing steam. Depending on the grade of paper and the speed of papermachine, the low rate of contact heat transfer requires the use of 40-70 such cylinder dryers, each up to

2 m diameter and 9 m long, making the dryer section with its air circulation system a simultaneous heat and mass transfer process of enormous size.

Uniformity of moisture content in the cross-machine direction (CD) is desirable both to minimize drying cost and for reasons of paper quality. The drying of paper constitutes not only a transport phenomena process but one of materials engineering, the strength of paper being developed entirely during drying. Recent work in this laboratory has demonstrated that both the physical and optical properties of paper can be altered by changing the drying process. In addition to providing relatively low drying rates the cylinder drying process is not adapted for effective CD control of sheet local moisture content. With recent advances in sheet forming and wet pressing technology, cylinder drying is now the bottleneck for the use of higher speed papermachines. Thus for printing and heavier papers there is a strong incentive for a fundamental change in drying technology. The Table 1.1 record of the types of dryers for paper in the U.S. according to grade, from tissue paper to paperboard, provides a list of potential candidates as an alternative drying technology for printing grades.

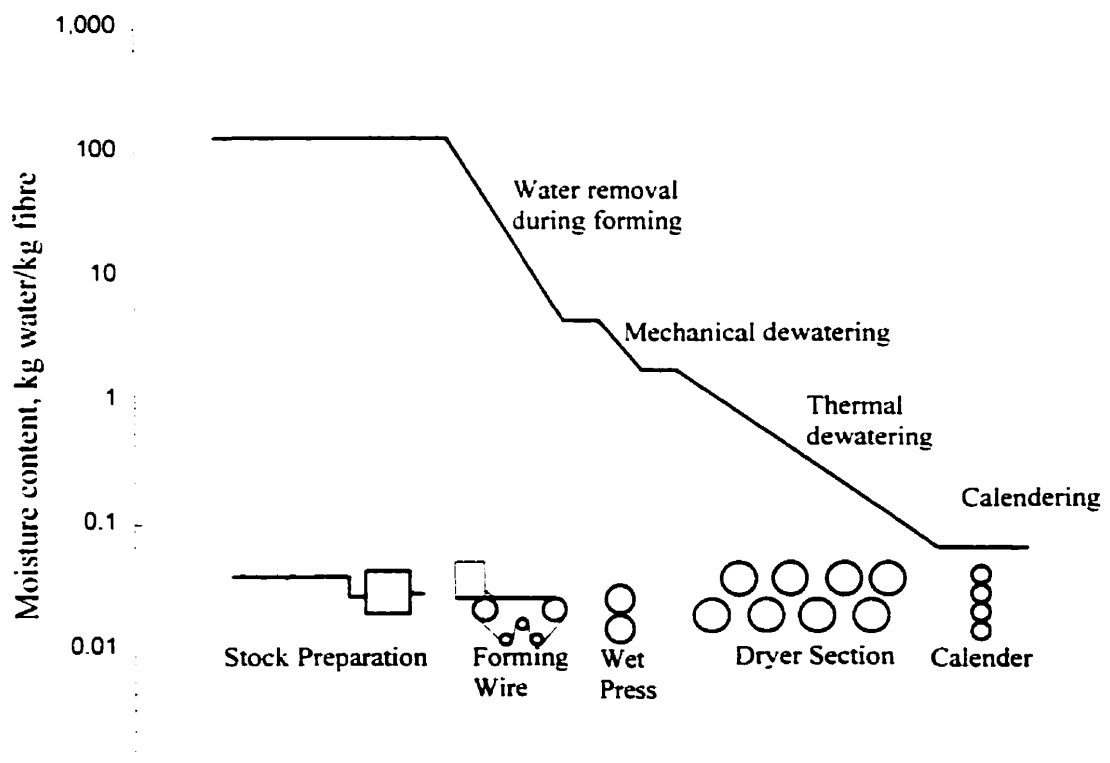


Fig.1.1 Various stages of water removal in paper manufacturing

Table 1.1 Distribution of dryers in paper industry, after McConnell [1980]

	Paper Industry Drying Application					Total	Drying Rate kg/m ² h
	Pulp	Tissue	Paper	Board	Coating		
	Water removed, %						
	7	6	34	51	2		
	Dryer Distribution, %						
Cylinder Dryer	-	15	95	95	35	82.3	10-20
Impingement dryer	70	-	2	2	50	7.6	100
Yankee Dryer*	-	70	-	-	-	4.2	200
Infrared Dryer	-	-	3	3	15	2.8	-
Through Dryer	-	15	-	-	-	0.9	300
Flash Dryer	15	-	-	-	-	1.1	-
Vacuum Dryer	15	-	-	-	-	1.1	--

* air impingement plus heat transfer from steam condensing inside the cylinder

Air through drying use has grown substantially since that 1980 survey, becoming a standard process for permeable products, tissue and toweling, as well as for textiles and nonwoven materials. For reasons of product quality with light weight papers through drying is typically followed by air impingement Yankee drying. The high rate of through drying derives from the drying medium being in contact with the wet material throughout the bed or wet web rather than only at an external surface. Thus not only is the area for heat transfer to the wet material much greater, but the length of the diffusion path for moisture removal is reduced from the order of the thickness of the sheet to that of the individual fibre. Advantages claimed for through drying over cylinder drying are:

- 1- Better thermal performance due to a higher degree of the saturation of the exhaust air. Through air dryers consume as little as 3300 kJ/kg of evaporated water compared to about 3800 kJ/kg water for cylinder dryers.
- 2- Much smaller dryer building corresponding to the much higher drying rate.
- 3- With an appropriate support fabric a broad range of products can be through dried.
- 4- Operating problems such as threading and breaks are minimal.

Although there are flat bed through dryers, tissue and toweling are dried on rotary through dryers. Figure 1.2. The advantage of the high drying rates given in Table 1.1 are effective for very permeable grades of paper for which the flow of drying air through the wet sheet is achieved at a reasonable capital and operating cost for the air fan. Through drying is not used for drying printing and heavier grades of paper because their permeability when wet is an order of magnitude lower, leading to a high cost for the air fan. The present study of through air drying of semi-permeable grades such as newsprint and printing papers was carried out to provide fundamental knowledge of this

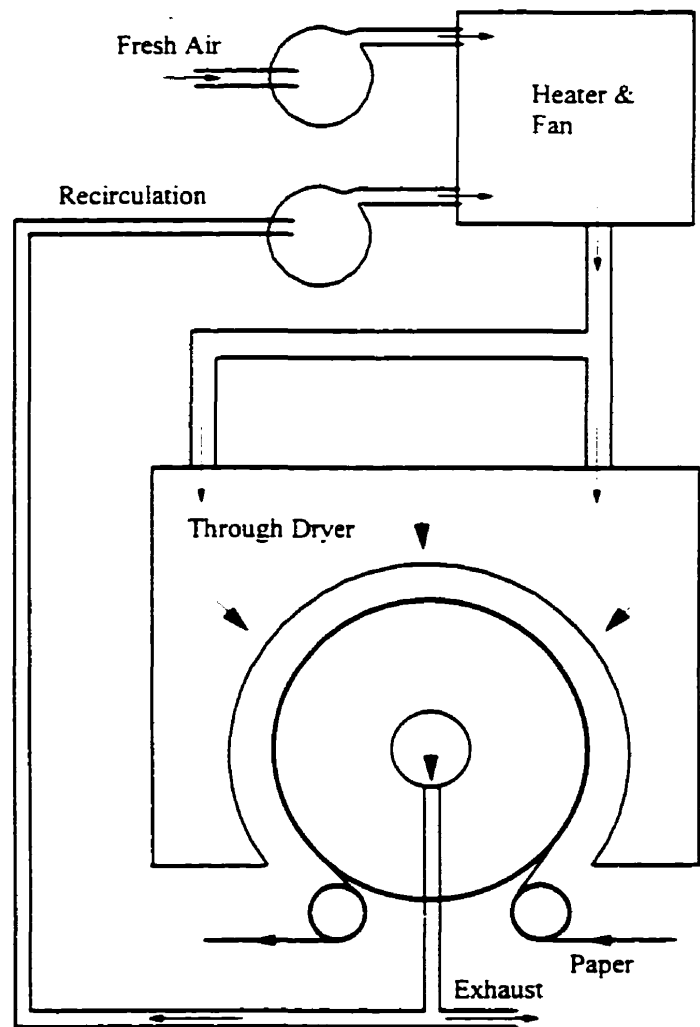


Fig. 1.2 A rotary through dryer

process for such sheets, and thereby to explore whether this drying process could in the future have any role in drying these heavier grades of paper.

As the drying air flows through the paper, which thereby acts as a thin packed bed of fibres, this process is expected to be highly sensitive to paper structure via effects on sheet permeability and drying rate characteristics. With the variety of types of pulps and of parameters in papermaking, machine produced paper has a correspondingly great range of specifications. As previous studies on through air drying have not focused on the interrelation of the properties of machine-formed sheets of printing grades of paper with the air permeability and drying rate characteristics, these aspects were taken as the basic orientation of the present study.

1.3 Moisture Diffusivity and Drying Nonuniformity

Through drying rates depend on the through flow rate. Through flow rate is affected by the resistance of the sheet to air flow. The resistance to through flow depends on the sheet structure. As the structure of all paper is locally nonuniform, then through drying rates are expected to be locally nonuniform. This local nonuniformity of through drying rates affects not only the sheet average drying rates, which determine the dryer size, but may also degrade the quality of paper dried with a locally nonuniform moisture content. As drying nonuniformity from this source is unique to through drying, this aspect must be included in a study of the fundamentals of this process as applied to printing and heavier grades of paper.

Development of a nonuniform local moisture content during drying creates the potential for moisture to diffuse from wetter to dryer regions in the plane of the paper. How fast moisture diffuses to reduce nonuniformity in moisture profile across the sheet is not known because of the lack of determinations of lateral moisture diffusivity in paper, another aspect of basic knowledge to be obtained.

1.4 Objectives

The objective of this thesis is to make the first fundamental study of the through drying characteristics of machine-formed sheets in the range of printing and heavier papers, including the following aspects:

- (1) Determination of the momentum transfer and drying rate characteristics for a variety of machine-formed printing papers.
- (2) Determination of these characteristics using handsheets in order to permit systematic investigation of individual papermaking parameters.
- (3) Development of techniques for quantitative characterization of drying nonuniformity and for determination of in-plane moisture diffusion relevant to nonuniformity of drying.

CHAPTER 2:

Through Drying Characteristics of Machine-Formed Paper

2.1 Introduction and Objectives

Of the various segments of paper industry, those that produce “*semi-permeable*” products such as printing and heavier types of paper are restricted as to drying method. All such grades are dried by the standard process over steam heated cylinder dryers, with the exception of the limited use of impingement floater type air convection dryers and infrared dryers for specialty grades. Cylinder drying is characterized by low drying rates and is not adapted for cross-machine direction (CD) control of moisture content. Grades referred to here as “*semi-permeable*” are those with a Darcy permeability in the order of $10^{-13} - 10^{-14} \text{ m}^2$, which includes printing paper, newsprint, linerboard, sack paper and some pulp sheets. The present study examines factors relating to the possible applicability to such grades of through air drying, a technique now restricted to light weight products made from permeable furnishes - tissue and toweling.

Through air drying involves coupled flow, heat and mass transfer processes within the thin packed beds which constitute the moist sheet, the structure of which forms a central element of the process. Three principal advantages of through air drying are high drying rate, hence small dryers; a high level of saturation of the exhaust air with water vapor, which is an aid to obtaining high energy efficiency; the capability to provide good CD control of moisture content. The product quality aspect of high bulk which is of central importance in drying tissue is not a factor for heavier grades. In short, through air drying can provide smaller, energy efficient dryers with good CD control capability. The air permeability of a sheet controls whether through drying could be economic, as too low a permeability corresponds to excessive capital and operating cost for the air fan. The current practice not to use through drying with semi-permeable grades of paper could change if both the drying and momentum transfer characteristics were determined for

such grades. This knowledge of the fundamentals could then be used as the basis for developing novel paper mill dryer sections employing multiple techniques of drying as is now proposed by Kuhasalo [1995] and Bond et al. [1996], with through drying in appropriate combinations with other drying techniques.

The objectives of this study were:

- 1- To modify a laboratory through dryer facility, previously used for high permeability sheets, for use with semi-permeable paper.
- 2- To obtain an extensive set of measurements of the through drying rate and momentum transfer aspects with machine produced papers dried under a range of conditions.
- 3- To analyze the fundamentals of the process of through drying paper in terms of the transport phenomena involved.

2.2 Literature Review

Through air drying of paper first appears in the literature in the mid-sixties. Only a few investigators have attempted to develop a basic understanding of the through drying of permeable webs such as paper and textiles. Crotagino [1975] reviewed the growing significance of air drying processes including through drying. Concerning the potential for extending the use of through drying from permeable light papers such as tissue to semi-permeable grades such as newsprint he concluded that at the wet end, where the latter have a low permeability, the use of through drying did not appear attractive. In their general review Polat et al. [1992 b] attributed the inconclusive and contradictory results of through drying studies to deficiencies in the design of laboratory experiments and to oversimplified approaches to this complex process. In the Table 2.1 summary, the most comprehensive investigations are those of Polat [1989] and Chen [1994].

As the equipment design of Chu and Kuo [1967] did not provide either constant flow rate, G , or constant pressure drop, ΔP , across the paper, their through flow rate varied greatly during a drying experiment. All sheets were dried from an initial moisture content, X_0 , of 1.8 kg water/kg fibre to the equilibrium moisture content, $X_f=0.03$ kg/kg.

Table 2.1 Previous studies on through air drying

Investigator	Grammage g/m ²	Type of Paper
Chu and Kuo [1967]	Unspecified	Tissue, Machine-Formed
Walser and Swenson [1968]	2 ply of 43 52 150	Toweling Toweling (All Machine-Formed) Kraft
Martin [1972]	100	Kraft Handsheets
Raj and Emmons [1975]	13-64	Unspecified
Roher and Gardiner [1976]	16-19	Tissue and Toweling, Machine-Formed
Wedel and Chance [1977]	25-50	Handsheets
Gummel [1977]	20-23	Tissue, Machine-Formed
Polat [1989]	25-150	Mostly Kraft Handsheets
Chen [1994]	25-50	Kraft Handsheets

They did a series of drying experiments at each of two air temperatures, 22° and 71°C, for air through flow rates in the range $0.8 < G < 3.3 \text{ kg/m}^2\text{s}$. Sheet moisture content was measured directly using a specially designed capacitance gauge requiring tedious calibration. The porosity of their dry tissue paper was determined by the mercury penetration method. Three drying periods were identified, distinguished according to the mechanism controlling water movement, i.e. simultaneous two phase flow, capillary action and diffusion. They proposed a correlation for critical moisture content, X_c , and mathematical models for each of their three drying periods, models which agreed reasonably well with their experimental data for through drying of tissue paper. With the very high through flow rates used most of the free water was removed mechanically from the pores, so their drying rate curves reflect a combination of drying and mechanical dewatering. Because the experimental design permitted more than 40% change in air flow rate during a drying experiment their results can be subject to only limited interpretation.

Walser and Swenson [1968] reported through drying rates for both laboratory and mill tests. Their laboratory equipment did not provide either constant ΔP or constant G , with G varying greatly, by more than 100%, while the sheet went from wet to dry. In the laboratory experiments they measured paper moisture content with a back scatter beta ray gauge. The only variation in basis weight was by using two 38 g/m^2 sheets to obtain 76 g/m^2 paper. In their experimental range, $60 < T_i < 260^\circ\text{C}$ and $0.05 < u_s < 0.25 \text{ m/s}$, they

reported that air leaves a 76g/m^2 sheet saturated during the constant rate period of drying. In mill tests with filter paper, toweling and heavier grades of high permeability kraft paper of basis weight $52\text{-}147\text{g/m}^2$ they could not detect the effect of basis weight on drying rate, which may have been changed by the additional drying from air swept over the sheet in the draws between drying cylinders.

Martin [1972] measured rates of through drying of 100g/m^2 kraft handsheets during transient experiments in a laboratory dryer under the condition of constant pressure drop. With an initial moisture content of $4.85\text{ kg water/kg fibre}$ the through flow rate would have changed 3-5 fold during each experiment. Martin reported that the drying air exiting the paper was not saturated. The drying rates measured were simply averages over the entire drying, with only the initial and final moisture content and total drying time reported. These limitations may be the source of his claim, not credible, that the average drying rate reaches a plateau with increasing temperature of the drying air.

Raj and Emmons [1975] dried paper of $13\text{-}64\text{ g/m}^2$ with ambient temperature air in their laboratory through dryer. They may have attempted to maintain the through flow rate constant but this important aspect was unfortunately not made clear. Paper moisture content was followed by monitoring the weight of sheet plus holder during drying, providing results of low accuracy because of an unfavorable noise-to-signal ratio and the large correction needed for the time lag from the spring dashpot system used for noise damping. Through drying was analyzed as an internal flow in ducts, reported as a nondimensional mass transfer number - Peclet number correlation. For the Peclet number characteristic dimension they used the square root of the Darcy permeability of the dry sheet, which Polat [1989] showed is much too small. On this basis they concluded that air passed through the paper in pure viscous flow. A notable feature was their modeling of the falling rate drying period by solving numerically the heat transfer and evaporation equations for the paper - air system. From three forms tested they recommended the model which considered both solid heat conduction and fibre shrinkage as giving the best agreement with their experimental results.

Rohrer and Gardiner [1976] developed a through drying model assuming this process analogous to pure turbulent flow through ducts. Using an industrial through dryer

they measured the parameters needed in their model and claimed good agreement between measurements for tissue and that model, without however providing any quantitative documentation. Subsequent Scanning Electron Microscopy (SEM) evidence shows that the actual pore structure of paper is far from that of simple ducts.

Wedel and Chance [1977] considered flow through paper as an external flow over cylinders, another model which bears little relation to the complex structure of the pores through which flow occurs. They also assumed that the exit through flow air was saturated and claimed that their calculations agreed well with their laboratory data, which were not provided. They used Darcy's law, applicable for purely viscous flow, and solved the heat and mass balance equations for through drying of paper, neglecting heat conduction in the sheet but allowing for the decrease of vapor pressure of water in the falling rate period. Their use of experimental data with the exiting through flow air essentially saturated provides a very insensitive test of any rate model.

Gummel [1977] attempted to perform laboratory through drying experiments at a constant through flow rate and determined drying rate indirectly by monitoring exit air humidity with an infrared analyzer, thereby obtaining complete drying rate curves. The subsequent analysis of their data by Polat [1989] indicated that although Gummel attempted to have constant mass flow rate during drying, this objective was not achieved, apparently because of leakage and by-passing at his sheet holder. The drying rates measured for 20 and 23 g/m² paper at a constant through flow rate of 22 to 87°C air are considerably lower than for the exit through flow reaching adiabatic saturation. He explained these findings for textiles and very thin tissue products (without significant change in a key variable, basis weight) in terms of a laminar internal flow with entrance effects. The theoretical drying rates for that flow were however substantially higher than those he measured. Gummel explained this discrepancy in terms of the pore size distribution and uneven drying due to permeability variation. These laboratory data were subsequently shown by Polat [1989] to display an effect of T_i , which was not detected by Gummel. Polat also noted that Gummel used Darcy's law, which applies for purely viscous flow, although at his high through flow rates substantial inertial effects would exist.

In spite of the evidence from Gummel's work that through flow air remains significantly below saturation, that study provided no reliable basis for the prediction of humidity in the exit through flow. Thus in a mathematical model for combined impingement and through drying Crotogino and Allenger [1979] continued the use of the assumption of through flow exiting the sheet as saturated air. They also assumed no evaporation during an initial period, considered to involve only sheet warm-up, and calculated drying rates during the falling rate period as determined only by two thermodynamic effects with no allowance for rate effects. Thus they allowed for the decrease in vapor pressure and increase heat of desorption of water at low moisture content, but not for the diffusional resistance of moisture transport from the interior of the fibres or for the decrease in heat transfer driving force with the increase in paper temperature during the falling rate period. In the absence of any experimental basis for doing otherwise, they assumed the total drying rate to be simply a linear combination of the rate of pure through drying and pure impingement drying determined for the flow rates of the through flow and impingement exhausts.

Because of the problems with these studies noted above, the understanding of the basic transport processes involved in the through drying of paper has remained incomplete. For low intensity through drying the extensive investigations of Polat [1989] and Chen [1994] under more precisely controlled conditions as described below have provided new insight into this complex process.

The first systematic study of the effect of B , T_i , G and X_0 on through drying paper was that of Polat et al. [1987, 1989, 1991a,b, 1992a,b, 1993]. Polat et al. [1989] established a new basis for determining the characteristic dimension for flow through paper, $d_p = \alpha/\beta$, where α and β are complex parameters in the momentum transport equation, and showed that the ratio between the correct ΔP and that given by the Darcy's law viscous flow simplification is $(1+1/Re)/(1/Re)$. The error from making the Darcy's law approximation was thereby determined to be 5% at $Re=0.05$ but 100% at $Re=1$. In industrial practice where G can be up to $4 \text{ kg/m}^2\text{s}$, corresponding to $Re=6$, the true ΔP would be six times the value predicted using Darcy's law. They showed that the

theoretical Reynolds number - friction factor - characteristic dimension ($Re-f-d_p$) treatment for air flow across moist and dry paper, because it results from a basic fluid mechanics characterization for momentum transport in paper, constitutes a more powerful treatment than the traditional permeability approach. Moreover, this approach provides a sound basis for analysis of heat and mass transport phenomena in paper during through drying by providing a theoretically based value for d_p , required as the characteristic dimension for Reynolds, Nusselt, Sherwood and Peclet number.

Polat et al. [1991 a] also established that the through drying of paper consists of three drying rate periods, those of increasing rate, constant rate and falling rate. They demonstrated the substantial importance of the increasing drying rate period, missed in earlier studies due to variable mass flow rate during drying experiments. The extent of each period was determined as a function of drying conditions, i.e. temperature and flow rate of air, basis weight and initial moisture content of paper. They introduced the concept of an increasing rate-constant rate-falling rate triple point condition, X_{icf} . For an initial moisture content $X_0=X_{icf}$ a constant rate drying period is reached only momentarily as drying passes directly from the increasing rate to the falling rate period, with $X_i=X_c$. Polat et al. [1992 a] reported a correlation for the transport phenomena during constant rate through drying in the form of $Sh=aRe^n$ with both coefficients, a and n , as a function of paper basis weight and through flow inlet temperature. Polat et al. [1991 b] integrated these individual components into their successfully tested model for the complete through drying of paper. This model relies on a general correlation of mass and momentum transport in which the controlling factors during the increasing and falling rate periods are, respectively, development of transport area and increase of heat of desorption. The drying rate curves made with the predictive form of this model provide the best agreement yet obtained with experimental measurements, especially during the increasing rate period, the drying period not recognized in earlier models.

In the next major study of through drying paper Chen [1994] obtained a normalized drying rate curve of universal form to represent the complete through drying rate data for the same type of unbleached kraft handsheets used by Polat [1989]. Chen

developed an unsubjective procedure for obtaining the five drying kinetics parameters, i.e. R_c , X_i , X_c , n_i and n_f , where n_i and n_f are his universal parameters for the R-X curves in the increasing rate and falling rate periods. Drying time and drying rate were successfully predicted with his general correlations. To test one possibility of improving the effectiveness of through drying Chen [1994] changed the air approach from a uniform velocity profile to a turbulent impinging jet flow. Thus the air would enter the sheet at a higher humidity because of the higher convective heat and mass transfer coefficients at the air inflow surface of the sheet. As no measurable difference was found in through drying rates with and without impinging jets this evidence established that the through drying process is so dominated by transport phenomena within the sheet as to be essentially unaffected by changing the boundary condition at the air inflow surface.

Some patents granted for through drying are. Villalobos and Ramsey [1970]. Chance and Han [1977]. Huostila et al. [1979]. Morton [1980]. Leitner [1982]. and Trokhan [1983]. As these provide general information about the technique and its application, but not an understanding of the process, they are not reviewed here.

Although the studies of Polat et al. and Chen et al. provide the basis that had been lacking for a comprehensive analysis of through drying, they were restricted to handsheets made from one laboratory made pulp. As the through flow of air is influenced by the structure of the sheet, this drying process is very sensitive to the nature of this thin packed bed of fibres. With the structure of machine - produced paper made from commercial pulp furnishes being substantially different from unfilled kraft handsheets, the present investigation using paper mill produced sheets was undertaken.

2.3 Experimental Apparatus

2.3.1 Overall design concept

General equipment concepts used by Gummel [1977], Polat [1989] and Chen [1994] were refined and implemented for the first study of transport phenomena in through air drying of papermachine produced printing papers. The objective was to obtain

the instantaneous values of all parameters required to describe the history of through drying from wet to dry. The values monitored were the pressure drop across the web, humidity and temperature of exhaust air, from which the sheet moisture content and drying rate were determined continuously. Paper moisture content was calculated indirectly by monitoring continuously the exhaust air humidity with a fast response IR air humidity analyzer. In this way the instantaneous drying rate - sheet moisture content data were obtained.

Three options exist in the design of through drying experiments. If pressure drop ΔP is kept constant, then the air mass flow rate G changes greatly during drying because of the permeability - moisture content dependence. If G is kept constant, there is a correspondingly large variation in ΔP during drying. The worst option is if neither ΔP or G are maintained constant, as was the case in some previous studies. Although the option of constant ΔP - variable G corresponds to industrial through dryer operation, for research this option has two disadvantages: rapidly changing flow rates are difficult to monitor precisely, and the analysis of results is difficult because drying rate R is a function of two variables, the air flow rate G and sheet moisture content X . With the alternate option of fixing the flow rate G , the rapid transients in ΔP may easily be monitored and the measured drying rate is then a function only of paper moisture content. The latter option was chosen as superior for characterizing through drying. The constant air flow rate G was achieved by having a pressure regulator upstream of a valve across which critical flow was maintained.

2.3.2 Equipment specifications

In this equipment for drying 103 mm diameter sheets, Figure 2.1, the supply air pressure was regulated to 552 kPa by a pressure regulator, 1, (Norgren F17-801-RLNA) after passing through an oil filter, 2, (Norgren F17-800-A3D). A constant mass flow rate was achieved using a manual control valve, 3, (Whitey Union Bonnet, model SS-6LRF4) operated to ensure critical flow across the valve. As the pressure downstream of this valve never exceeded 60 kPa, critical flow of the drying air across the valve was maintained as the ratio of down stream to upstream absolute pressure was always less than the critical

ratio for air, 0.45. Pressure downstream of the valve was measured by a mercury manometer, 4. The air through flow rate was measured with two rotameters upstream of the electrical heater, for lower range of flow rate, 5, (Omega, FL-4215) and for higher flow rate range, 6, (Omega, FL-1502A). Calibration of these rotameters was carried out with a dry test meter with error less than 0.1%. The heater, 8, contained four electrical elements installed with a 90° angle between adjacent elements and fitted very compactly into a sealed plexiglass cylindrical housing. A perforated plate placed immediately downstream of the heater provided completely uniform air temperature and velocity to the moist paper. The volume of the system between the critical flow valve, 2, and the sheet being dried was minimized in order to minimize the change in this inventory mass of air, thus ensuring a close approach to constant G through the sheet, as detailed in Appendix 1 of Polat [1989]. The sheet holder is detailed in section 2.3.3. The pressure drop across the moist paper was measured with differential pressure transducers, 11, of three ranges of ± 1 , ± 5 and ± 15 psi. (either Statham P69 ± 1 D-350 or P6 ± 5 D-350 or PM722TC ± 15 D-350). Air leakage was eliminated by the use of O-rings at the three flanged connections. The air exhaust flow from the paper passed through the humidity measurement cell, 12, of IR-detector analyzer of fast response, less than 0.2s, 13 and 14. Inlet air temperature above the sheet and exhaust air temperatures immediately downstream of the paper were monitored at various locations with Omega E-type thermocouples of time constant less than 0.1s. The mixing-cup exit air temperature 10 cm downstream of the paper and the IR-cell temperature were also monitored.

Signals from the IR analyzer, pressure transducers and thermocouples were sent to an IBM 386 microcomputer, 15. The A/D board was Omega Engineering, Model WB-ASC with 8 double-ended or 16 single-ended channels. Sampling frequencies ranged from 0.4 to 21 Hz for the wide range of drying times provided by the experimental conditions. T-valves were used to by-pass the air flow from the IR measurement cell, 16, to keep the IR detector at ambient temperature between experiments. A processing file using macro commands in Quattro Pro™ converted raw data to calculated parameters.

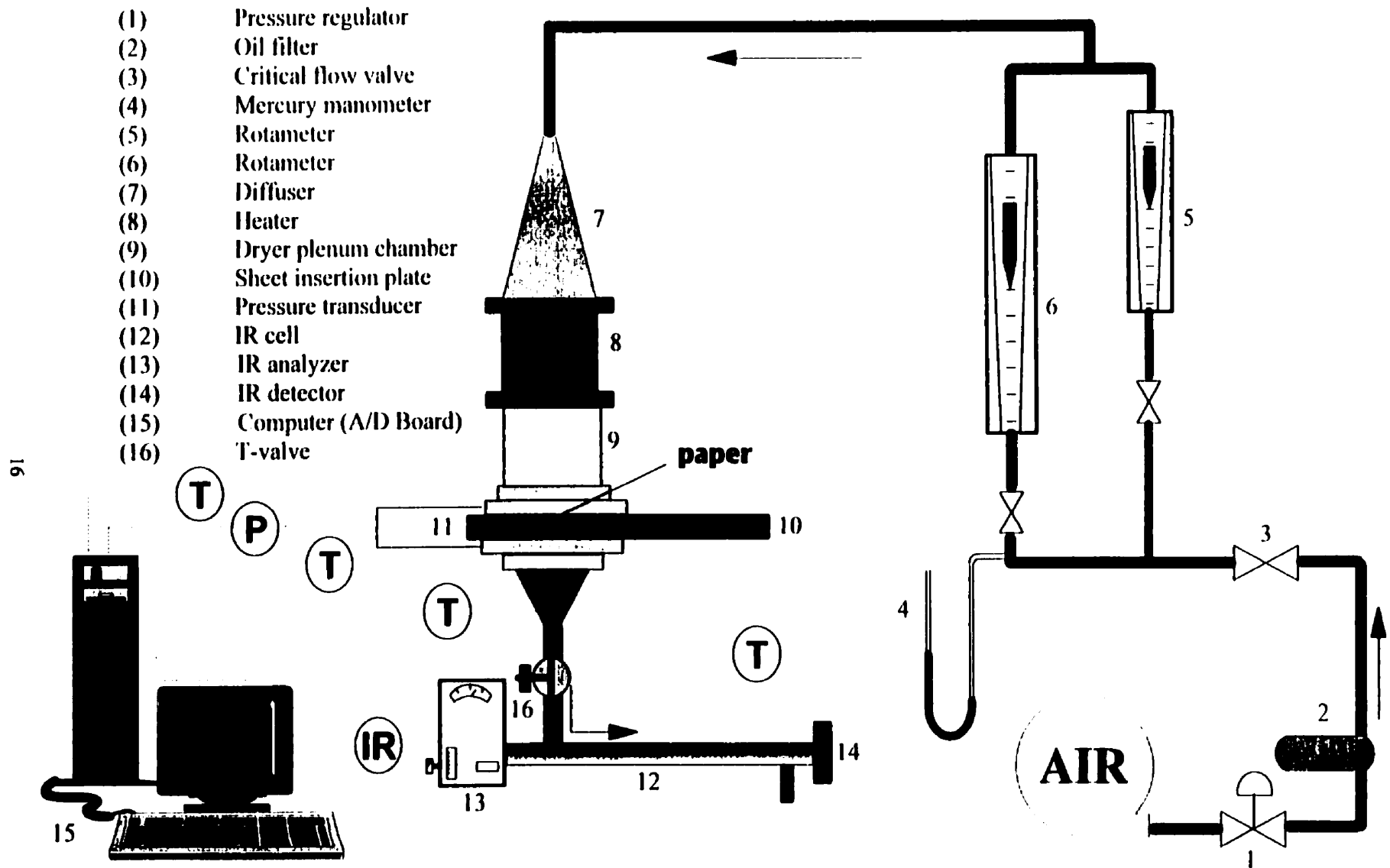


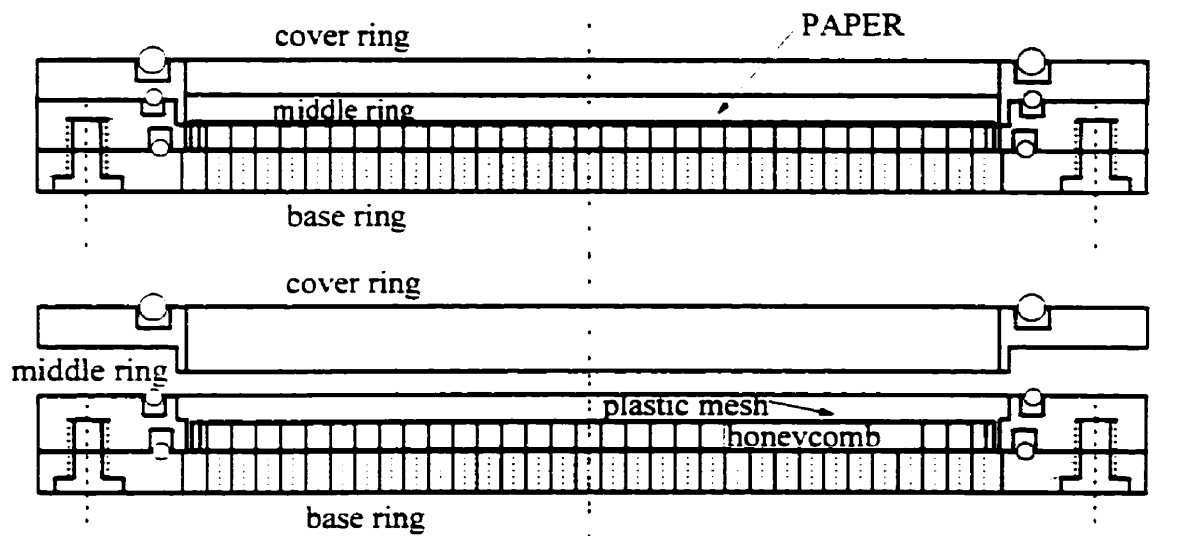
Fig 2.1 Experimental setup

2.3.3 Sheet holder

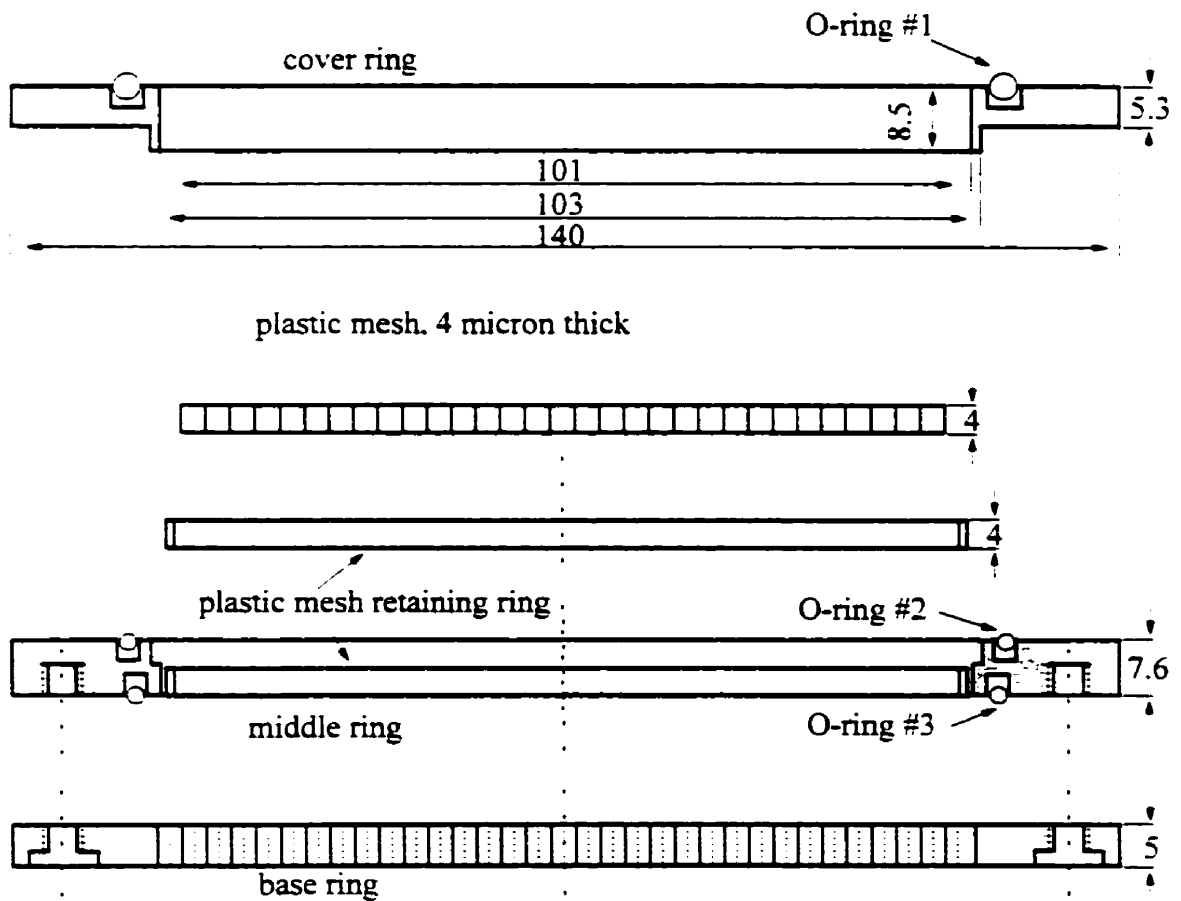
Design and fabrication of a new sheet holder for machine produced paper of much lower permeability than that in the previous use of this equipment with unfilled kraft handsheets was a major challenge. Preliminary experiments with a new sheet holder based on the design used by Polat [1989] and Chen [1994] revealed significant air leaks and by-passing around these lower permeability sheets. In order to maintain industrial relevance for the results the pressure drop across the paper was kept below 40-50 kPa, which dictated a much lower range of air flow rates than used previously, imposing more severe criteria on the tolerable air leakage. The previous use of screws to clamp the sheet in the holder was abandoned because of the wide range of types of paper tested, the unevenness of shrinkage of PM paper in the CD and MD dimensions and, most important, ambient drying of the sheet in the time required to assemble a sheet holder secured by screws.

The completely new design of sheet holder, Figure 2.2A, fabricated to accommodate paper of wide ranging thickness and permeability, consists of three major plexiglass rings (base ring, middle ring, cover ring), a honeycomb sheet support, a thin plastic mesh, a plastic retaining ring (shown both in position and separately), and 3 O-rings. These elements must be secured with O-rings to prevent air leakage to either the exterior or through by-passing the paper. A 4 μ m thick plastic mesh covering the 4mm thick aluminum honeycomb of open area more than 95%, showed negligible deformation up to 150 °C, thereby eliminating sagging of the wet sheet across the 4.2mm wide honeycomb cells. Without the need to stretch this plastic mesh tightly over the honeycomb, the sheet holder middle ring would not be needed.

Two kinds of leakage must be eliminated: air (after measurement of its flow rate) leaking to the exterior, and air reaching the exhaust flow and IR humidity meter but having by-passed the paper. O-ring #1 prevents air leakage to the exterior by sealing between the cover ring and the bottom plate of drying chamber. The wet sheet is placed on the plastic mesh with its edge clamped between the 1mm wide lip of the plexiglass middle ring which engages in the cover ring. The air reaching the sheet at this stage must



(a) Sheet holder (overall layout)



(b) Sheet holder elements (dimensions in mm)

Fig 2.2A Sheet holder design

be prevented from either leaking to the exterior from gaps between these three layers or by-passing the paper. Even if leakage occurred here, O-rings #2 and #3 prevent leakage to the exterior. The main mechanism of preventing air by-passing is by pressing the edge of the paper tightly between the top and middle rings. Moreover, air at this point cannot by-pass the sheet because the bottom of the retaining ring is sealed to the Plexiglas base ring. O-ring #3 also prevents air leakage through the holes for the screws connecting the middle and base rings. There are also O-rings installed in the flanges between the heater and diffuser, heater and dryer, dryer and insertion-retraction plate and finally between this plate and the screw rotating mechanism used to close the dryer tightly after introducing the sheet. These 7 O-rings serve to provide a leakproof system of the sheet holder, drying chamber and related piping.

As the sheet holder described above is accommodated in a sliding insertion-retraction plate, the pressure tight seal of O-ring #1. Figure 2.2A, and the two O-rings below this sliding assembly is obtained by a screw-mounted sealing ring actuated by the handle shown on Figure 2.2B. Also the insertion-retraction plate and the two supporting plates above and below this sliding plate were tightened using adjustable retaining plates. Figure 2.2B.

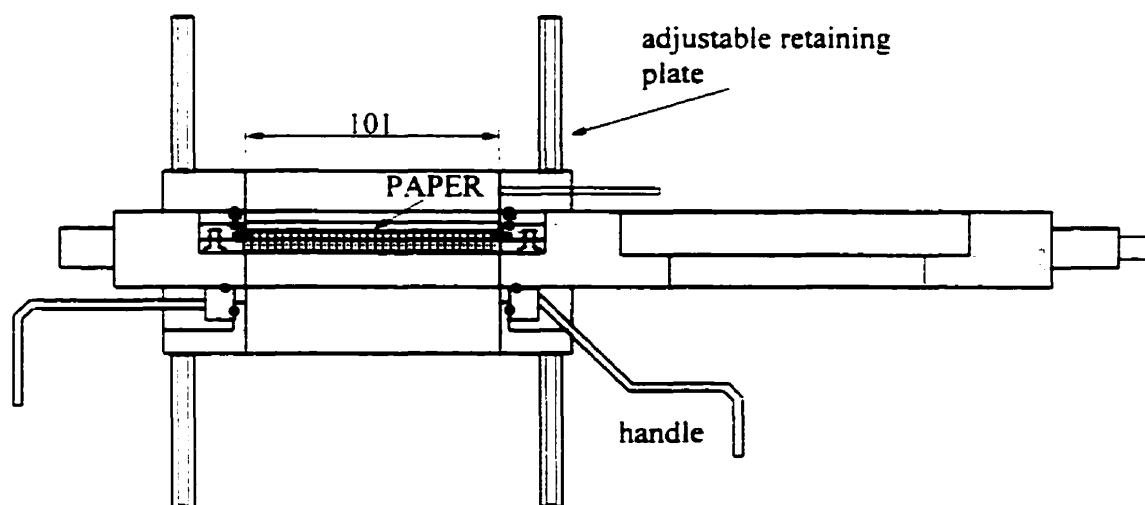


Fig. 2.2B Sheet insertion assembly

2.3.4 Pressure test

Since the prime objective of this study was to use semi-permeable machine produced printing paper, it was therefore essential for equipment to be tightly sealed. The permeability of these PM sheets is two orders of magnitude lower than the kraft handsheets used by Polat [1989] and Chen [1994]. For those sheets there is a very short transient high pressure drop at the beginning of drying, but in

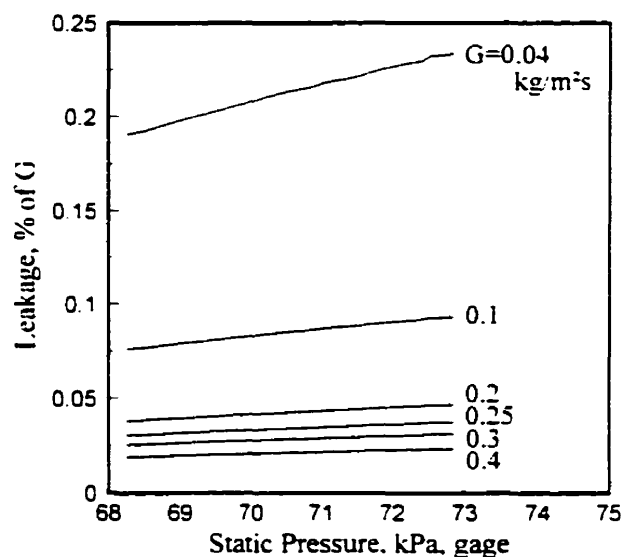


Fig. 2.3 Leakage test

the present study the pressure remains at much higher values for a longer time due to lower intensity drying conditions used. The leakage was minimized as described in section 2.3.3. The pressure test, carried out using an impermeable plastic sheet instead of paper, measures the sum of the leakage to the exterior from downstream of the critical flow valve plus any by-passing of air around the paper to the IR analyzer. Figure 2.3 shows that at a pressure of 10 psig (69 kPa), i.e. 2½ times the typical pressure drop across the paper of 4 psi, the air leakage from the system including the sheet holder, when expressed relative to the lowest flow rate used for present study, is less than 0.2%. The objective of pressure tight equipment was clearly achieved.

2.3.5 Infrared air humidity analyzer

The instantaneous values of drying rate and paper moisture content are calculated from the through flow air humidity and flow rate. The Foxboro Miran 1-A IR analyzer was adapted to the present use with a measurement cell 0.5m long, 25.4 mm inside diameter. The detector determines the light absorption of water vapor at a wavelength of 2.7 μm . Of the five strong IR absorbent bands, 2.55, 2.60, 2.66, 2.70 and 2.74 μm , excluding near and far IR regions, 2.70 μm was selected as having the best

reproducibility. Polat [1989]. By removing the C12 capacitor of the sensor, its response time was further improved to less than 0.2 s. At the IR source end of the measurement cell a concave CaF_2 lens of focal length of 250 mm was mounted, while a plane CaF_2 window was placed at the detector end.

The choice of length of IR measurement cell involves a balance between high sensitivity of the measurement, for which a longer cell is desirable, and a low time constant, given by a shorter cell. The IR spectrophotometer was calibrated against a cooled-mirror dewpoint meter (EG&G model 660) using a number of saturated salt solutions of known vapor pressure. Figure 2.4 shows the second order polynomial of a typical IR analyzer calibration curve. The calibration curve shifted slightly with lab temperature, requiring recalibration prior to use when the heat and mass balances were not satisfactory, detailed in section 2.3.6.

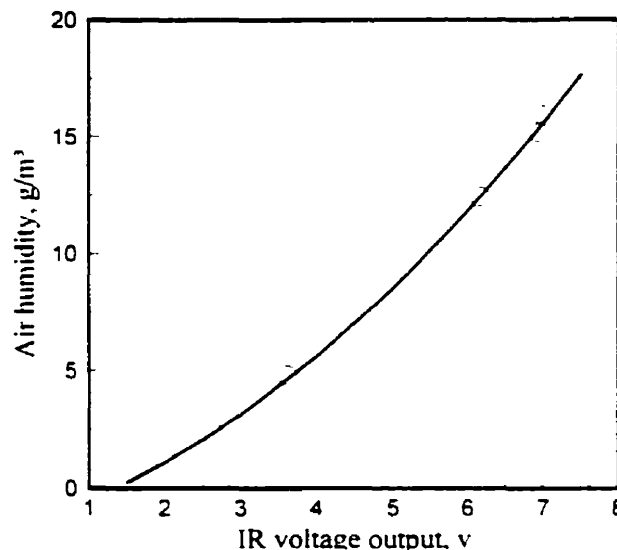


Fig. 2.4 IR analyzer calibration curve

2.3.6 Performance test

High accuracy of the measurement of drying rate was confirmed using both a continuous heat and mass balance, and an integral mass balance for water. With respect to the first check, the continuously measured exit air temperature may be compared with that temperature calculated via a continuous heat and mass balance from the monitoring of exit air humidity. The

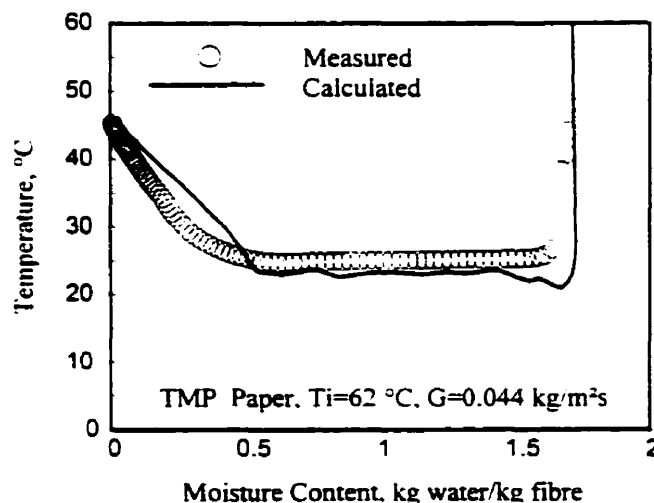


Fig. 2.5 Heat and mass balance check

typical results of Figure 2.5 show an example of the good agreement obtained. The integral mass balance was made by comparing the total amount of water removed from paper as determined gravimetrically, with that determined by integrating the drying rate curve. Carried out for every run, this check gave excellent agreement, generally within 5%, often within 2%. If the agreement was not within 10% the results were rejected. Thus the complete drying rate curves as recorded in Appendix E are of high accuracy.

Also, a high flow rate experiment of Polat [1989] was replicated at his precise conditions. For this replicate, Figure 2.6, the integral mass balance of water was 98% and very good agreement was obtained for the continuous balance over the full range, wet to dry.

As pressure drop across the paper is shown to be the most sensitive factor to any changes in paper specifications, Figure 2.7 illustrates the excellent ΔP reproducibility for a machine formed sheet. This sheet had been rewetted and redried several times prior to this test in order to eliminate any effect of the wetting-drying process on sheet structure, as elaborated subsequently.

The success of all these checks indicate that all significant air leakage was eliminated and that the experimental method produced consistent and accurate measurement of all aspects of the through drying of paper.

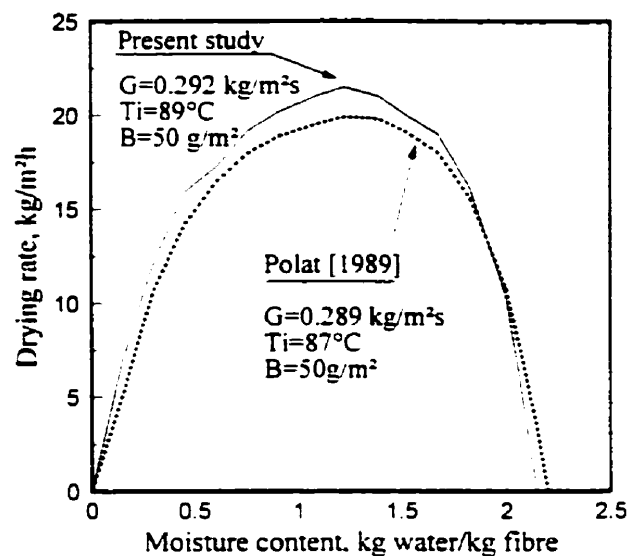


Fig. 2.6 Drying air reproducibility

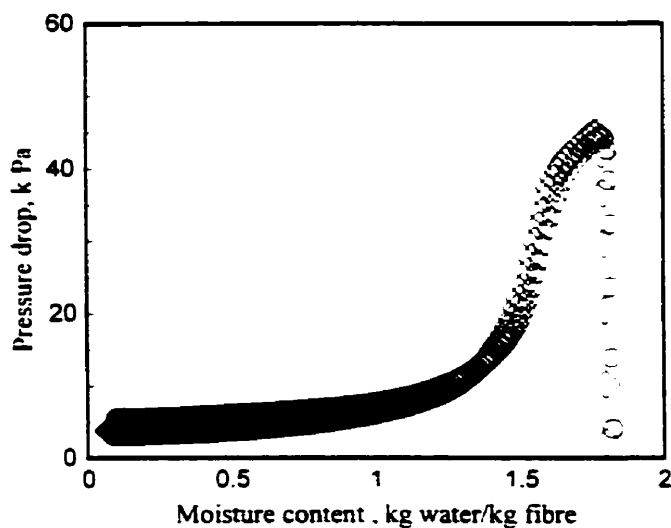


Fig. 2.7 Pressure drop reproducibility

2.4 Experimental Conditions

This study examined the effect of six parameters, for the paper: basis weight and initial moisture content, with paper from various pulp furnishes formed on various papermachines; for the drying conditions: the mass flow rate and inlet temperature of the drying air. The ten printing papers examined, all uncalendered, were made from a wide range of furnishes and formed on ten papermachines, Table 2.2 and Appendix F. All paper of each type was from a particular papermachine at the same production time. Paper from mechanical pulp furnishes has much lower permeability than the unfilled kraft paper used by Polat [1989] and Chen [1994]. For the two bleached kraft (BKP) papers, the ash contents indicate 13% inorganic filler.

Earlier industrial practice for through air drying was to operate with through flow rates limited to those giving a pressure drop of about 20 kPa. Evans [1976]. More recently Randall [1984] reports the use for semi-permeable products of through dryers capable with a vacuum up to 35 kPa and more. Browning [1978] reported installation of a through dryer with fans capable of maintaining a pressure drop of about 30 kPa for drying a special grade of toweling. In their test of drying newsprint with combined impingement and through air drying Burgess et al. [1972a,b] used vacuums to 71 kPa in their pilot plant and to 24 kPa in their mill trial without having wire marking. With the sheet support screens used here, unacceptable wire marking occurred for pressure drop higher than 60 kPa. The limit of 40 to 50 kPa pressure drop was adopted here for determining the maximum through flow rate, thus determining the generally low air flows in this study of the fundamentals of through air drying for a range of machine formed papers which are not now dried by this technique.

Whenever possible, four levels of drying air inlet temperature from 20 to 80 °C were selected. For the air used, dew point about -20 °C, these temperatures correspond to adiabatic saturation temperatures, T_{as} , of 7.2 to 30 °C. Thus the heat transfer driving force until the beginning of the rise of paper temperature at the start of falling rate drying period, $T_i - T_{as}$, ranged from 12.8° to 50°C. It was not possible to make experiments at very

low flow rates with inlet air temperatures higher than 60 °C due to condensation of water vapor on the humidity sensor cell lens of the IR analyzer, making it impossible to determine air humidity. Most experiments were carried out with sheets of initial moisture content 1.5-1.6 kg water/kg fibre, a common value for paper entering a papermachine dryer section. A few experiments were done at initial moisture content from 1.3 to 2 kg/kg in order to document the effect of this parameter on through drying characteristics.

Table 2.2 Specifications of paper tested

Type	Basis Weight g/m ²	Pulp Furnish	Freeness ml	%Fines Content
1	42.8	100% TMP	168	30.7
2	57.3	100% TMP	134	33.1
3	47.5	100% TMP	188	32.4
4	43.8	100% TMP	115	36.2
5	44	100% TMP	143	34.3
6	44.2	33% TMP, 59% GW, 8% SBK	272	36.5
7	44.5	48% TMP & 52% Flotation deinked	236	37.3
8	47.7	71.5% SGW & 28.5% Bleached kraft	365	44.2
9	68.5	100% Bleached filled kraft	426	28.3
10	81.7	100% Bleached filled kraft	440	28.8

Table 2.3 lists the complete experimental conditions. For each type of paper from 39 to 54 tests were carried out, typically with 4 levels of flow rate, at 4 levels of inlet air temperature, with one replicate of each leading to 32 experiments. For some types of paper additional replicates or experiments at other drying conditions were carried out. In total more than 400 experiments were completed, the most comprehensive investigation reported for through drying of machine-formed paper.

Table 2.3 Drying conditions

Inlet Air Temperature °C	Air Flow Rate std. m ³ /m ² s	Air Mass Flow Rate kg/m ² s	Initial Moisture Content kg water/kg fibres
20-80	0.01-0.027	0.0127-0.034	1.3-2.0

Figure 2.8 shows a typical result. The exhaust air temperature drops very rapidly, remains at about the adiabatic saturation temperature through the increasing rate period and all of the constant rate drying period, then during the falling rate drying period rises

towards the inlet air temperature. Although drying rate curves had earlier been taken as consisting of a very short temperature adjustment period and then the main drying periods of constant and falling rate. Polat et al. [1991 a] showed that the through drying process starts with an important period of increasing rate drying during which up to half of the total drying may occur. The mechanism determining the duration of the increasing rate period is not the adjustment of paper temperature, which occurs very quickly, but the development of area for heat and mass transfer within the sheet. In industrial practice the sheet passes from the press section to the dryer inlet at a moisture content, X_0 , well above that of the fibre saturation point, X_{FSP} , hence with a substantial fraction of the pores filled with water. Thus for drying under constant G , the maximum ΔP that is reached very quickly is determined by resistance to flow and by the surface tension forces holding unbound water in the pores, forces which must be overcome to establish continuous channels for air flow. As drying continues the pore volume fraction with water decreases and then vanishes, with sheet permeability increasing and ΔP decreasing sharply as displayed in Figure 2.8.

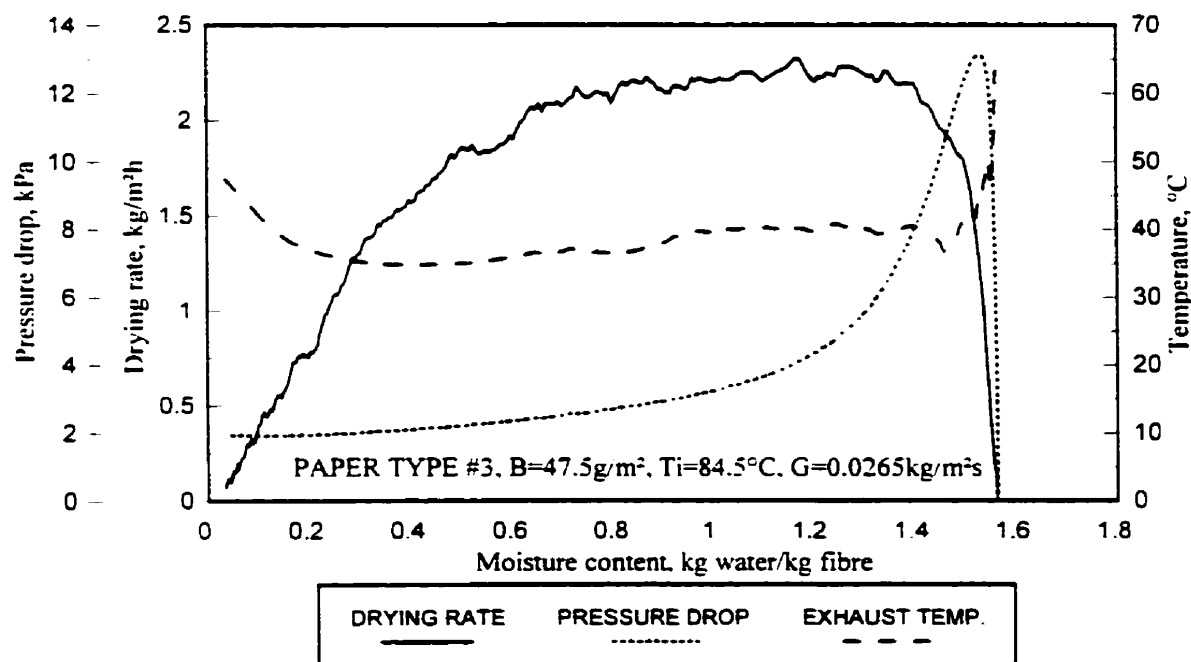


Fig. 2.8 Results from a typical through drying test

2.5 Flow Through Dry and Moist Paper

Fluid flow through porous media is involved in numerous aspects of papermaking including drainage from wet webs, dewatering, pressing and drying by the air through flow process. Permeability, porosity and specific surface, three interrelated properties of paper, are fundamental to its behavior in through drying, coating and gluing. The many studies on permeability and specific surface of paper reviewed recently by Polat et al. [1993] were mostly with handsheets or calendered machine-produced (PM) paper. The aim of this section is to investigate air flow through uncalendered dry and wet PM paper.

2.5.1 Flow through dry machine-formed paper

For analyzing flow-pressure drop characteristics, the viscous, inertial and molecular flow contributions were considered. Deviation from pure viscous flow was assessed with the power law equation:

$$\Delta P = mG^n \quad (2.1)$$

where G is air mass flow rate. For $n=1$, Darcy's law for viscous flow applies, for $n>1$ there is an inertial contribution while for $n<1$ slip flow must be considered. However, Polat [1989] for paper and several other researches for different porous media demonstrated that this equation does not provide a sensitive indication of the extent of deviation from pure viscous flow.

2.5.1.1 Permeability of dry paper as received

The pressure drop of three different sheets of each type of paper was determined at seven flow rates between 0.0127 to 0.034 kg/m²s (0.01-0.027 std. m³/m²s superficial velocity) of dry air, 21°C. Parameters m and n calculated from equation 2.1 and statistical parameters are reported in Table 2.4. The value of σ_n , less than 6% of n , derives primarily from the variation of structure between different sheets. With values of n all below but close to one, the inertial contribution is negligible but there may be some molecular flow effect. The asymptotic correlation matrix of m and n indicates strong correlation between

these two parameters. By assuming $n=1$ all the experimental data could be fitted with an acceptable $R^2 > 0.95$.

With PM paper the effects of paper specifications such as basis weight, freeness and fines content are interrelated and therefore cannot be separated. However, for just the five pure TMP papers, types 1 to 5, the deviation of n below unity increases consistently

Table 2.4 Power law exponent “n” for paper

Paper type	n	σ_n	95% Limits	$m \times 10^{-5}$	R^2
1	0.989	0.032	0.99-1.06	1.52	0.992
2	0.937	0.062	0.81-1.07	2.08	0.969
3	0.964	0.026	0.91-1.02	0.63	0.989
4	0.977	0.022	0.93-1.02	1.12	0.992
5	0.971	0.037	0.89-1.05	0.21	0.978
6	0.821	0.017	0.79-0.86	0.31	0.998
7	0.870	0.022	0.81-0.93	0.81	0.999
8	0.965	0.061	0.84-1.09	1.51	0.982
9	0.884	0.012	0.86-0.91	0.75	0.999
10	0.901	0.018	0.86-0.94	0.99	0.998

with grammage. This behavior might be caused by the effect of pin holes, of slip flow, or by both. Increase in grammage leads to a decrease in n , as the potential for slip flow effect increases with grammage and also reduction in pin holes. With paper type 1, sets of sheets were produced with 10 and 20 holes made by a precision punch of 50 μm diameter. The exponent n for these sheets was 0.99 without holes (Table 2.4), 1.09 with 10 holes and 1.2 with 20 holes. The number of pin holes has been reported to increase exponentially with decreasing basis weight for commercial paper. Corte and Kallmes [1962] and Corte and Lloyd [1966], so the increase of n with decrease of basis weight for the five TMP papers is consistent with a pin hole effect.

Lane [1943] found that for paper, air permeability was not equal to oil permeability. An important difference between the flow of liquids and gases in porous media is that in the latter case the velocity at the wall may not be zero (slip flow), Bublitz et al. [1948] and Bliesner [1964]. Slip flow is typically associated with low pressure flow which increases the mean free path of molecules, λ , but several investigators have shown

this effect in paper even at moderate pressure, Corte [1982]. To test whether molecular flow is significant, the modified Klinkenberg equation is used:

$$K_a = b + m / P \quad (2.2)$$

where P is average air pressure. To obtain meaningful results the permeability must be measured at sufficiently different values of P to cause a significant change in mean free path and not just in flow rate. For flow rate tests here with the thickest paper, the maximum reduction in mean pressure, P, corresponds to only a 3% increase in mean free path, λ , insufficient to quantify the slip flow.

For paper types 1 and 6, which give the extreme values of n, the mean pore size as determined by mercury porosimetry is 3.6 and 6.7 microns respectively, which could suggest more molecular flow for paper type 1, contrary to the evidence from values of the exponent n. However the differential intrusion data of Figure 2.9 reveal that the pore size distribution curve for paper type 1 is narrower, with a lower

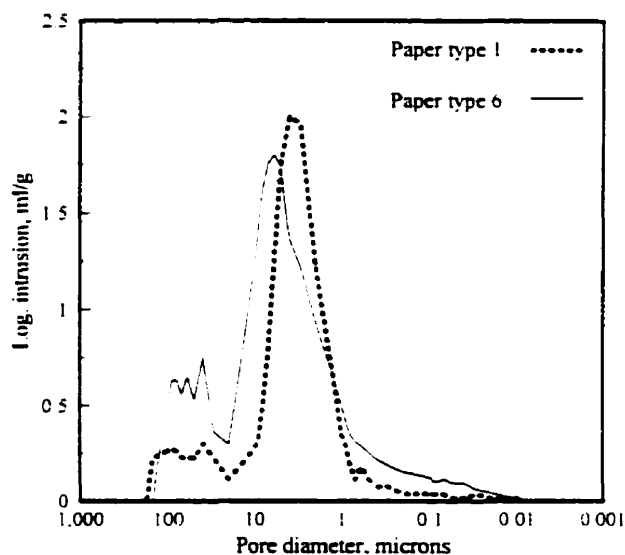


Fig. 2.9 Pore size distribution for paper types 1 and 6

percentage of pores of small radius than for paper type 6. These pore size distribution data lead to the opposite conclusion than from mean pore size, consistent with paper type 6 having the lowest value of n and thus the largest effect of slip flow.

As noted earlier, statistical analysis shows that flow through all types of paper tested here may, with $R^2 > 0.95$, be treated by Darcy's law:

$$\frac{\Delta P}{v} = \frac{L}{k} G \quad (2.3)$$

where L is paper thickness, v kinematic viscosity and k the Darcy permeability, giving the linear ΔP -G curve of Figure 2.10. The slight increase in permeability with flow rate,

Figure 2.11. is believed due to molecular flow as air pushes into smaller pores where some slip flow may occur. Quantitatively this effect is seen to be negligible.

As the present measurements were made in specialized research equipment, these results are compared in Table 2.5 with those determined with standard techniques, i.e. the Gurley densometer and Bendtsen porosimeter. The difference is small but measurable, the values for k_R averaging 8% and 14% greater than permeabilities from these test instruments.

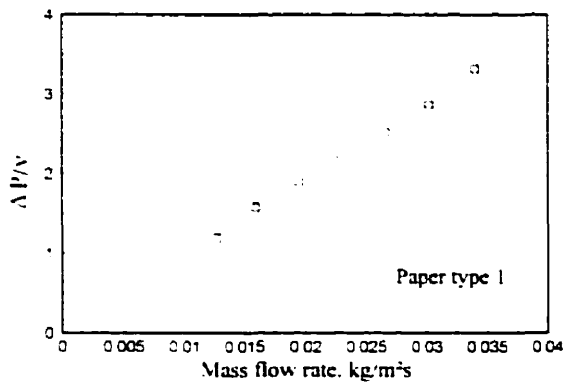


Fig. 2.10 Pressure drop-flow rate relation

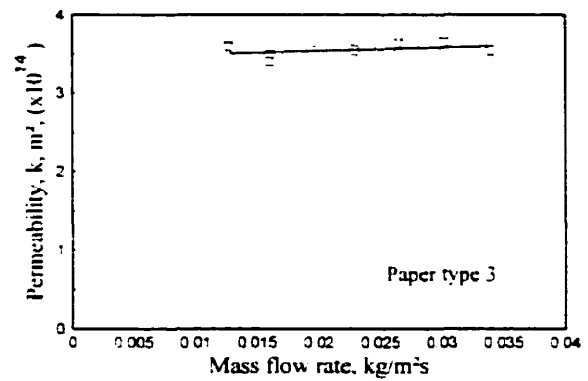


Fig. 2.11 Permeability-flow rate relation

Table 2.5 Permeability of PM paper

Paper type	k_R $\times 10^{14}$	$\% \sigma_{KR}$	k_G $\times 10^{14}$	k_B $\times 10^{14}$	$(k_R - k_G)/k_R$ %	$(k_R - k_B)/k_R$ %
1	1.33	0.1	1.12	1.00	16	24
2	1.03	1.8	0.93	1.00	9	2
3	3.57	0.7	3.12	3.00	13	16
4	1.79	0.6	1.51	1.35	16	24
5	0.91	1.0	0.77	0.77	15	15
6	4.04	1.5	3.96	3.58	2	11
7	1.51	2.3	1.46	1.14	3	24
8	1.03	1.9	0.95	0.80	8	29
9	1.48	0.9	1.46	1.48	1	0
10	1.40	0.9	1.41	1.44	0	-3

k_R : Permeability measured with present research equipment, m^2

k_G : Permeability measured with Gurley densometer, m^2 $k_G = 0.233 \times 10^{-14} \frac{L}{t}$

k_B : Permeability measured with Bendtsen porosimeter, m^2 $k_B = 2.08 \times 10^{-10} \frac{QL}{t}$
where t is seconds and Q is volumetric flow rate, ml/min.

2.5.1.2 Permeability of dry paper after a wetting-drying cycle

Laboratories studying the drying of machine-formed paper generally must use paper initially dry, which is then wetted before use. In his study of the effect of such a wetting-drying cycle for kraft

handsheets. Polat [1989] determined that after a cycle of drying the never-dried sheet, then wetting and redrying, the permeability of the dry paper approximately doubles. When this effect was tested now, starting with dry papermachine sheets, it was again found that major changes in the drying part of the cycle had no effect on permeability of the dried sheet, thus identifying wetting as the cause of the change in permeability from a wetting-drying cycle. For ten PM papers after a wetting-drying cycle, Table 2.6. shows that these permeability increases for pure TMP paper average about 25% while for filled kraft paper the increase is about 40-50%. i.e.

less than half the increase reported by Polat et al. [1993] for unfilled kraft handsheets from unbeaten pulp. Laivins and Scallen [1993] also noted the lower sensitivity of TMP paper to wetting, reporting that TMP pulp showed no changes in permeability after a wetting-drying cycle while for chemical pulp the increase was considerable.

Table 2.6 Effect of wetting

Paper type	$k \times 10^{14} \text{ m}^2$	$\sigma_k \times 10^{14}$	R^2	% Increase
1	1.73	0.020	0.941	31
2	1.25	0.015	0.920	22
3	3.90	0.052	0.928	9
4	2.30	0.036	0.879	29
5	1.11	0.011	0.960	23
6	4.57	0.045	0.946	13
7	2.01	0.015	0.972	33
8	1.55	0.025	0.903	51
9	2.10	0.025	0.917	42
10	2.02	0.025	0.910	45

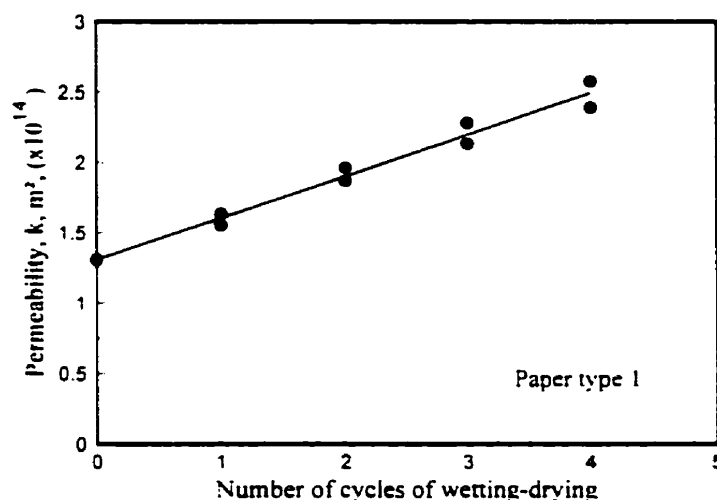


Fig. 2.12 Effect of wetting on permeability

Because of the need to subject PM paper to wetting before any laboratory drying, it is of interest to determine the response of the paper to repeated cycles of wetting-drying. For TMP paper type 1 the Figure 2.12 results indicate that permeability continues to increase for up to 4 such cycles, with

$$k_N = k_0 + A(N_w) \quad (2.4)$$

where N_w is the number of wetting-drying cycles, k_0 is the permeability of dry paper before the first wetting.

2.5.1.3 Effects of papermaking parameters on permeability

The structure of paper is significantly affected by the composition of the pulp stock, the furnish, from which it is made. Also, processes such as wet pressing, beating and bleaching used in the manufacture of paper would affect paper structure. Here these factors are termed *papermaking parameters*. Between different machine-produced papers, typically several of these parameters are changed, so the effect on permeability from each variable generally cannot be determined. However the Figure 2.13 comparison does suggest that for pure TMP papers the modified permeability, k/L , is decreased by increased refining.

In a series of experiments using 60 g/m^2 TMP handsheets prepared by the CPPA standard technique, with the fines content changed between 10 and 40%, Figure 2.14 illustrates the great sensitivity of paper permeability, which decreases by more than two orders of magnitude as the fines content increases from 10 to 40%. The fines used in these handsheets were obtained from the same pulp at the Pulp and Paper Research Institute of Canada using a Float Wash Fractionator equipped with a 200

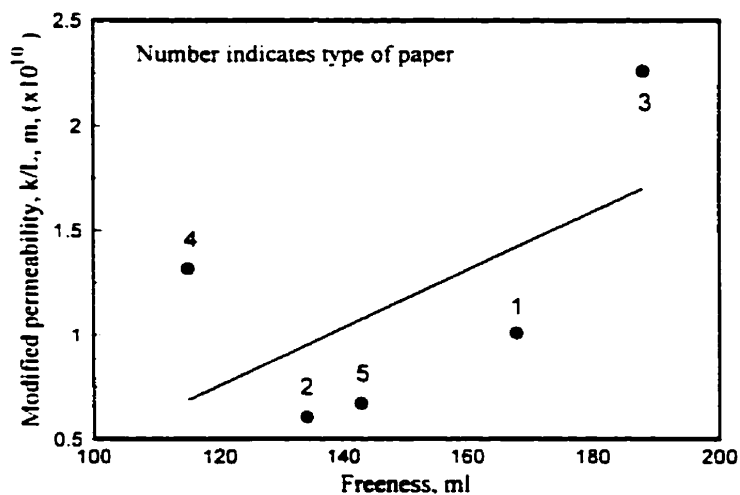


Fig. 2.13 Effects of freeness on modified permeability

Mesh screen. The long fibre fraction was obtained with the Bauer-McNett classifier.

As it is common practice in laboratory studies to use handsheets, it is of interest to examine the effect on permeability of sheet formation. Thus a machine produced TMP paper, was wetted and dried several times to

minimize the effect of the wetting process on sheet structure, discussed in the previous section. Some of this paper was reslushed and five handsheets of the same basis weight were produced. A closed water recycle system was used so that the fines content of handsheets could be considered the same as in the original paper, 26 wt% as determined by the Bauer-McNett classifier. For the five handsheets the average value of permeability was $1.46 \times 10^{-14} \text{ m}^2$, compared to $1.74 \times 10^{-14} \text{ m}^2$ for the PM paper. The 15% lower permeability for the handsheets of the same fines content would derive from their more uniform formation structure.

2.5.1.4 Summary

Although it was demonstrated that for uncalendered machine-formed papers, some molecular flow behavior occurred for some paper types as well as effects coming from pin holes, but the use of Darcy's law for all 10 commercial papers was shown to be acceptable for the flow rate range used. Permeability determined from standard methods, the Gurley densometer and Bendtsen porosimeter, differed by less than 15% from the more precise values determined in the specialized through flow equipment. As only certain combinations of papermaking parameters are used commercially, with interaction between their effects on permeability, it is not possible to quantify the effects of individual papermaking parameters.

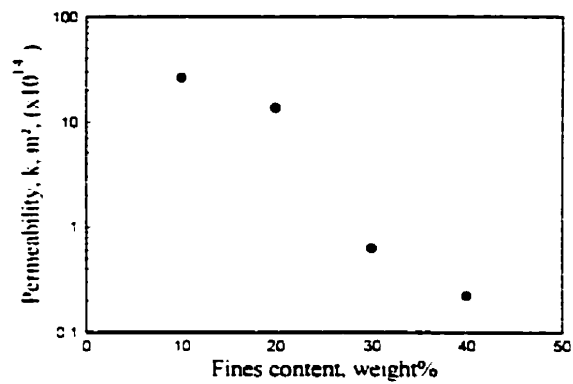


Fig. 2.14 Effect of fines on permeability

2.5.2 Flow through moist machine-formed paper

Air flow through wet paper is important when the sheet passes over papermachine suction boxes and in through air dryers. Sheet permeability depends on moisture content and paper structure, the latter being determined by the furnish, formation and type of paper. Examination of the extension of through air drying beyond its current use for tissue and toweling to heavier grades of paper requires information on the permeability of wet, machine-formed papers. In the limited data available, Table 2.7, those of Burgess et al. [1972 a] were for only a few sheets of Papriformer newsprint at a single, very high value of moisture content, 2 kg water/kg fibre. The handsheets made from unfilled, unbeaten kraft pulp used by Polat [1989] differ significantly from commercial paper both by furnish and formation. Thus a comprehensive characterization of air flow through moist, uncalendered, commercial papers is required.

Although the present work was carried out with a specialized research facility, an objective was to develop a method of estimating the permeability of wet paper based on measurements with standard test equipment usable with dry paper only.

2.5.2.1 Effects of sheet characteristics on ΔP -X-G relation

The initial very sharp rise in ΔP for all results, Figures 2.15 and 2.16, occurs during the short transient period of pressurizing the system after sheet insertion when air flow through the sheet is less than the constant mass flow rate into the system. This transient period was made very short by minimizing the system volume. Only ΔP -X data were used when G through the sheet was within 1% of the set value of G .

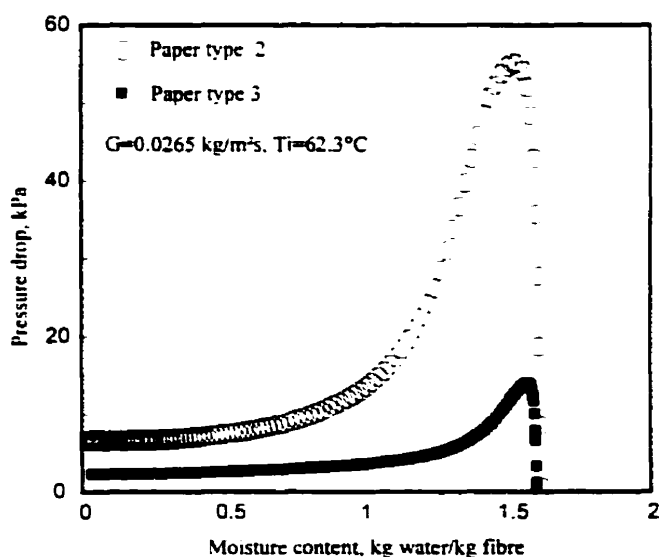


Fig. 2.15 Effect of TMP refining on ΔP -X

Table 2.7.. Summary of air flow through moist paper

Investigation	Type of Paper (Formation & Furnish)	Grammage (g/m ²)	Range of Moisture Content kg water/kg fibre	Air Quality	Limitations
White and Marceau [1962]	Blotter and Filter Paper Bleached Soda and Sulfite Paper Kraft Paper*	41-196	0.35 to dry	Saturated	Low measurement accuracy Very limited moisture content Use of Darcy's law
Brundrett & Baines [1966]	Handsheets from kraft newsprint furnish, and bleached sulfite pulps	48-86	0.4 to dry	Saturated	Low measurement accuracy Inconsistent results Handsheets only Use of Darcy's law
Burgess et al [1972]	Machine-Formed Newsprint Douglas Fir, Mixed Hardwood furnish	115-131	0-2.0	Unsaturated	A few experiments only Use of Darcy's law
Polar [1989]	Handsheets, from Unbleached Kraft	25-250	3.5 to dry	Unsaturated	Handsheets only

*may contain cotton linter, clay and starch

Effects of primary papermaking parameters, refining, formation and fines content, on the k - ΔP - X - G characteristics were examined. For a specific through flow rate, G , Figure 2.15 shows the effect of refining on the ΔP - X curve for two TMP papers of almost identical basis weight and fines content but with 40% different freeness. Table 2.2. Paper made from the less refined, lower freeness pulp (type 3) gives a much

reduced ΔP , i.e. a higher permeability. For paper types 1 and 5 of the same furnish and almost identical basis weight and freeness. Figure 2.16 shows the effect of fines content. Comparisons cannot be made at high X because the initial moisture contents differ, but from about 1.4 kg water/kg fibre to dryness the higher fines content paper, type 5, causes a significantly higher ΔP , that is, a lower permeability.

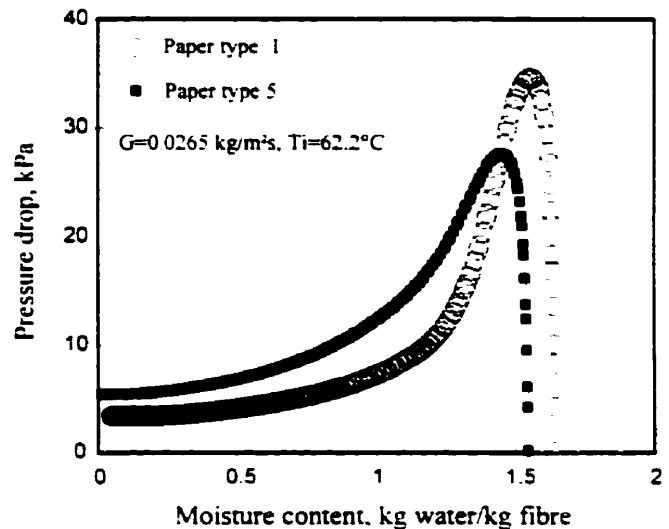


Fig. 2.16 Effect of fines content on ΔP - X

Drying five sheets of one type of machine-formed paper from different initial moisture contents, Figure 2.17, shows the substantial variability between nominally identical 103 mm diameter sheets in the sensitive, high moisture content range. However the permeability curves for all sheets converge at approximately the fibre saturation point, X_{FSP} , about 0.72 kg water/kg fibre for this TMP paper, Table 2.2. For drying below X_{FSP} , flow is through a 2-phase packed bed of unsaturated fibers and pores occupied entirely by air, while above X_{FSP} the presence of some free water in the pores provides a 3-phase packed bed of reduced permeability to air flow. Thus below X_{FSP} , the ΔP - X curves become independent of X_0 , over the range of initial moisture content tested here. Figure 2.17, as would be expected. From X_{FSP} down to dry paper the ΔP decreases by only one-half or less, while in the range 1.3 to 2 kg/kg the ΔP can be 10 to 20 times that of dry paper.

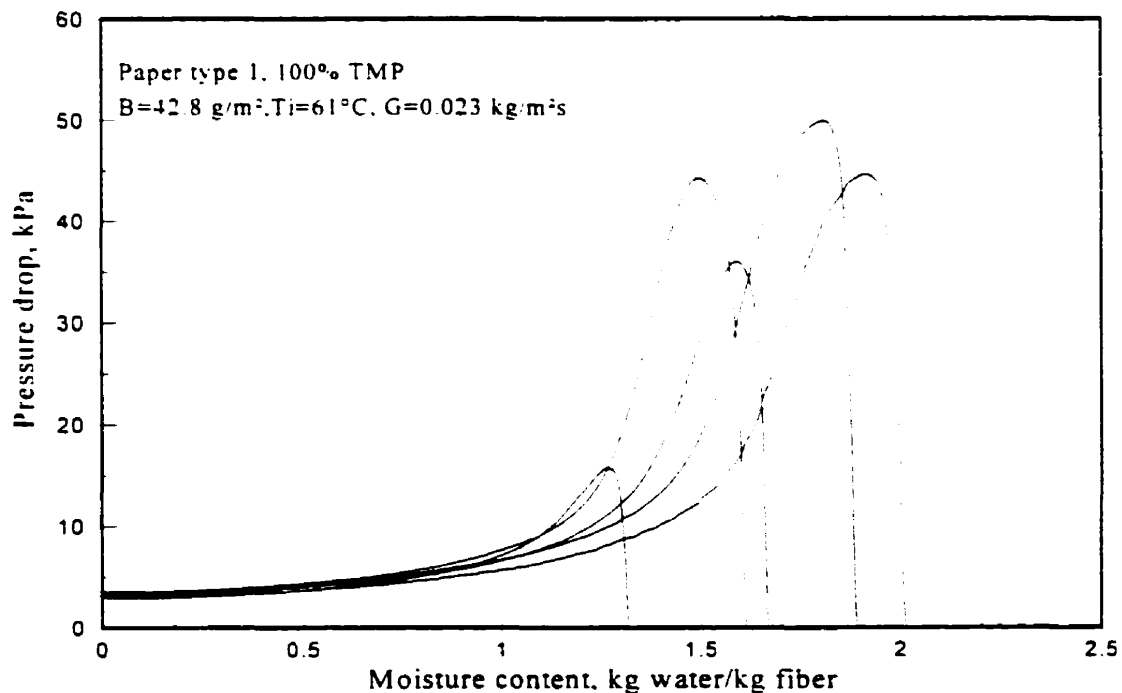


Fig. 2.17 Effect of initial moisture content on ΔP - X

The ΔP - X curves for $X < X_{FSP}$ of Figure 2.18 for six sheets of the same TMP paper indicate the variation in permeability attributable to differences in sheet structure between small (103mm diam.) samples of machine-formed paper. With the ΔP - X relation expressed as:

$$\Delta P = A + BX + CX^3 \quad (2.5)$$

all coefficients depend on the type of paper, on G and to a small extent on X_0 . Coefficient A is slightly lower than the ΔP for dry paper as received from the mill because of the rewetting effect, as discussed earlier. The lines and equation 2.5 coefficients shown in Figure 2.19 derive from 6 sheets of each paper types, dried under the Figure 2.18 conditions. For drying below the FSP the fibres shrink, providing a more permeable sheet, while the sheet shrinks, decreasing its permeability. The fiber shrinkage effect is seen to dominate over that of sheet shrinkage.

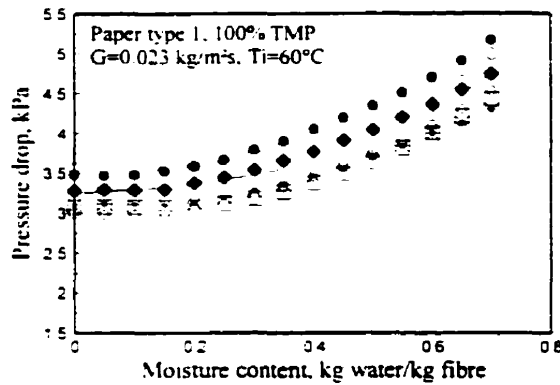


Fig. 2.18 ΔP - X relations below FSP

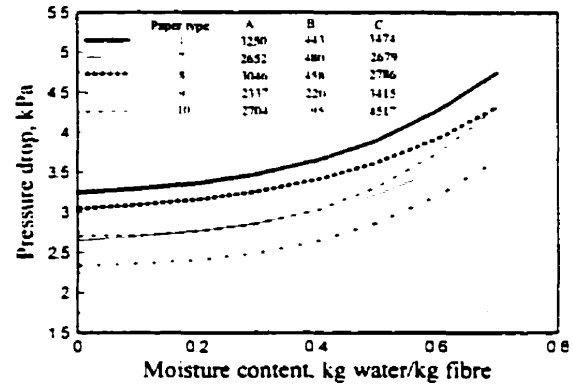


Fig. 2.19 Eqn. 2.5 for 5 types of paper

For $X > X_{FSP}$, the distribution of free water in the pores is governed by surface tension. Smaller pores, having higher specific surface and surface tension forces, retain water preferentially over larger pores. Thus for drying from high X_0 down to the X_{FSP} , larger pores become available first for air flow, the smallest pores losing their water only as $X \rightarrow X_{FSP}$. Thus mean pore size decreases as X decreases.

The overwhelming importance of the effect of furnish is illustrated by tests made for two machine-formed sheets of 44g/m^2 , one from

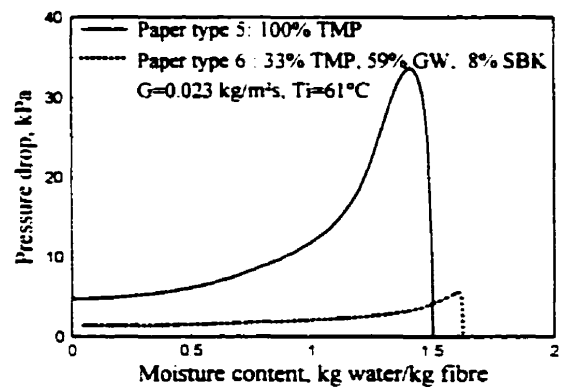


Fig. 2.20 Effect of furnish on ΔP - X

100% TMP, the other from a blended furnish only one-third TMP. Figure 2.20 shows that for the blended furnish with only 8% of the high permeability kraft pulp, the ΔP when wet and when dry is only, respectively, 1/5 and 1/3 that for pure TMP paper.

While Figures 2.17 to 2.20 and Table 2.2 show the ΔP -X-G relation to be a sensitive function of papermaking parameters, these effects cannot be analyzed quantitatively using machine-formed paper because each paper has a particular combination of these parameters.

2.5.2.2 Permeability of moist machine-formed paper

Depending on sheet structure, moisture content and through flow rate, one may have molecular, viscous or inertial flow in some or all of the flow in a packed bed where, as in paper, the pores constitute a complex network of tortuous and irregular shape. The extent of deviations from Darcy's law (pure viscous flow) was therefore tested by applying the power law relation, equation 2.1, to the ΔP -X-G data. The exponent n was calculated for the ΔP -G data at a specific moisture content, X , for individual paper types. Figure 2.21 shows such plots at $X=0.5$ kg water/kg fibre for several paper types, with the value of " n " given in Appendix H for all cases for which the correlation coefficient, R^2 , exceeded 0.8. At higher moisture content naturally the values of σ_n increase and of R^2 decrease due to the higher degree of scattering of data at higher X .

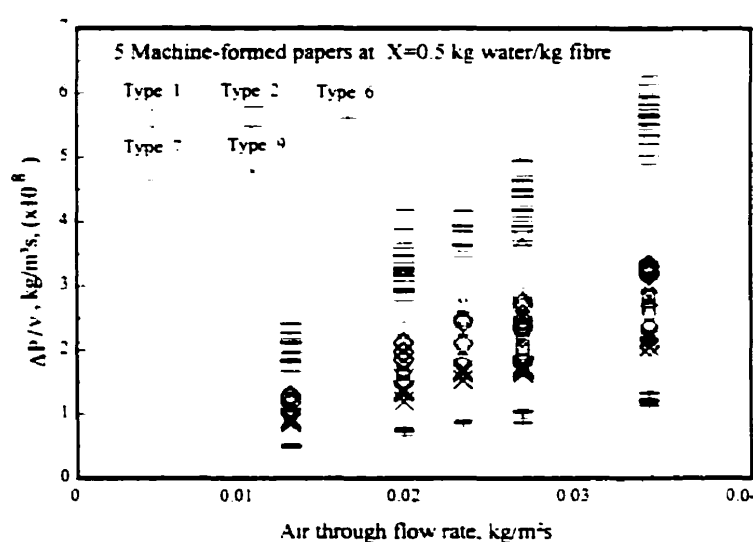


Fig. 2.21 ΔP -G relationship of moist paper

Figure 2.21 shows such plots at $X=0.5$ kg water/kg fibre for several paper types, with the value of " n " given in Appendix H for all cases for which the correlation coefficient, R^2 , exceeded 0.8. At higher moisture content naturally the values of σ_n increase and of R^2 decrease due to the higher degree of scattering of data at higher X .

Figure 2.22 shows the exponent " n " (determined for the Figure 2.21 data) becoming independent of moisture content at low levels of moisture content, generally for $X < X_{FSP}$. There n - X relations permit several comparisons. The n - X curves for papers types 3, 4 and 5 show the considerable variability between pure TMP papers, those for papers 6 and 8 show

the effect of adding unbeaten kraft pulp to a mechanical pulp furnish, while the values of $n < 1$ for papers 9 and 10 show that fine mineral fillers give a sheet with small pores, producing molecular flow effects. For $X > X_{FSP}$ the higher values of n reflect the higher interstitial air velocities as the increasingly water-filled pores become less available for air flow, hence the contribution of inertial effects to pressure drop become more important.

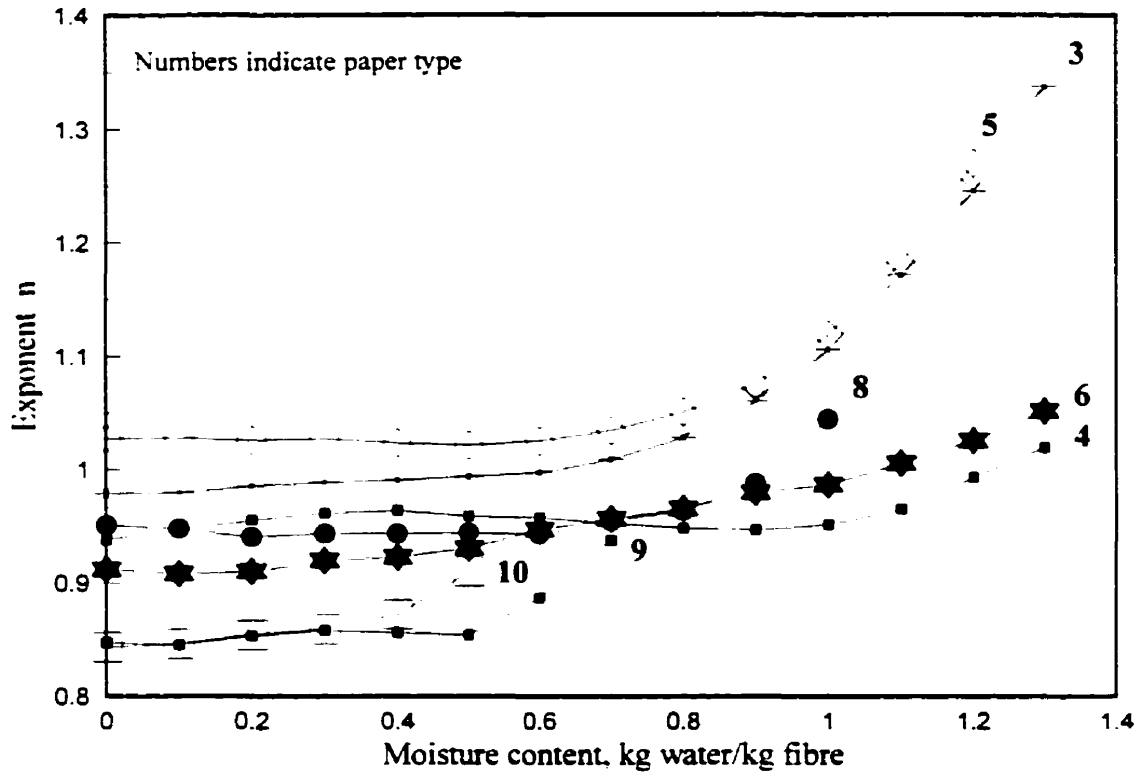


Fig. 2.22 Effect of moisture content on exponent n

Sheet permeability for viscous flow ($n=1$) is calculated from Darcy's law but when the flow includes inertial as well as viscous effects, the complete momentum transport equation, often called the Forchheimer equation, for additive resistances applies:

$$\frac{\Delta P}{vGL} = \alpha + \beta \frac{G}{\mu} \quad (2.6)$$

in which $\alpha = 1/k$ and $\beta = c/\sqrt{k}$, with c the inertial flow constant. For the low permeability printing papers used here, with flow rate restricted to maintain ΔP across the wet sheet below 50 kPa, the inertial contribution was generally not sufficiently large to enable

determination of β , as Polat [1989] was able to do for high permeability kraft handsheets. Thus β was determined when acceptable statistical reliability so permitted, but generally permeability was calculated using Darcy's law. Because the paper thickness-sheet moisture content relation, a difficult determination, is not available, the k/L modified permeability was calculated. At each moisture content there were from 38 to 52 ΔP -G data available to calculate permeability. The sample results of Figure 2.23 for three of the TMP papers show that the only case for which there is a measurable inertial contribution to ΔP for $X > 1.2$ kg/kg is for TMP paper type 3.

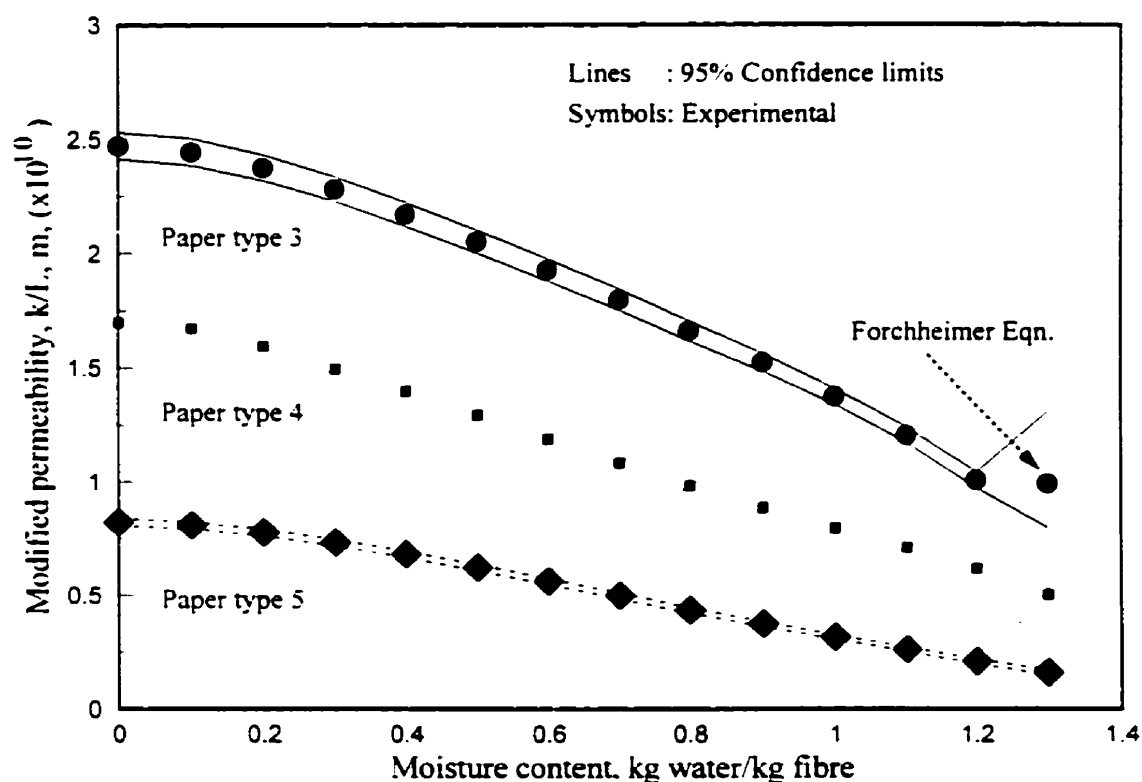


Fig. 2.23 Effect of moisture content on modified permeability, k/L

2.5.2.3 Effect of paper characteristics on modified permeability

Although interaction between the effects of various papermaking parameters makes it impossible to separate these effects, some limited comparisons are possible. From Table 2.2 the fines content of paper types 6, 7 and 8 are 36.5%, 37.3% and 44.2%.

Adding unbeaten kraft pulp to the mechanical pulp furnishes increases pulp freeness. Paper type 7 with no kraft in its furnish has a freeness of 236 ml while the freeness of papers 6 and 8 with, respectively, 8% and 28.5% unbeaten kraft, is 272 ml and 365 ml. Although lower pulp freeness is associated with lower paper

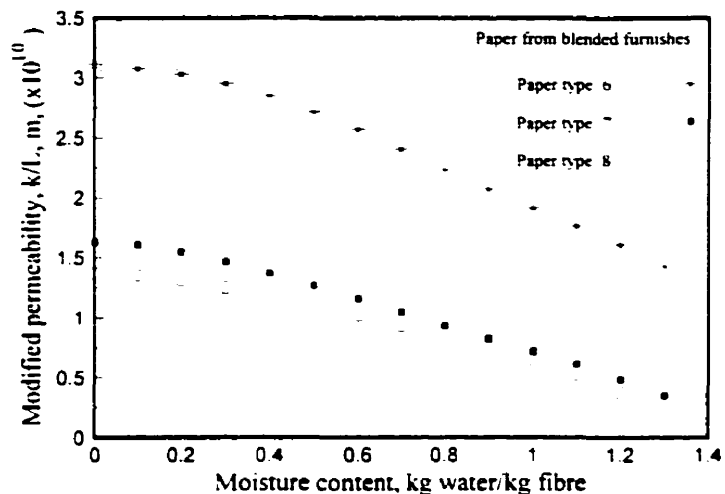


Fig. 2.24 Effect of fines content on k/L

permeability. Figure 2.24 indicates that for these papers the differences in fines content have more effect on permeability than those for freeness. Paper 6 from the furnish of lowest freeness but also lowest fines content has by far the highest modified permeability.

Corte [1958] and Bliesner [1964] showed that as paper thickness increases, mean pore size decreases and the pore size distribution becomes narrower. Thus the k/L permeability decreases with increasing basis weight, as was found by Polat et al. [1993] for unfilled kraft handsheets. Table 2.2 shows that the two beaten, filled kraft papers, are of almost identical freeness, fiber saturation point (FSP), fines content and furnish, but are substantially different in basis weight: 68.5 g/m² for type 9, 81.7 g/m² for type 10. Figure 2.25 shows that paper type 10, of about 20% greater basis weight, has a 20-25% lower k/L modified permeability. With k/L decreasing with basis weight, k decreases less with increasing basis weight than if k/L were independent of basis weight. With the normal nonuniformity in local grammage of machine-formed paper the locally heavier regions will of course have a lower permeability k but not so low as if k/L were independent of basis weight. Although local nonuniformity of

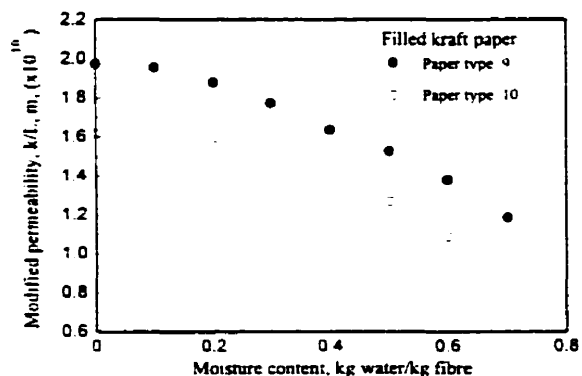


Fig. 2.25 Effect of grammage on k/L

through flow rate across the sheet under a uniform ΔP in through air drying is a topic beyond the scope here. the present results will be seen subsequently to be relevant to this important practical aspect.

2.5.2.4 Correlation of modified permeability with moisture content

For water flow through paper webs in press nips. Nilsson and Larsson [1968] used a power law for the moisture content dependence of the inverse of modified water permeability. Polat [1989] followed their approach in relating the reciprocal of modified air permeability L/k , with X as:

$$\frac{L}{k} = A' + B' X^C \quad (2.7)$$

Based on the Poisson distribution of fibres in paper. Corte [1982], the probability of a pore space at a given point is an exponential function of the number of fibres. Hence an alternate L/k - X relationship would be analogous to the pore diameter-moisture content relation, as follows:

$$\frac{L}{k} = a + be^{cx} \quad (2.8)$$

The fitted parameters for both the power law and the exponential equations are summarized in Table 2.8. the exponential form giving a marginally better correlation.

2.5.2.5 Generalized permeability curve

For the ten types of machine-formed paper tested plus standard kraft handsheets, Figure 2.26 shows the effect of moisture content on the modified permeability normalized to the value $(k/L)_0$ of the same paper when dry. Although these sheets cover a wide range of furnish and formation, the normalized permeabilities follow a similar trend. The best power law fit for all 11 paper types is

$$(k / L) / (k / L)_0 = 1.0 - aX^b \quad (2.9)$$

where $a=0.52$, $b=1.35$. Table 2.9 gives the maximum error by use of equation 2.9. Below the fibre saturation point the maximum deviation is $\pm 7\%$, while at $X=1.3$ kg water/kg fibre the deviation reaches a maximum of $\pm 23\%$. Figure 2.26 shows that over the range from

X=0.6 kg/kg to dryness, the region with no water in the inter-fibre pores, permeability increases an average by only about 20%.

Table 2.8 Parameters for modified permeability-moisture content correlations

Paper type	Exponential model				Power law model			
	$a \times 10^{10}$	$b \times 10^{10}$	c	R^2	$A' \times 10^{10}$	$B' \times 10^{10}$	C'	R^2
1	0.840	0.101	4.523	0.99	0.904	0.848	5.400	0.98
2	1.400	0.218	4.420	0.99	1.516	1.685	5.222	0.99
3	0.407	0.141	3.149	0.99	0.439	0.303	3.677	0.99
4	0.500	0.915	2.120	0.99	0.627	0.657	2.536	0.99
5	1.125	1.043	2.976	0.99	1.343	1.885	3.471	0.99
6	0.276	0.381	1.848	0.99	0.325	0.199	2.298	0.99
7	0.628	0.242	3.458	0.99	6.962	7.131	4.040	0.99
8	0.836	0.027	5.527	0.99	0.877	0.592	6.717	0.98
9	0.469	0.331	3.448	0.99	0.511	0.731	2.288	0.99
10	0.613	0.085	6.023	0.99	0.634	2.157	3.819	0.99

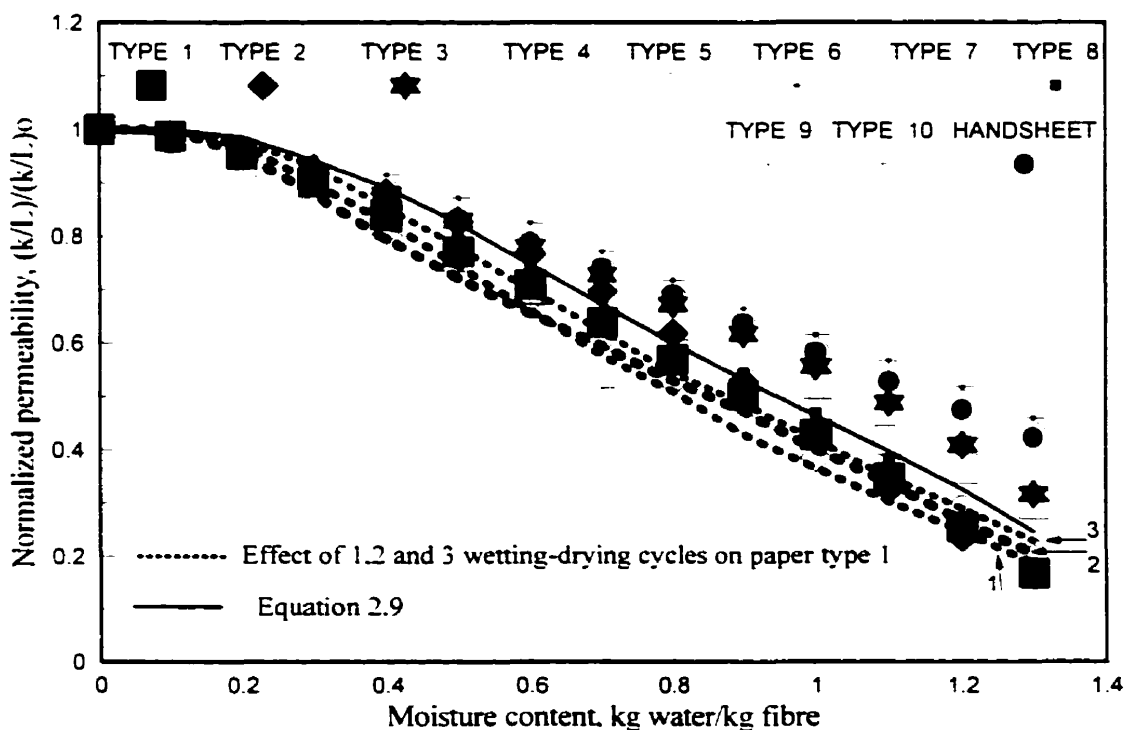


Fig.2.26 Effect of moisture content on normalized modified permeability

Table 2.9: Maximum error in use of equation 2.9

X, kg/kg	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3
Error (%)	0	1	2	4	5	7	10	12	15	19	23	27	37	47

From high moisture contents down to the fibre saturation point, permeability increases because of removal of water from pores. With X_{FSP} being the condition with all water in the fibres and none in the pores, a sharp change might be expected in the permeability - moisture content curve at that point. The results in Figures 2.23-2.26 show no such break point. The standard X_{FSP} determination is for an equilibrium condition, whereas drying is a dynamic process. Due to local nonuniformity in structure, machine-formed paper has a locally nonuniform moisture content during drying. During the drying, then, when the sheet average moisture content reaches the X_{FSP} , some regions of the sheet are locally above the FSP while other regions are below this moisture content. For this reason it should be expected that when the sheet average moisture content is being reduced by drying, the transition between permeability behavior with and without water in the pores would be gradual, with no sharp change when sheet average moisture content is at the fibre saturation point value.

For laboratory studies involving the drying of papermachine formed paper, including the present work, dry commercially produced paper is rewetted before drying. In order to examine the application of equation 2.9 for such use, this rewetting - redrying cycle was repeated three times for TMP paper type 1. The dashed lines for the k/L - X relation in Figure 2.26 become progressively lower with each repetition of this cycle, but this relation remains within the range of experimental variability around equation 2.9.

2.5.2.5 Application in through drying of paper

Without specialized through flow apparatus suitable for wet paper such as used here the ΔP across moist paper can be estimated as follows. The standard methods for measuring dry permeability are the Gurley densometer and the Bendtsen porosimeter which, for dry paper only, provide data comparable to that obtained for paper of any moisture with the present specialized equipment. Equations were obtained in the previous section for

conversion to paper permeability from those results as Gurley seconds and Bendtsen milliliters.

Thus with a single measurement of k/L for dry, machine-produced paper made with the Gurley, Bendtsen or other valid method, equation 2.9 enables estimation of moist permeability and hence pressure drop for air flow through that paper at any moisture content, to an accuracy as given in Table 2.9. For precise determination of the ΔP -X-G relationship for a specific type of machine produced paper, measurements over a range of moisture content must be made using equipment designed for measurements with wet paper, as in the present study. The knowledge of wet paper permeability and pressure drop are relevant to the performance of suction boxes and are essential in determining process economics and feasibility for through air drying.

2.5.2.6 Summary

A comprehensive set of air through flow measurements for paper from wet to dry has documented the relationship between pressure drop, through flow rate, sheet moisture content and permeability for a wide range of grades of uncalendered machine-formed paper from different papermachines. For flow through this nonuniform thin packed bed, deviations from Darcy's law behavior were determined. The complete momentum transfer equation was used to calculate permeability when there was a significant inertial contribution to pressure drop. Correlations of k/L modified permeability to moisture content were obtained. Effects on pressure drop-moisture content-permeability relations of moist paper were investigated for the papermaking parameters of furnish, fines content, formation and basis weight.

While providing knowledge about air flow through wet, machine-formed paper, this investigation also establishes a method for estimating the permeability and pressure drop over a significant range of sheet moisture content. This method derives from demonstrating that for diverse types of paper the nondimensional ratio of permeability of moist to dry paper shows a generalized dependence on sheet moisture content. Application of this method requires only one measurement, which may be obtained using any of the standard

methods of determining the resistance of dry paper to air flow. Combination of this simple measurement with the general correlation obtained here for the permeability - moisture content relation provides the method of estimating, for diverse types of paper, the permeability and hence the pressure drop-air through flow rate relation as a function of sheet moisture content. When more accurate values of moist paper permeability than this estimate are required, one must use equipment especially designed for air flow through wet sheets, such as that described here.

2.5.3 Specific surface and porosity of paper

As permeability is structure dependent, efforts have been made to relate it to properties of the porous medium by assuming a model of the structure. As an alternative, most models use highly idealized geometries that can be described with just a few parameters. These models are of three types, those based on flow through networks of conduits, on flow around solid obstructions (drag theories), or based on empirical correlations. In consolidated, dense systems such as paper, conduit flow models are the most appropriate, Bird et al. [1956], Polat et al. [1992 a]. The best known of this type is the Kozeny-Carman equation where the porous medium is assumed to be equivalent to a single channel with an effective diameter equal to four times the hydraulic radius of the medium. This equation has been widely used for paper, Carson [1934], Ingmanson et al. [1959], Knauf and Doshi [1986] and Polat et al. [1993].

2.5.3.1 Comparative porosity and specific surface of unwetted PM paper

The most common phenomenological approach, based on geometric considerations, is the Kozeny-Carman equation

$$a_p^2 = \frac{1}{\kappa} \frac{\varepsilon^3}{(1-\varepsilon)^2} \frac{1}{k} \quad (2.10)$$

where ε is porosity and κ the Kozeny constant, generally taken as 5.55 in determining specific surface a_p , m^2/m^3 . With the form in which porosity enters equation 2.10 with power of 3, this property must be determined precisely. Porosity may be evaluated from paper thickness by a caliper gage according to CPPA standard D4, its basis weight and

fibre density, ρ_f , or directly by mercury porosimetry. The accuracy of thickness by caliper is limited due to surface roughness and paper compressibility. Kraft pulp fibre density is usually taken, with reason, as that of pure cellulose, 1550kg/m^3 , with this value being often assumed for TMP fibres also. With these uncertainties porosity was also determined by mercury porosimetry. For the grades as received from paper mills the results in Table 2.10 indicate that porosity from paper density averages 10% higher than by porosimetry. The specific area values listed were calculated using equation 2.10 and $\rho_f = 1550\text{ kg/m}^3$.

Stone and Scallen [1965] reported nitrogen adsorption method a_p values of $0.5\text{--}1.0\text{m}^2/\text{g}$ for bleached kraft paper. For unbleached unfilled kraft handsheets of $25\text{--}250\text{g/m}^2$ made from pulp of freeness 685ml , Polat et al. [1993] obtained a_p values of $0.51\text{--}0.95\text{m}^2/\text{g}$, close to those of Gurnagul and Gray [1987] using inverse gas chromatography (IGC). For calendered newsprint (70% TMP, 30% SGW) they determined $a_p = 1.4\text{m}^2/\text{g}$ with the IGC method. Previous researchers generally did not document the freeness and fines content.

Table 2.10 Porosity and specific surface of paper

Paper type	L_{caliper} μm	ε Mercury Porosimetry	ε Caliper & Grammage	a_p Unwetted $\text{m}^2/\text{m}^3 \cdot 10^{-6}$	a_p Unwetted m^2/g
1	129.6	0.736	0.803	8.82	4.94
2	170.2	0.670	0.730	6.97	5.34
3	158.0	0.637	0.736	3.15	2.59
4	136.4	0.687	0.759	5.78	4.07
5	136.9	0.703	0.776	8.86	5.80
6	148.0	0.721	0.781	4.64	3.22
7	123.4	0.681	0.757	7.37	4.69
8	108.5	0.635	0.713	5.80	3.56
9	105.0	0.538	0.638	2.98	1.58
10	122.0	0.514	0.563	2.72	1.70

2.5.3.2 Validity of Kozeny-Carman equation

The above literature citations for specific surface are much lower than the Table 2.10 values. Many researchers have reported the Kozeny factor to be a strong function of

web porosity. In his study on water permeability, Ingmanson et al. [1959], after Davies [1952], documented the Kozeny factor as a function of porosity as follows:

$$\kappa = a \frac{\varepsilon^3}{(1-\varepsilon)^{\frac{1}{2}}} \left[1 + b(1-\varepsilon)^{\frac{1}{2}} \right] \quad (2.11)$$

where constants a and b are 3.5 and 57 respectively for mats made from glass and nylon fibres. This equation also fits the results of Brown [1950] from air permeability measurements with glass fibre sheets. Values of the Kozeny constant by Equation 2.11 of about 5.55 in the porosity range 0.7-0.8 apply for all these papers used here except types 9 and 10, for which the calculated Kozeny constant is 5.3 and 5.1 respectively. Thus the higher values of specific surface obtained here were not due to the effect of porosity on Kozeny constant.

Three major factors which may increase the specific surface are beating, formation and fines. Ingmanson and Andrews [1959] showed that treatment of a bleached sulphite pulp in a ball mill for 250 minutes prior to forming an unconsolidated fibre mat increased a_p from 0.75 to 2.6 m²/g, presumably by fibrillation, while a_p of the fines increased from 8.0 to 26.0 m²/g. When a kraft pulp was beaten, reducing its freeness from 725 to 345ml, Knauf and Doshi [1986] reported that the a_p values of 60 to 200g/m² handsheets as calculated from Kozeny-Carman equation increased from 0.60 to 1.6 m²/g. Although this beating would produce fines, this was not documented, the results being correlated only with freeness. Applying the Knauf and Doshi [1986] correlation to the case of a 60g/m² handsheet from kraft pulp of freeness 685ml used by Polat et al. [1993] gives an a_p of 0.69 m²/g, comparing well to the 0.76 m²/g value they reported for a 50g/m² handsheet. Applying the Knauf correlation for two 60g/m² sheets from bleached kraft with freeness of 426 and 440ml, similar to the freeness of paper types 9 and 10 here, gives a_p values of 1.45 and 1.40 m²/g. These levels of specific area for sheets containing 13 and 11% fillers are quite close to the Kozeny-Carman equation values given in Table 2.10 for types 9 and 10 with 28-29% fines, which would increase a_p somewhat. Paper types 9 and 10 illustrate the interaction in paper characteristics. Relative to paper type 10, type 9 shows that more beating, i.e. decreased freeness, causes higher porosity, hence higher permeability, and also a higher a_p .

To check for the effect of formation and fines content on the Kozeny-Carman equation validity, three types of tests were carried out. First, to examine the formation difference between handsheets and PM paper, the a_p value of a TMP handsheet with 26.4% fines was calculated both from that equation and by mercury porosimetry. For five TMP handsheets, a_p averaged $5.4 \text{ m}^2/\text{g}$ with the Kozeny-Carman equation but $2.1 \text{ m}^2/\text{g}$ as determined with mercury porosimetry, considered the absolute measurement. Thus with handsheets as well as with the PM papers of Table 2.10, the Kozeny-Carman based values appear too high.

In the next test, the linear correlation proposed by Haselton [1955] and Swanson and Steber [1959] between optical scattering coefficient and specific surface determined by nitrogen adsorption was used, as recommended by Scallen and Borch [1974]. Comparison of the Table 2.10 and 2.11 results show that a_p from the Kozeny-Carman equation is always substantially higher than that determined from scattering coefficient.

Table 2.11 Scattering coefficient and specific surface comparison

Paper type	1	2	3	4	5	6	7	8	9	10
Scattering coefficient	60	57.8	58.8	59.3	65.1	60.2	65.7	68.6	55.8	54.9
$a_p, \text{ m}^2/\text{g}$, from scattering coefficient	1.30	1.25	1.27	1.28	1.41	1.30	1.43	1.49	1.20	1.18
$a_p, \text{ m}^2/\text{g}$, from Kozeny-Carman eqn.	4.94	5.34	2.59	4.07	5.80	3.22	4.69	3.56	1.58	1.70

In the third set of tests the effect of the 10-40% fines content in TMP handsheets was studied. In Figure 2.27 the slight increase in a_p with fines content by the light scattering method is reasonable, while the enormous increase by the Kozeny-Carman equation is not. The Kozeny-Carman equation with $\kappa=5.55$, derived for straight cylindrical pores, is clearly not valid for paper with substantial fines content. To obtain a_p values for high fines content paper from the Kozeny-Carman equation comparable with those from scattering coefficient would require an unreasonable change in the Kozeny constant by up to two orders of magnitude.

The Kozeny-Carman equation can however be used to indicate relative changes in specific surface, m^2/m^3 , of dry paper caused by wetting. Comparison of the Table 2.12 and 2.10 results shows an average decrease of about 11% in specific surface after a wetting- drying cycle. Although Gray [1982] reported no effect of wetting- drying on specific surface of calendered newsprint, all others report a decrease in surface area. For unfilled handsheets

from unbeaten kraft pulp Polat et al. [1993] reported a drop in specific surface after wetting-drying of 2-11%, a change attributed to the wetting. Gurnagul and Gray [1987] reported that wetting decreases the surface area of bleached kraft handsheets by 16-19%.

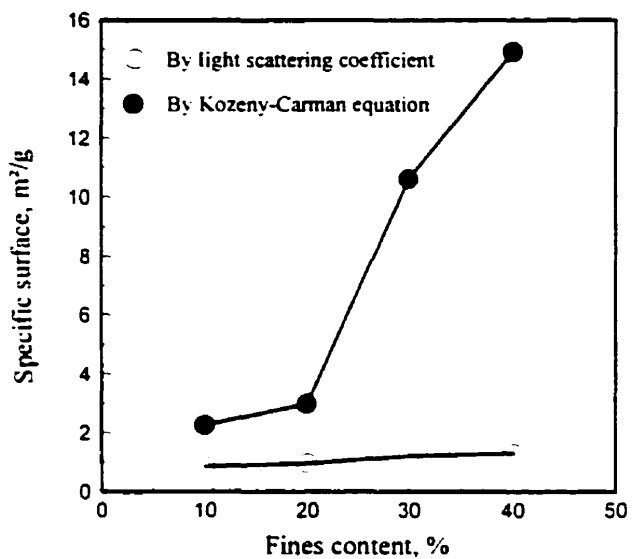


Fig. 2.27 Effect of fines content on a_p

Table 2.12 Change in specific surface of paper from a wetting-drying cycle

Spec. Surface $a_p, \text{m}^2/\text{g}$	Paper type									
	1	2	3	4	5	6	7	8	9	10
Before cycle	4.94	5.34	2.59	4.07	5.80	3.22	4.69	3.56	1.58	1.70
After cycle	4.82	4.73	2.48	3.43	4.76	2.82	3.31	3.54	1.46	1.60
% decrease	2	11	4	16	18	12	29	0	8	6

2.5.3.3 Summary

Porosity calculated from paper density was about 10% higher than that from mercury porosimetry. Specific surface area calculated from the Kozeny-Carman equation using the standard value of $\kappa=5.55$ was substantially higher than that obtained from scattering coefficient and mercury porosimetry. For a kraft furnish the change in Kozeny constant by beating could explain part of the higher values obtained for specific surface. However for paper from TMP and mechanical-chemical pulp blends neither this factor nor sheet formation could justify these anomalously high values of specific surface.

Experiments with handsheets established that the Kozeny-Carman equation is not applicable to paper with a substantial fines content. The failure of this equation for paper of significant fines content could be attributed to the actual sheet structure deviating greatly from that of the straight cylindrical pores assumed in the derivation of this equation. The permeability of dry paper increases and the specific surface decreases after a wetting-drying cycle, due apparently to the collapse of fibrils during the wetting.

2.5.4 Characteristic dimension analysis

The alternative to the common characterization of air flow through paper as permeability is the nondimensional Reynolds number-friction factor model for flow through packed bed. Polat et al. [1989] applied this approach for the first time to paper. They reviewed previous attempts to define and measure a characteristic dimension for flow through paper, essential for nondimensional parameters such as Reynolds, Nusselt, Sherwood and Peclet numbers. For this nonhomogeneous anisotropic porous medium they showed that all previously proposed empirical approximation for the characteristic dimension are unsatisfactory approximations. They established that the theoretically correct characteristic dimension for flow through paper, d_p , is provided by the ratio of the constants of the inertial to viscous terms in momentum transport equation. For the high permeability unfilled kraft handsheets used to demonstrate this approach they showed that the values of the characteristic dimension thus determined from momentum transport equation were consistent with the results from Scanning Electron Microscopy (SEM) and were about an order of magnitude larger than those given by two widely used definitions, i.e. square root of permeability and reciprocal of specific surface. To determine this valid d_p for a sheet requires, as a minimum, two independent pieces of information on the mass flow rate-pressure drop relationship covering the region of measurable inertial effects. The range of flow rates used here for through air drying, Table 2.3, is limited to low flow rates to keep the maximum pressure drop across the wet sheet at the start of drying at about 50 kPa. For the semi-permeable grades paper used, this ΔP constraint limited the flow rates to the range for which the contribution to ΔP from inertial effects for moist paper was too small to be measurable.

Although it was for this reason not possible to calculate d_p for moist paper from data taken during through drying, higher flow rates could be used to calculate d_p for these semi-permeable grades when dry. For this purpose two flow rates, 0.419 and 0.207 $\text{kg/m}^2\text{s}$, were used as it can be demonstrated that the best choice of flow rates to calculate d_p are the maximum flow rate practical and one-half of that value. For the 10 types of machine-formed paper used after a wetting drying cycle, Table 2.13 shows that this fluid mechanics based d_p as well as the mean pore size as determined from mercury porosimetry.

Table 2.13 Characteristic dimension for paper

Paper type	1	2	3	4	5	6	7	8	9	10
d_p , μm	2.7	4.4	4.9	3.2	1.2	9.3	6.7	5.0	4.4	4.3
2σ of d_p , μm	0.7	0.5	0.2	0.1	0.4	0.5	0.3	0.2	0.2	0.1
Mean pore size, μm	3.5	5.0	4.4	4.7	4.1	6.7	4.1	3.7	2.7	3.0

Bliesner [1964] showed that the pore size distribution in paper does not change significantly with basis weight above 50 g/m^2 . The study of Polat et al [1989] documented that for kraft handsheets d_p does not decrease much, by perhaps 20%, for basis weight from 50 to 250 g/m^2 , but that d_p increases by a factor of four as paper basis weight decreases from 50 to 25 g/m^2 . As the range of basis weight of the 10 types of paper tested here is from 43 to 82 g/m^2 it is other factors, such as the type of pulp and type and content of fines, which would be the source of variation in values of the characteristic dimension d_p .

Two comparisons with the d_p characteristic dimension are shown. Figure 2.28 for mean pore size from mercury porosimetry, and Figure 2.29 for permeability. Examination of the range

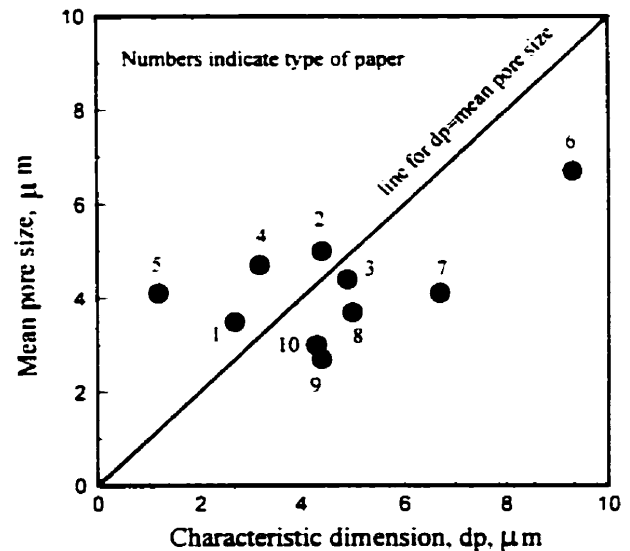


Fig. 2.28 d_p -mean pore size relationship

of values of freeness of the pulp with fines content (Table 2.2), porosity (Table 2.10) and specific surface by scattering coefficient (Table 2.11) does not lead to any conclusion as to the range of values of d_p nor the relationship between d_p and mean pore size. The interaction between these variables in the structure of the sheet that determines the nature of the flow through the paper is evidently

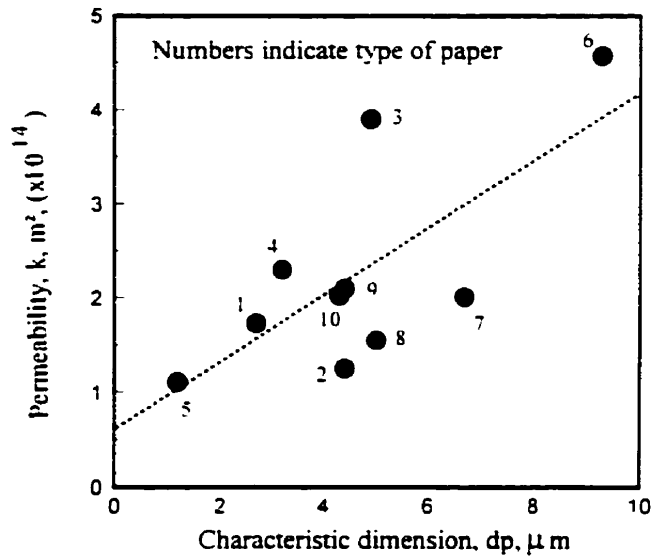


Fig. 2.29 d_p - permeability relationship

too complex to enable drawing general conclusions yet. As permeability is the reciprocal of the coefficient α for the viscous term in the momentum transport equation, while $d_p = \beta/\alpha$ is the ratio of the coefficients of the inertial and viscous terms in this equation, the d_p characteristic dimension contains information not present in permeability. None the less, for these 10 machine-formed grades there is a very approximate correlation between their d_p and permeability as illustrated in Figure 2.29, with type 5 having the lowest values of both d_p and permeability while type 6 has the highest values of each of these parameters.

2.5.4.1 Reynolds number-friction factor relationship

The literature provides various definitions of friction factor for representing in nondimensional form the energy loss from flow as a function of Reynolds number. Introduction of the new characteristic dimension for paper, d_p , based rigorously on the momentum transport equation enables characterizing the flow through this thin packed bed as a Re - f relation. The momentum transport equation 2.6, may be rearranged to

$$\frac{\Delta P}{\beta G^2} \frac{L}{\rho} = 1 + \frac{\alpha \mu}{\beta G} \quad (2.12)$$

Using the definition of $d_p = \beta/\alpha$ and of Reynolds number leads to

$$\frac{\Delta P}{\beta G^2} \frac{L}{\rho} = 1 + \frac{1}{Re} \quad (2.13)$$

or

$$f = 1 + \frac{1}{Re} \quad (2.14)$$

Polat et al. [1989] noted that using this approach eliminates the need for the various porosity, pore size distribution, particle or pore shape empirical factors required in earlier treatments.

For the low range of air flow rate used during through drying experiments and the high range of flow rates used just with dry paper, Figure 2.30 shows the pressure drop measurements for paper type 1 expressed as friction factor based on the above equation. In the range of low flow rate the contribution of the inertial term to pressure drop is seen to be negligible. For this semi-permeable grade of paper the deviation from Darcy's law due to the effect of the inertial term only starts to be significant at highest flow rate used, which for these experiments was $G=0.4 \text{ kg/m}^2\text{s}$.

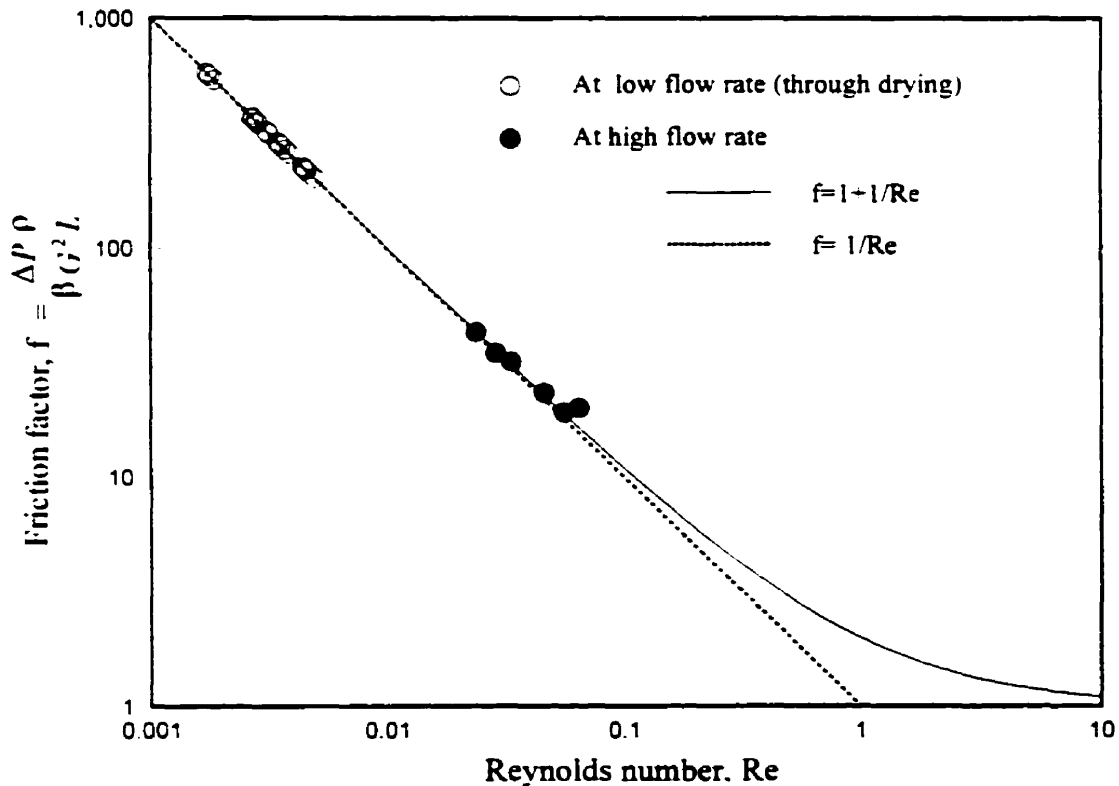


Fig. 2.30 Re-f relationship for dry TMP paper, type 1

2.6 Through Air Drying History Curve

The intimate contact of drying air and moist fibres is the source of the higher rate of through drying relative to the standard cylinder drying process where heat transfer is by conduction from sheet contact with a hot surface. The typical result, Figure 2.8 in section 2.4, illustrated that the air temperature at the through flow exhaust, T_e , follows the constraint for adiabatic drying with T_e at first much below the inlet air temperature, T_i , then rising to approach T_i as the drying rate drops toward zero. As very low humidity air was used, a completely dry sheet was obtained. In the processing of results first the different drying periods must be distinguished, then parameters characterizing each drying period are determined for analysis. In developing basic understanding of the interaction of sheet parameters and drying process conditions the present study was carried out at low intensity drying conditions, hence the low level of drying rates.

2.6.1 Effects of process parameters on drying rate curves and drying rate periods

Figures 2.31 and 2.32 show sets of typical through drying data at the extremes of low and high intensity conditions tested. For the lowest T_i used, the drying rate first passes through a sharp maximum before approaching a nearly steady value, the constant drying rate. This spike at the beginning of drying reflects the paper cooling to the adiabatic saturation temperature, here about 8°C. This feature is not treated as it is not

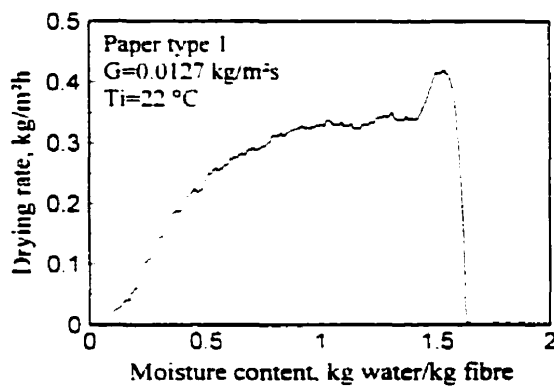


Fig. 2.31 Typical R-X curve at lowest intensity drying

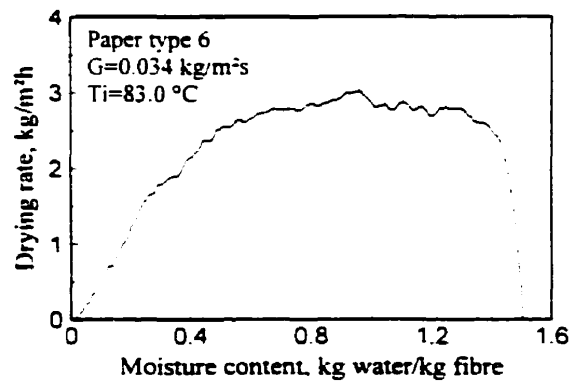


Fig. 2.32 Typical R-X curve at higher intensity drying

relevant to industrial drying. The drying rate remains relatively constant until the paper moisture content drops to that for the start of the falling rate period. At the higher intensity drying condition, Figure 2.32, the same trend is observed without that initial spike in drying rate, with the increasing, constant and falling rate drying periods apparent. For through drying with constant G , Polat [1989] showed that of the three drying periods the increasing rate period had previously been taken incorrectly as a very short transient for the sheet to adjust to the adiabatic saturation temperature. He established that the increasing rate period ends only when the area available for heat transfer within the web has been increased sufficiently by the opening of pores so that the rate of drying reaches that of the constant rate period. He determined that the increasing rate period could provide as much as 40% of the drying. With the lower through flow rates here for semi-permeable sheets and the correspondingly low values of the constant drying rate, the extent of the increasing rate period is at most 20% of the total drying. The transition from constant to falling rate drying is always gradual, as discussed subsequently.

Effects on the drying rate curve were examined for four parameters, drying air temperature and mass flow rate, T_i and G , the paper initial moisture content X_0 and the sheet grammage B . The dependence of drying rate curves on drying intensity is illustrated on Figure 2.33 for variable inlet air temperature T_i and on Figure 2.34 for variable air mass flow rate G . Paper initial moisture content could be considered either a drying process parameter or paper specification. Figure 2.35 reveals that although X_0 has no effect on R_c , the onset of falling rate drying period at X_c increases as paper initial moisture content increases.

The basis weights of these ten types of machine-formed paper, Table 2.2, are all in the range of 40-57 g/m² except paper types 9 and 10, 68.5 and 81.7 g/m². For kraft handsheets Polat [1989] showed that for sheets heavier than tissue paper the effect of grammage is small, as is again seen on Figure 2.36. After these qualitative observations on the drying rate curves the quantitative treatment follows.

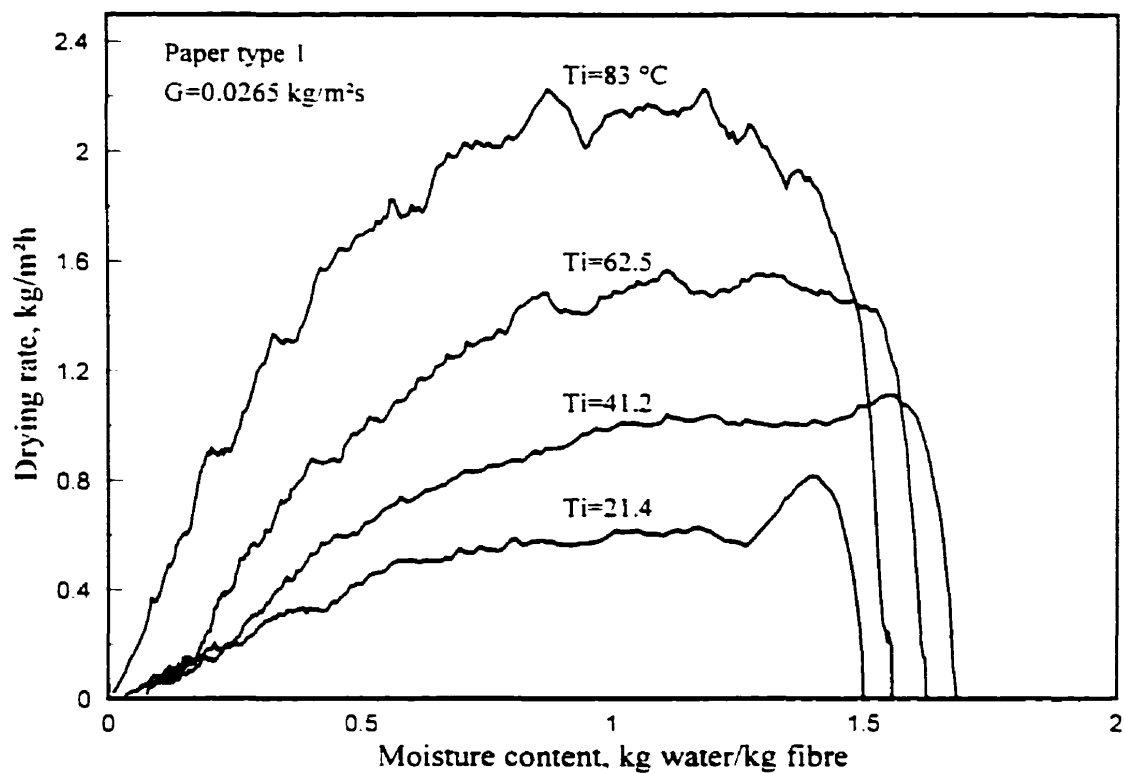


Fig. 2.33 Effect of inlet air temperature

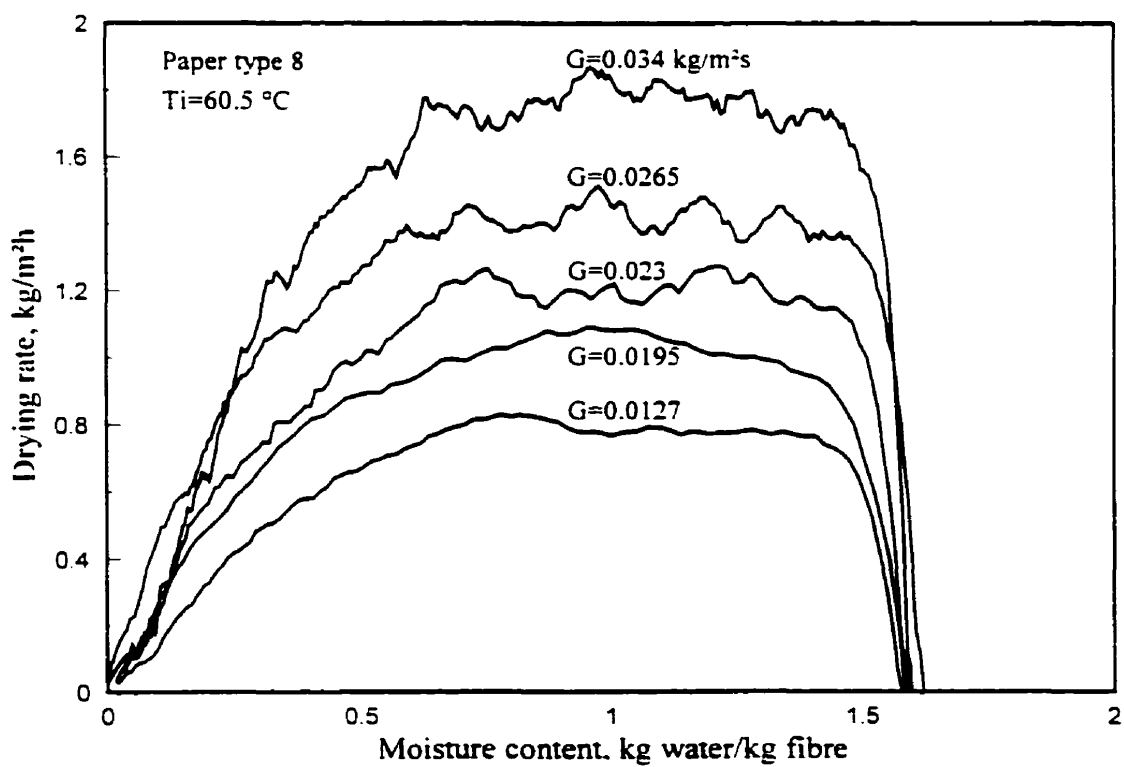


Fig. 2.34 Effect of air mass flow rate

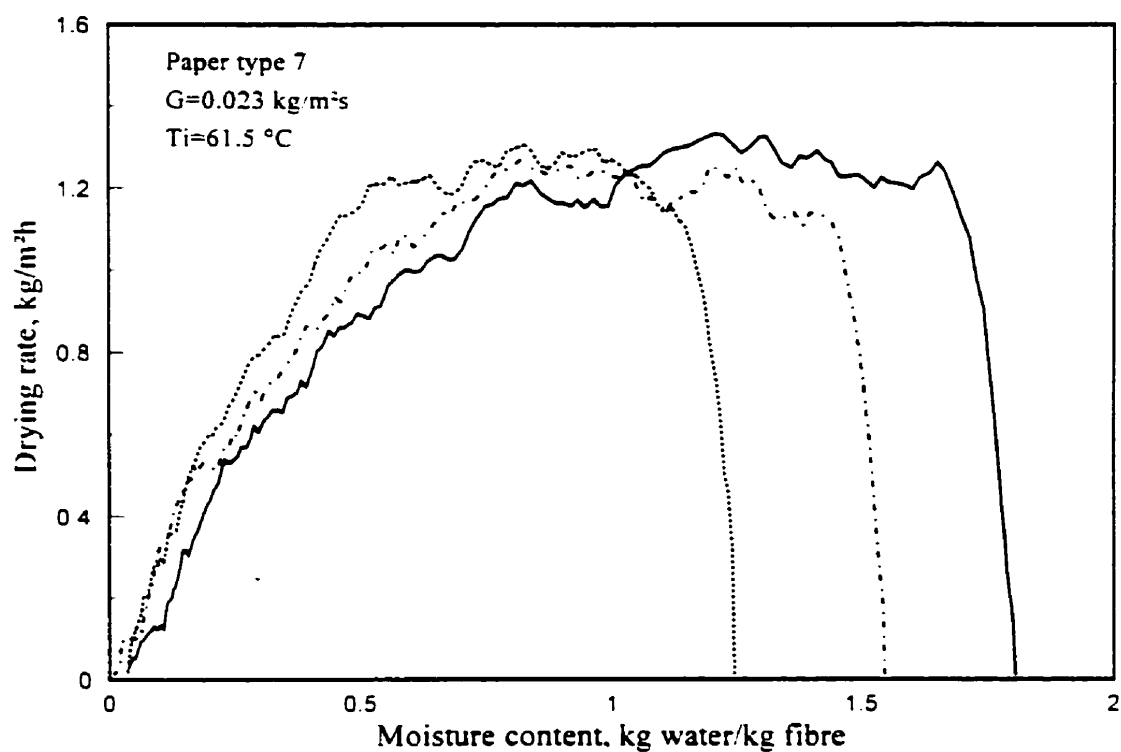


Fig. 2.35 Effect of sheet initial moisture content

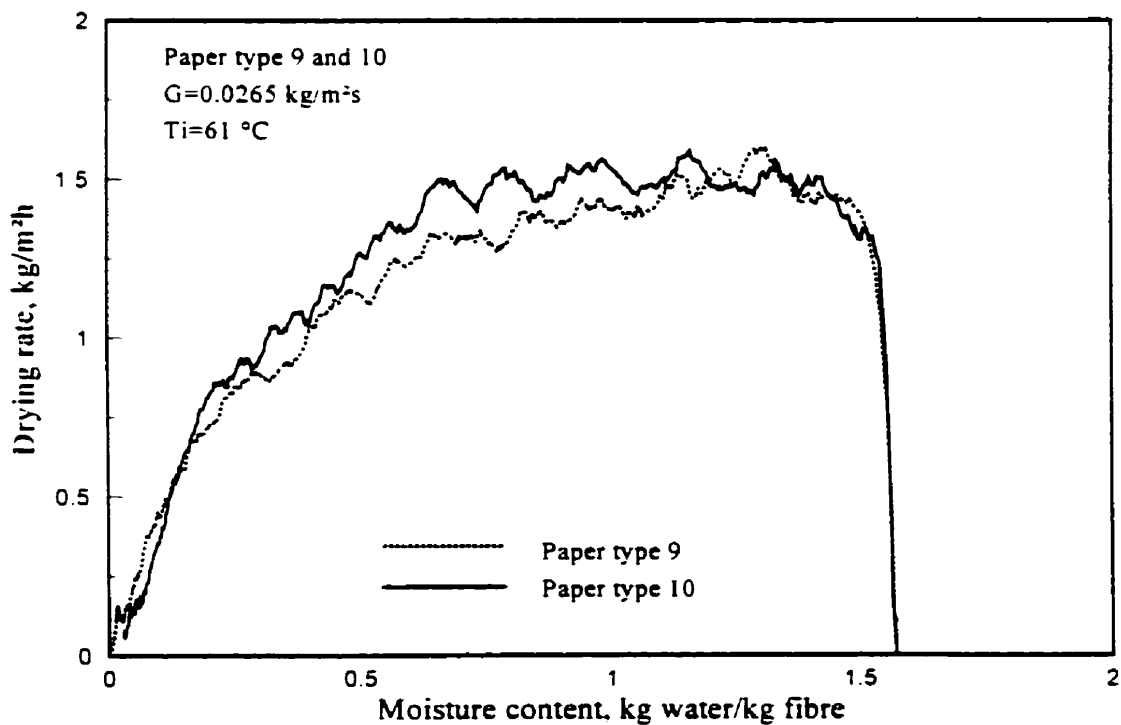


Fig. 2.36 Effect of paper grammage

2.6.2 Quantitative representation of drying rate curves

2.6.2.1 Method of identifying drying rate periods

Polat [1989] developed a more comprehensive method of treating through drying rate curves than that of Keey and Suzuki [1974] or Schlunder [1976]. The key of Polat's technique is determination of the two transition points, from the increasing rate to constant rate period at X_i , and from the constant to falling rate period at X_c . For drying rate curves with a clear period of constant rate drying over an appreciable range of moisture content Polat took as X_i and X_c the moisture contents where the drying rate was $0.95R_c$. For R-X curves without a significant range of moisture content over which drying rate remains constant or where the drying rate was irregular, he took as X_i and X_c the moisture content at $R=R_{\max}$ and took R_c as $0.95R_{\max}$. His choice of 95% was arbitrary.

The alternative approach of Chen [1994] involved obtaining a quantitative relationship for the complete R-X curve, with X_i and X_c as parameters in those relations. Based on a theoretical analysis derived from packed bed theory he obtained an exponential R-X relationship in the increasing rate period as

$$\frac{R}{R_c} = \frac{1 - e^{-n_i \left(\frac{X_o - X}{X_o - X_i} \right)}}{1 - e^{-n_i}} \quad \text{for } X_o \geq X \geq X_i \quad (2.15)$$

with the exponent $n_i = ha_p L / (GC_p)$. During the constant rate drying period

$$\frac{R}{R_c} = 1 \quad \text{for } X_i \geq X \geq X_c \quad (2.16)$$

He represented the falling rate period data by the power law relation

$$\frac{R}{R_c} = 1 - \left(1 - \frac{X}{X_c} \right)^{n_f} \quad \text{for } X_c > X > 0 \quad (2.17)$$

Analysis of his rate data indicated that the most realistic definition for the end of the increasing rate period, X_i , and the onset of the falling rate period, X_c , is where $R=0.98R_c$. Use of Chen's technique requires an iterative procedure, first determining initial values for five parameters, R_c , X_i , X_c , n_i , n_f by fitting R-X data to the above equations, then determining improved values in two subsequent iterations. His technique has the advantage of being not subjective, the disadvantage of being much more time

consuming, an important consideration with the over 400 drying rate curves of the present study. After checking the results using both methods for 6 types of paper it was found that Polat's much faster technique was adequate, so was used for the remaining 4 types of paper. Figures 2.37 shows the application of Chen's method for PM sheets of various furnishes from TMP to filled kraft and blends. Appendix E records the through drying characteristics obtained by this method.

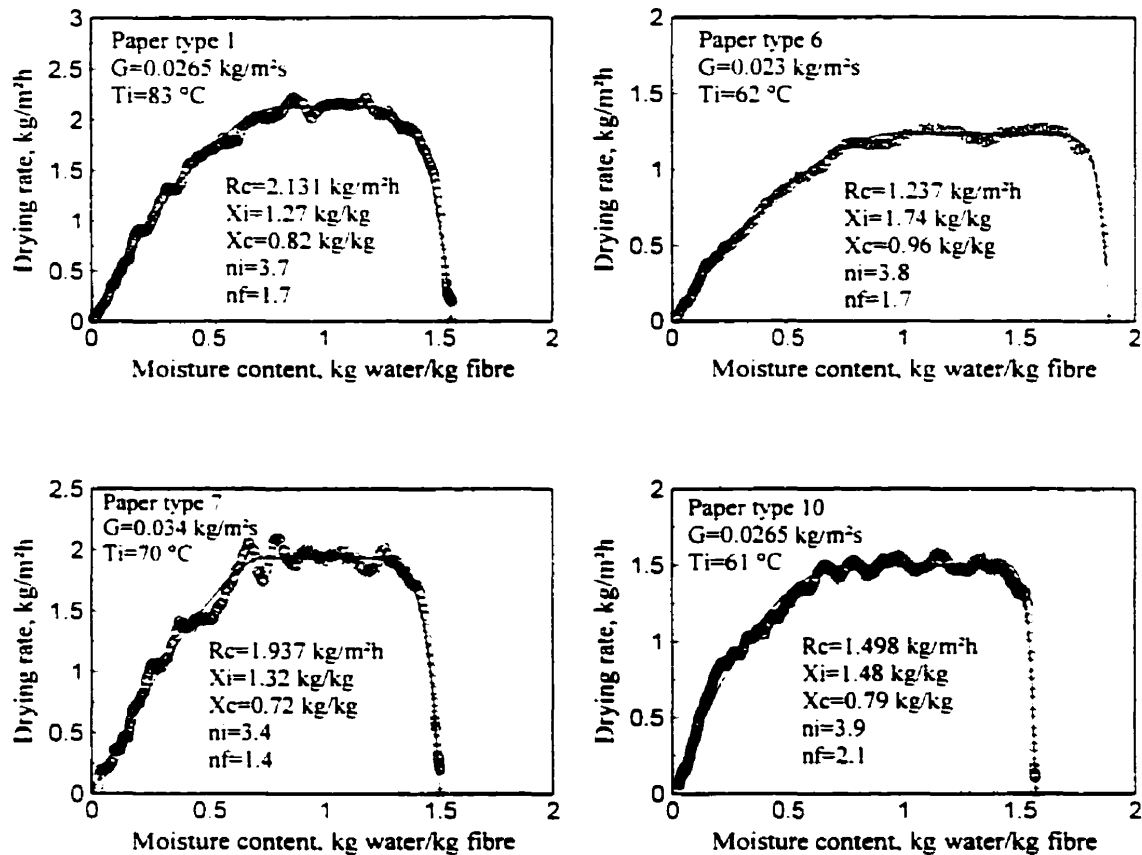


Fig. 2.37 Fitting of R-X data using technique of Chen

2.6.2.2 Increasing rate period, X_i and n_i

During the increasing rate drying period the progressive removal from the pores of the water which prevents drying air from contacting the fibre surfaces blanketed by this pore water is the mechanism for an increase in the interfacial area for heat transfer until the drying rate reaches that for the constant rate period. For kraft handsheets both Polat et al. [1991 a] and Chen [1994] showed that the extent of the increasing rate period,

$X_0 - X_i$, correlates with paper basis weight, B, and the drying conditions, G and $\Delta T = T_i - T_s$, in the form

$$X_0 - X_i = aG^b \Delta T^c B^d \quad (2.18)$$

The parameters a, b, c, and d were reported as 0.3, 0.41, 0.78 and -0.73 by Chen, and as 1, 0.27, 0.39 and -0.37 by Polat. The differences in the values of these parameters derive from important differences in the ranges of variables between their studies: Chen's range of G extended to considerably higher values, while Polat used a much wider range in B, which affects sheet structure. The curvature of this part of the R-X relation is reflected by the parameter n_i , introduced by Chen into equation 2.15. The independence of $X_0 - X_i$ from paper initial moisture content indicates that the increase in interfacial area during this period is by opening pores, from larger to smaller ones, not by relation to sheet permeability, which increases exponentially with decreasing paper moisture content during drying. Thus although most experiments here were with X_0 of about 1.6 kg/kg, the results for $X_0 - X_i$ are valid also for other levels of X_0 within the range of X_0 covered by Polat and Chen, i.e. between 1 and 3 kg water/kg fibre. In order to obtain a relation for $X_0 - X_i$ that would apply also for the much higher drying intensities and wider range of paper basis weight used by Polat and Chen, the dependence of $X_0 - X_i$ on G, ΔT , and B as reported by them was accepted and the proportionality constant, a, of equation 2.18 was determined to minimize the residual between experimental and calculated values of X_i with the present results.

Using Polat's technique for determining X_i with the data for machine-formed paper, types 1 to 8, the proportionality constant, a, was calculated using all experimental conditions including 20°C air. Also, values of X_i determined using Chen's technique for only those experiments with heated air and only for four types of paper, 1, 6, 7, and 8, were used to calculate the proportionality constant, termed a' in this case. For the values of a and a' for these machine-formed papers given in Table 2.14, note that the values of parameters b, c and d in equation 2.18 are those reported either by Polat or Chen.

The values for aB^d and $a'B^d$ were calculated based on each paper basis weight and the values of d of -0.37 and -0.73 reported by Polat and Chen respectively. For paper

Table 2.14 Proportionality constant for X_i correlation

Paper type	1	2	3	4	5	6	7	8
a	0.51	0.65	0.43	0.40	0.48	0.45	0.38	0.55
$aB^{-0.37}$	0.127	0.134	0.103	0.100	0.118	0.111	0.093	0.132
a^*	0.69	-	-	-	-	0.60	0.67	0.71
$a^*B^{-0.73}$	0.044	-	-	-	-	0.038	0.042	0.042

type 6 Figure 2.38 compares values for X_i determined from the experimental R-X data using Chen's technique with those determined using the above correlation with a proportionality constant of $a^*=0.6$. A similar good agreement between experimental and calculated values of X_i was found for the other types of paper. For paper type 1, the Figure 2.39 example using parameters for b, c and d reported by Polat and the best fit proportionality factor of $a=0.51$, shows the satisfactory fit to the experimental values of X_i determined from the R-X data also by his technique. Therefore it was concluded that for PM sheets from this range of furnishes the dependence of X_i on drying conditions, G and ΔT , and on paper basis weight, B, is the same as reported for kraft handsheets, but that the extent of the increasing rate period, indicated by proportionality constant in equation 2.18, is consistently much lower for machine-formed paper.

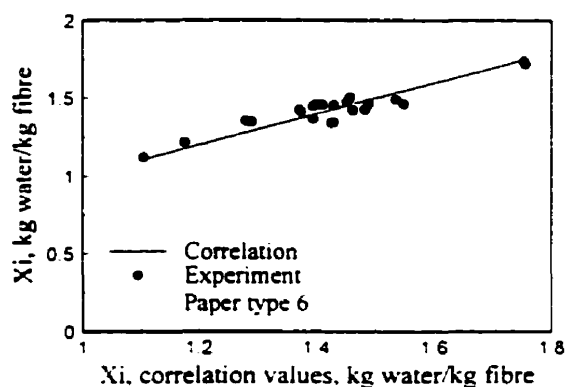


**Fig. 2.38 Comparison of X_i :
Experimental and correlation**

With X_i thus determined, the parameter n_i calculated with equation 2.15 for paper types 1, 6, 7, and 8 was determined to be respectively 3.2, 3.9, 3.5, and 3.2.

2.6.2.3. Comparison of increasing rate period

To compare the R-X relationship during the increasing rate drying period two factors must be considered: the extent of this period, X_0-X_i , and the curvature of this part

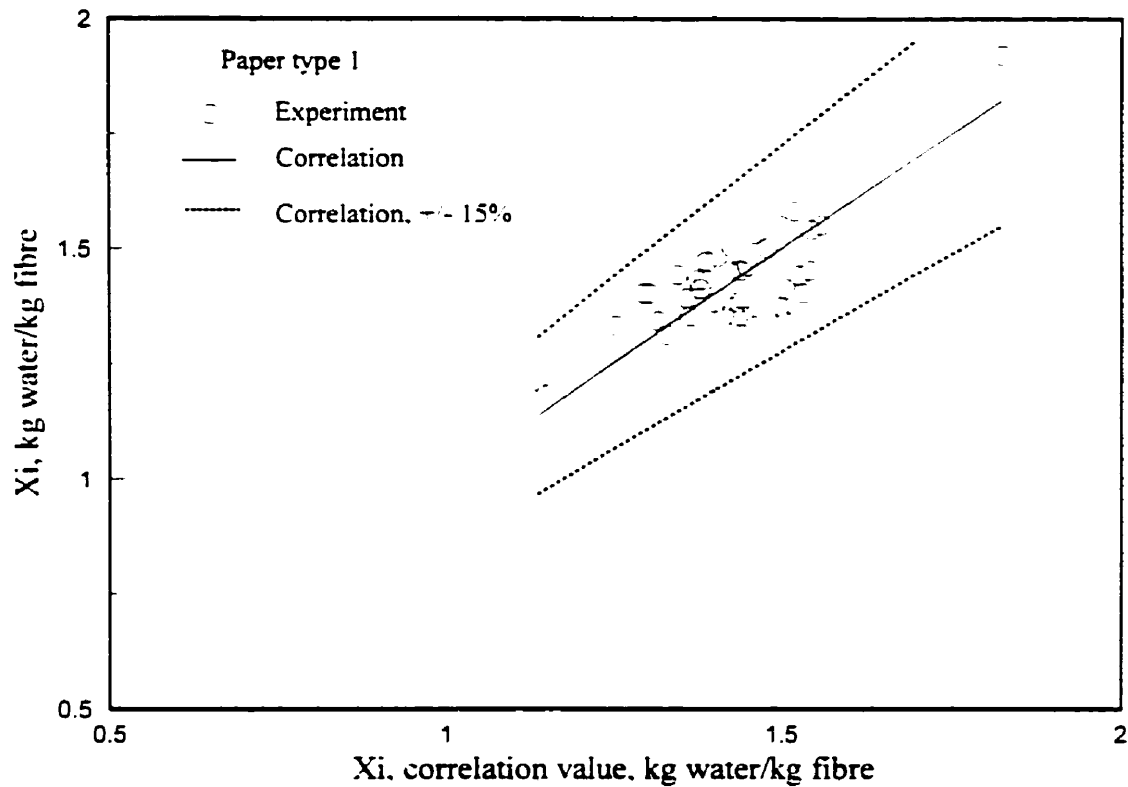


Fig. 2.39 Comparison of X_i experimental and correlation

of the R-X relation, given by the n_i value. To compare the extent of the increasing rate period the Table 2.14 values of $aB^{-0.39}$ and $a'B^{-0.73}$ must be used, not just the values of the parameters a or a' . For example, between paper types 1, 6, 7, and 8 which vary from pure TMP to a blended furnish with a substantial content of kraft pulp, the values of $a'B^{-0.73}$ change only between 0.038 to 0.044. This range means that at an initial moisture content of 1.6 kg/kg the difference between X_i for the two extreme cases, paper types 1 and 6 is only 5% at the highest intensity drying conditions used here.

As for the curvature of the R-X relation during this period, the values of the parameter n_i for paper types 1, 6, 7, and 8 remain within the narrow range of 3.2 to 3.9. Therefore it can be concluded that, over the drying conditions used, both the extent of the increasing rate drying period and its R-X curvature are effectively the same for the wide range of commercial printing papers tested.

Chen's value of the parameter n_i for kraft handsheets is 3.6, which is in the range of 3.2 to 3.9 found here for PM paper from various furnishes. However, the extent of the

increasing rate drying period for the tests of the present study is significantly less than that found by Polat and Chen because the drying intensity conditions and hence the level of constant drying rate was significantly lower for these low permeability papers.

2.6.2.4. Constant drying rate, R_c

As discussed by Polat [1989] and Chen [1994], the development of interfacial area for heat transfer during the increasing rate drying period continues during the constant rate period. However two effects acting to decrease the drying rate are that the heat transfer coefficient, h , decreases due to the drop in interstitial air velocity in the pores at constant G , and the effective thickness of the bed of moist fibres decreases from progression of the drying front in the thickness direction as drying proceeds. Interfacial area is a function of paper basis weight and sheet moisture content while the heat transfer coefficient is a function of local air velocity. Depending on the drying conditions, the constant rate period value of R_c can range up to the maximum possible, the adiabatic saturation drying rate, R_s . By definition, R_s is directly proportional to air flow rate G and the saturation air humidity, Y_s , which in turn is a function of adiabatic saturation temperature, T_{as} . As T_{as} depends on the temperature and humidity of the inlet air, T_i and Y_i , with inlet humidity not varied in the present work, R_c may be correlated with paper basis weight and the drying air temperature and flow rate. Due to the low range of flow rates required for low permeability sheets, the R_c values determined here are in the range of 85 to 100% of the saturation drying rate. As G was varied by a factor of 3 and the air - to - sheet ΔT by more than a factor of 4, the small range of basis weight, $\pm 5\%$ around the average for types 1-8, was not sufficiently large to be included in the correlation, which thereby simplified to:

$$R_c = aG^b \Delta T^c \quad (2.19)$$

The correlations of both Chen and Polat consider the effect of paper basis weight by the term B^d in their equation. Using their correlations to predict R_c for present study over-predicted this rate by as much as 30%, including predicting R_c up to 20% higher than R_s as they have used a higher drying intensity. This discrepancy is a natural

consequence of using correlations obtained for conditions giving R_c significantly higher than that of present study. The reproducibility of R_c here for a particular drying condition and type of paper was always within a few percent. The experimental R_c values as determined using Polat's or Chen's technique differed little, with the latter being lower by 1-2%. More important, from R_c shown as a function of temperature driving force on Figure 2.40 one may conclude that there is no significant difference in R_c for these 8 types of commercial paper tested.

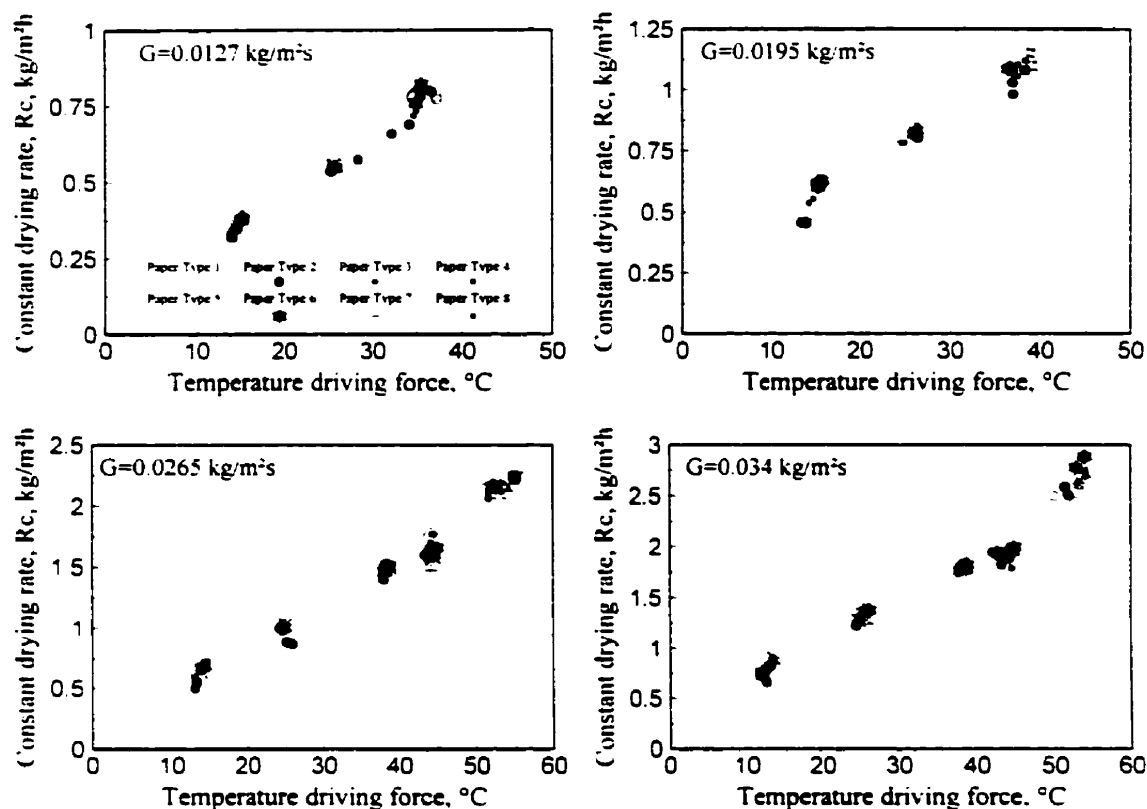


Fig 2.40 Effect of temperature driving force on R_c

With these R_c values for paper types 1 to 8, the parameters a , b , and c of the above correlation were then determined. Also, using experimental R_c values determined with Chen's technique these parameters, now designated a' , b' , and c' , were determined for paper types 1, 6, 7, and 8. From the listing of these parameters in Table 2.15 and the R_c - G plots based on the parameters a' , b' , and c' given in Figure 2.41 one can conclude that for

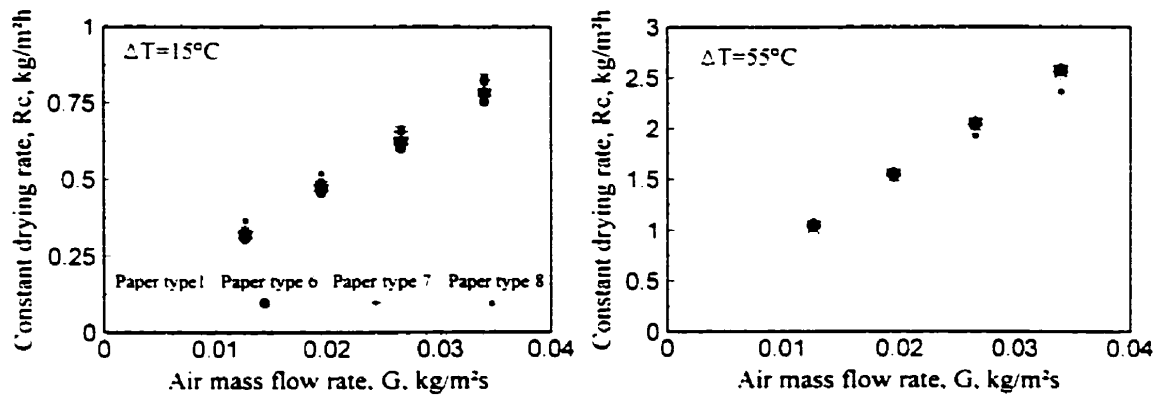


Fig. 2.41 Effect of air mass flow rate on R_c

Table 2.15 Parameters in correlation for R_c

Paper type	a	b	c	R^2	a'	b'	c'	R^2
1	1.76	0.95	0.90	0.97	1.69	1.02	0.97	0.95
2	1.27	0.91	0.94	0.98	-	-	-	-
3	1.87	0.93	0.87	0.97	-	-	-	-
4	1.90	0.94	0.87	0.96	-	-	-	-
5	1.45	0.90	0.90	0.97	-	-	-	-
6	1.41	0.91	0.92	0.97	1.40	1.00	1.01	0.95
7	1.76	0.93	0.88	0.95	1.71	1.00	0.98	0.93
8	1.42	0.82	0.82	0.96	1.39	0.88	0.88	0.90

the low intensity drying conditions used, the dependence of R_c on ΔT and G does not vary significantly between the various types of commercial paper used.

At the same basis weight the thickness of these sheets from dominantly mechanical pulp furnishes is 20-40% higher than the kraft handsheets of these reference studies. With also the one order of magnitude lower permeability for the commercial paper used here relative to unfilled kraft handsheets, the tortuosity factor for this paper would also be higher, hence further increasing the approach to saturation of the exhaust air. Using Darcy's law to characterize the momentum transfer the residence time for drying in this thin packed bed can be derived as $t = \frac{\epsilon \mu L^3}{2k\Delta P}$. Thus residence time not only

depends on sheet thickness but also on structure parameters such as permeability k and porosity ϵ . Each of these parameters has in turn a complicated relationship with other sheet properties, with tortuosity being dependent on paper thickness to a power of three. Although at this low intensity level of drying conditions these effects combine to give a similar R_c for all 8 types of paper, at high drying intensity R_c could become different for these various types of paper. However with no difference in R_c in this study for these sheets the average values of the parameters for R_c as determined with Polat's technique are given in Table 2.16. As the sheets used here had quite a small range in grammage it was not anticipated that the effect of this variable could be correlated, and a statistical test of the data confirmed that this was the case. Figure 2.42 shows the satisfactory fit of these experimental data.

Table 2.16 Parameters for R_c correlation

Parameter	ϵ	σ
a	1.61	0.22
b	0.91	0.04
c	0.82	0.14

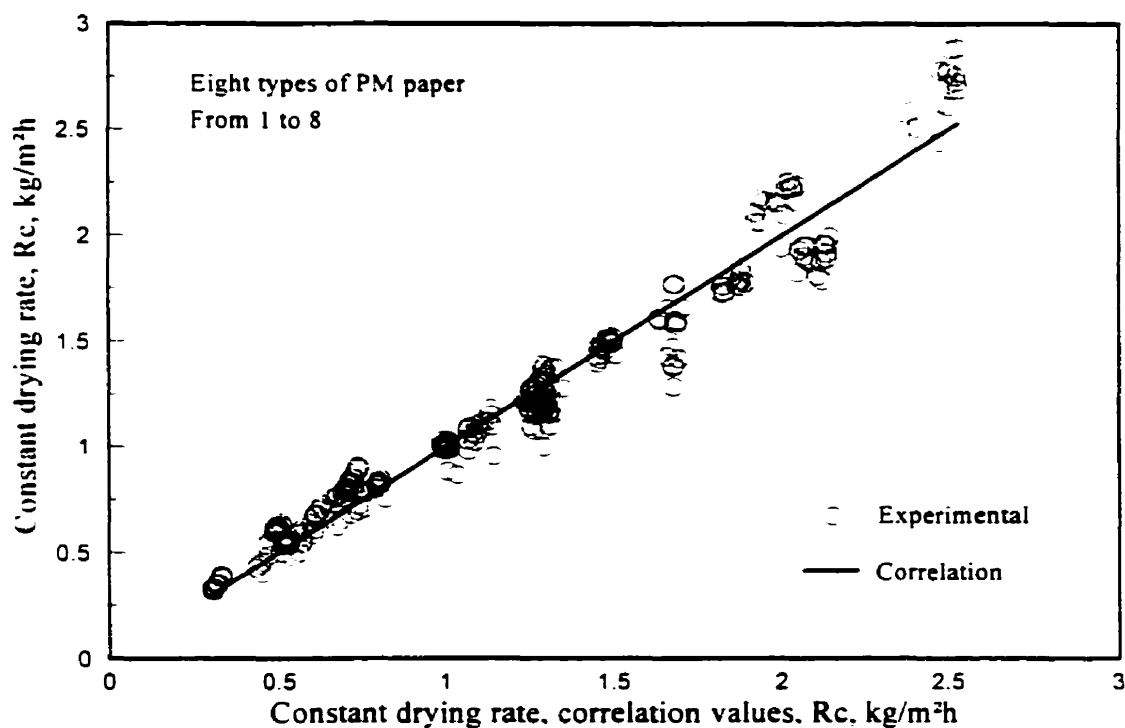


Fig. 2.42 Comparison of R_c : Experimental and correlation

2.6.2.5. Critical moisture content, X_c

The critical moisture content marks the transition from constant to falling rate at the point that the drying rate can no longer be maintained at R_c . Factors involved in the onset of the falling rate period as paper moisture content decreases include the transfer rates within the sheet as described earlier, moisture transport within the fibres as affected by the decrease in moisture diffusivity with decreasing moisture content and the increase in distance over which moisture must diffuse, and the thermodynamic factors associated with the decrease in moisture content - the decrease in vapor pressure of water and increase in heat of desorption of water. As through drying may be characterized by nonuniform moisture content in both the plane of the sheet and in its thickness dimension, the above factors may operate in a three-dimensional system. Thus for a front of relatively dry paper advancing through the sheet in the direction of the air flow the corresponding reduction in thickness of the remaining moist part of the sheet reduces the area effective for heat and mass transfer. No comprehensive analysis is yet possible of a system of this complexity, including nonuniformity in both the plane of the sheet and in the thickness dimension. The aspect of the effect on critical moisture content from local nonuniformity of through drying in the plane of the sheet is a topic discussed in the next two chapters. Briefly, with such local nonuniformity the sheet does not enter the falling rate period all at once but rather, when some regions of the sheet do so while the sheet average moisture content is still above what would be the X_c value for a sheet drying uniformly under the same conditions but without such local nonuniformity.

For unfilled kraft handsheets Polat [1989] determined that the critical moisture content, X_c , depends linearly on the initial moisture content, X_o , with a proportionality constant of 0.45 ($\pm 10\%$) for the range of experimental variables tested. Also, he found X_c to be independent of paper thickness or paper basis weight, drying rate or air flow rate, but that X_c increased, but only slightly, with the temperature driving force, $\Delta T = T_i - T_s$, as

$$\frac{X_c}{X_o} = c(\Delta T)^b \quad (2.20)$$

with $b=0.13$. In fact this dependence on ΔT was sufficiently small that it was dropped, leaving $X_c/X_o=0.45$ for the entire range of experiments.

With the same type of paper but a wider range of through flow rates Chen [1994] represented his results as

$$X_c = aX_o^b R_c^c B^d G^e \quad (2.21)$$

However Chen also had a local nonuniformity effect from his use of drying under impinging jets, the latter being an effect not present here or in the study of Polat.

For determining the values of X_c from the sets of R-X data Polat's technique was used for paper types 1 to 8 and Chen's method for paper types 1,6,7 and 8. Due to our limited range of G and B and to the absence here, as for Polat, of a local nonuniformity effect in the air flow to the sheet, the form developed by Polat for correlating X_c is more appropriate to the present study than that of Chen. Again X_c was determined to vary linearly with initial moisture content while the dependence on temperature driving force was likewise weak, proportional to $\Delta T^{0.09}$. For the relation

$$\frac{X_c}{X_o} = c \quad (2.22)$$

Table 2.17 shows the proportionality factors. As Chen's method determines X_c at $R/R_c=0.98$ compared to $R/R_c=0.95$ in Polat's method, the slightly higher value of c for R_c values determined by Chen's technique is as expected. With the range of c from 0.38 to 0.54 it is evident that this ratio is quite sensitive to the furnish and probably also to the formation, so an important finding is that this parameter should be determined for each type of paper.

While showing the comparison of measured and calculated values of X_c , using Polat's technique, Figure 2.43 also shows the considerable variability in the experimental

Table 2.17 Proportionality factor for X_c

Paper type	1	2	3	4	5	6	7	8
$c^{(1)}$	0.54	0.44	0.48	0.46	0.39	0.38	0.41	0.41
$\sigma_{c^{(1)}}$	0.05	0.05	0.06	0.05	0.03	0.04	0.04	0.04
$c^{(2)}$	0.55	-	-	-	-	0.40	0.45	0.47
$\sigma_{c^{(2)}}$	0.07	-	-	-	-	0.06	0.07	0.07

$c^{(1)}$ for X_c determined using Polat's technique

$c^{(2)}$ for X_c determined using Chen's technique

data . As X_c represents the transition between drying periods which, as can be seen from the R-X curves of Figure 2.31-2.38, occurs quite gradually it is inevitable that there will be considerable uncertainty as to the value of X_c .

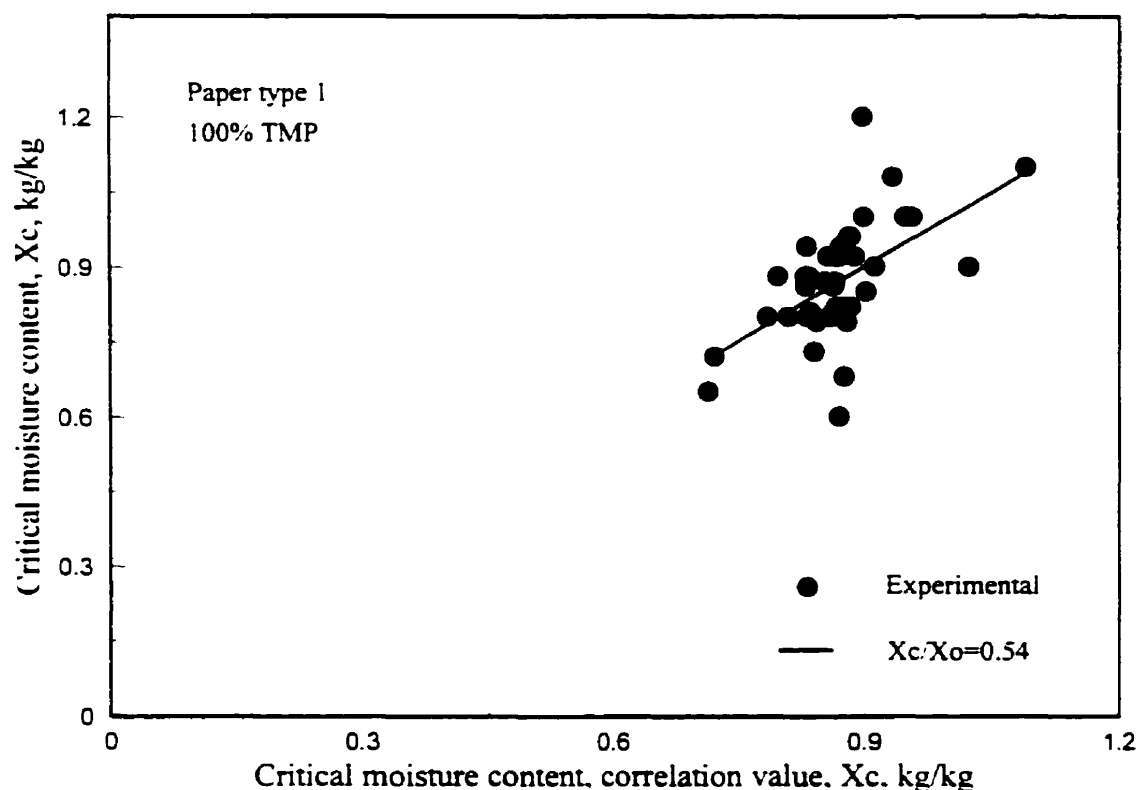


Fig. 2.43 Comparison of critical moisture content: Experimental and correlation

The average of all the values of the X_c/X_o ratio listed in Table 2.17 is 0.45, exactly the value found by Polat. It is notable that these values from the present study were determined with drying intensities, indicated by the R_c value, an order of magnitude lower than in Polat's study. The results of Chen demonstrate that X_c increases with an increase in intensity of through drying. Thus it is significant that the values of X_c determined here, although varying sensitively with furnish, are on average not lower than the $X_c = 0.45X_o$ value found by Polat at much higher levels of R_c . The fact that the X_c/X_o values determined here and by Polat are similar in spite of the great difference in drying intensity indicates that the X_c/X_o values found in the present study were determined by factors other than drying intensity. On pages 64, 67 and 68 of this section eight factors have been listed as potentially affecting the critical moisture content. One of these

factors, local nonuniformity of drying in the plane of the sheet, will in a subsequent chapter be shown to be quite sensitive to drying intensity. Although drying nonuniformity will be shown to be a factor determining X_c at high values of R_c , one may conclude that for the low range of R_c treated at this point, drying nonuniformity would not be an effect influencing critical moisture content.

2.6.2.6. Falling rate period for commercial paper

Analogous to the discussion for the case of the increasing rate drying period, the importance of the falling rate period may be characterized by two factors, the extent of this period, i.e. the value of X_c , and the curvature of this part of the R-X relation. These two aspects define the drying time during this period. The method adopted for use here was that developed by Chen [1994] to model the falling rate drying period by fitting R-X data to a power law, eqn. 2.16, with its exponent n_f determining the curvature of the R-X relation. For consistency, X_c was also determined from the R-X data according to Chen's procedure. Table 2.18 summarizes for paper types 1, 6, 7 and 8 the values of the proportionality constant for $X_c/X_0=c$, and the power law parameter n_f .

Table 2.18 Falling rate period parameters, Chen's technique

Paper type	1	6	7	8
c	0.55	0.40	0.45	0.47
n_f	1.55	1.47	1.49	1.74
σ_c	0.05	0.04	0.04	0.04
σ_{n_f}	0.3	0.3	0.3	0.4

A statistical analysis of the data relating the values of X_c , n_f and c , to paper specifications such as basis weight, freeness, fines content and furnish showed no significant relationship. In his study with handsheets of 25, 37 and 50 g/m² from a single furnish, unfilled kraft pulp, Chen [1994] found no relation between n_f and basis weight, with an average value of $n_f=1.7\pm0.4$. From the standard deviation values in Table 2.18 it is apparent that between these four types of paper there are significant differences in the

X_c/X_o ratio but not in n_f . The effect of paper type is examined next in terms of drying time, a more sensitive indicator than drying rate curves.

2.6.2.7. Drying time

For a process with drying rate curves of the type shown on Figures. 2.31-2.38, drying time is dominated by the falling rate period. Even differences which appear to be small in the R-X curve during this drying period can have a large effect on drying time. As a more sensitive method of examining the differences between the various types of paper tested, curves of the experimentally determined time for drying between initial and final moisture contents of about 1.6 and 0.05 kg water/kg fibre for paper types 1, 6, 7, and 8 were compared. Drying time in the increasing rate period for these types of paper is very short relative to the other periods, typically less than 20% of the total drying time. Also, as the maximum difference in R_c for different types of paper is not significant, about 3-4% at a particular drying condition, the time of drying during the constant rate period varied little between these papers. For X_c and n_f , the values used were for each paper type as recorded in Table 2.18. These experimental drying times for tests using drying air of 60°C or higher are shown in Figure 2.44 as a function of the term controlling the drying intensity, $G\Delta T$. The drying time for the slowest drying paper, type 1, is over 1/3 longer than for the fastest drying paper, type 6. These differences in drying time are due almost entirely to the falling rate period. Moreover, little of this variation derives from n_f , while almost all the difference between paper types is due to the variability in critical moisture content which is more than 1/3 higher for the slowest drying paper, type 1, than for the fastest drying type 6. The relative location of the drying times for the 4 types of paper correspond directly to the values of X_c/X_o ratio listed in Table 2.18.

2.6.3 Generalized drying rate curve

For through drying of textiles and tissue Gummel [1980] adopted the approach used earlier by Gottsching and Rhodius [1977] and showed that a single normalized drying rate curve, defined as the ratio of drying rate to constant drying rate, R/R_c , as a

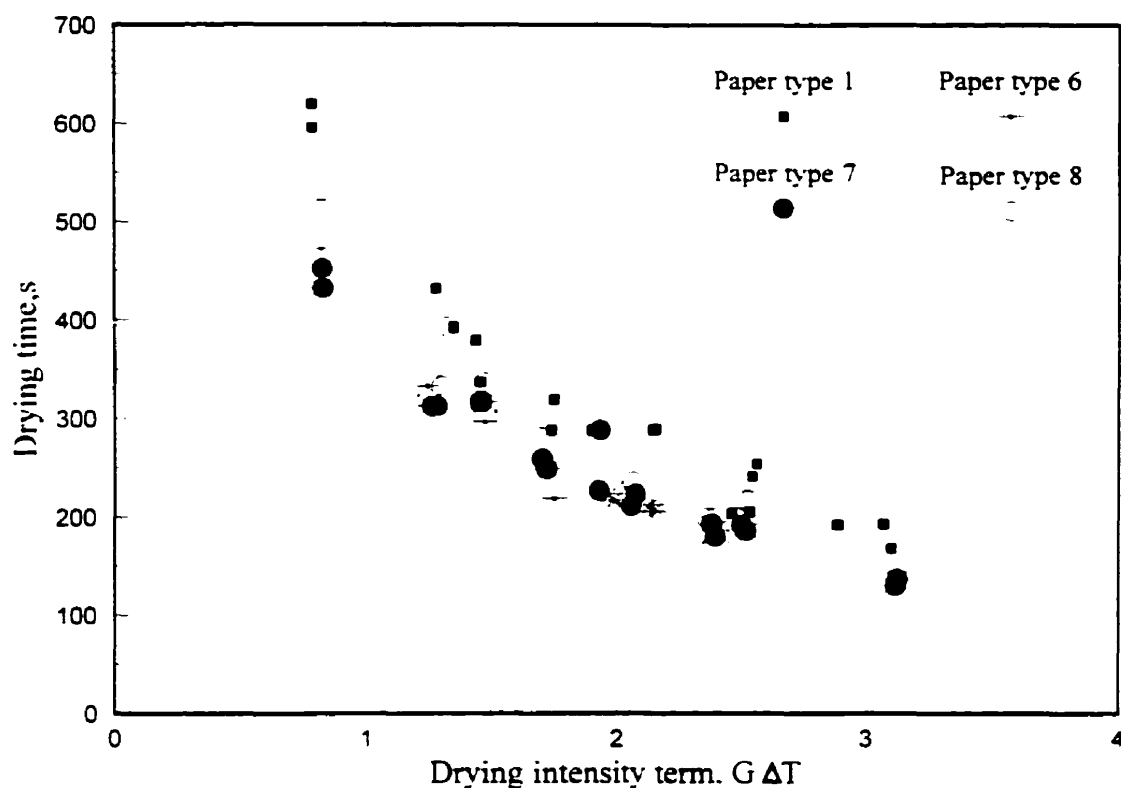


Fig. 2.44 Drying time for papermachine papers

function of the ratio of moisture content to critical moisture content, X/X_c , could represent the results for the falling rate period with no further dependency on drying conditions. Randall [1984] followed the same practice. To model through drying of unfilled kraft handsheets Polat [1989] and Chen [1994] developed a technique, discussed in section 2.6.2.1 and defined by equations 2.15 to 2.17, which differs from the above, especially their unique treatment for the increasing rate period. For the relationship in the increasing rate period Polat found the parameter $n_i=3$. Chen [1994] concluded that the values of the parameters $n_i=3.6$ and $n_f=1.7$ for the R-X curve in the increasing and falling rate periods applied for all conditions he tested, with a standard deviation of 0.4 for both parameters.

The application of equations 2.15 to 2.17 to determine the individual parameters of X_i , X_c , R_c , n_i , n_f , for the present experiments showed that for paper types 1,6,7 and 8 the value of n_i varied from 3.0 to 3.9, those for n_f from 1.5 to 1.7. Because the values of n_i and n_f for these types of paper are in the range of those found by Chen to be applicable to

unfilled kraft handsheets for all the conditions he investigated, it will be useful to test if there would be significant loss in accuracy by using Chen's values for the machine-formed semi-permeable printing papers used here. For this comparison Table 2.19 provides the values for the moisture content at the end of increasing rate and the constant rate periods, X_i and X_c , and the constant drying rate, R_c . This test showed that there is in general not an important difference in the standard deviations of these parameters when determined using Chen's general values of n_i and n_r instead of these parameters obtained for each individual experiment. For a case with one of the larger differences between n_i and n_r values determined individually and Chen's standard values, Figure 2.45 demonstrates more effectively yet the validity of values of n_i and n_r that he determined for unfilled kraft handsheets being used now for machine-formed paper of mechanical furnish as the difference in drying rate curves is scarcely perceptible.

Table 2.19 Drying characteristics: general and individual experiment bases

Paper Type	1	6	7	8
$(X_i)_{avg}^1$	1.40	1.51	1.34	1.44
$\sigma_{(X_i)avg1}$	0.15	0.17	0.12	0.15
$(X_i)_{avg}^2$	1.41	1.46	1.33	1.41
$\sigma_{(X_i)avg2}$	0.24	0.32	0.11	0.14
$(X_c)_{avg}^1$	0.88	0.66	0.68	0.75
$\sigma_{(X_c)avg1}$	0.17	0.17	0.16	0.17
$(X_c)_{avg}^2$	0.98	0.70	0.78	0.74
$\sigma_{(X_c)avg2}$	0.25	0.18	0.17	0.12
$(R_c)_{avg}^1$	1.44	1.48	1.56	1.40
$\sigma_{(R_c)avg1}$	0.55	0.48	0.55	0.40
$(R_c)_{avg}^2$	1.44	1.43	1.56	1.38
$\sigma_{(R_c)avg2}$	0.56	0.55	0.56	0.40

1: Values determined using n_i and n_r determined for individual experiment

2: Values determined using Chen's general values of $n_i=3.6$ and $n_r=1.7$

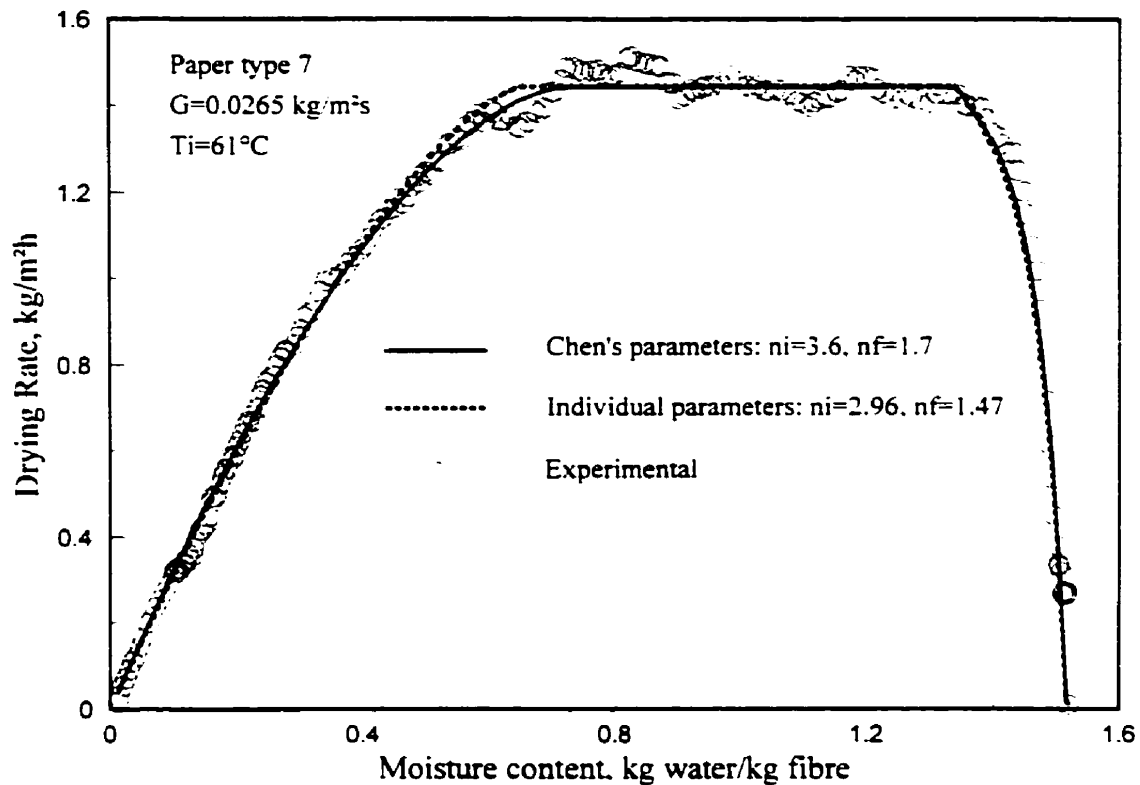


Fig. 2.45 Comparison of fitting of drying rate curves

2.7 Summary and Conclusions

- (1) A comprehensive study was carried out using more than 400 through drying experiments on 10 widely varying types of uncalendered paper produced by a variety of papermachines. Both momentum transport and through drying characteristics of these papers were determined by simultaneous measurement of the flow rate - pressure drop relation and drying rate.
- (2) The permeability of both dry and moist paper was determined using the proper momentum transport equation. The possible effects of molecular flow and inertial forces were checked using the power law relationship. At the low flow rates used here the simplification of Darcy's law was generally acceptable.
- (3) The permeability of dry PM paper determined from standard methods, i.e. Gurley densometer and Bendtsen porosimeter, is within 15% of the more precise determination with research equipment used here. The permeability of dry paper

for these commercial grades increases by from 10-50% because of effects of wetting during a wetting-drying cycle.

- (4) The limited comparison possible for the effect of papermaking parameters on permeability reveals some information as to how fines content, beating, furnish and formation affect porosity, permeability and specific surface of paper. However a more precise determination of the effect of each of these parameters requires the use of handsheets where these variables can be controlled individually.
- (5) An extensive set of air through flow measurements for paper from wet to dry has documented the relationship between pressure drop, through flow rate, sheet moisture content and permeability. The effect of papermaking parameters such as furnish and initial moisture content on ΔP -X-G relationship was shown as well as their effects on the permeability of moist paper.
- (6) A generalized curve for the effect of moisture content on permeability provides a method to predict the permeability of moist paper by only using any of the standard methods of determining the resistance of dry paper to air flow.
- (7) The porosity and specific surface of paper were measured using alternative techniques. The porosity calculated from paper density was about 10% higher than those measured by mercury porosimetry. The Kozeny-Carman equation gives the specific surface of two to three times that from the scattering coefficient and mercury porosimetry. By tests with paper of substantial fines content the Kozeny-Carman equation was shown to be invalid for use with such grades of paper. The specific surface of these machine-formed papers decreases by up to 30% after a wetting-drying cycle, due to the collapse of fibrils from the wetting, the same mechanism that leads to increase in permeability by 10-50%.
- (8) The characteristic dimension d_p for PM dry paper was calculated from the ratio of the constants of the inertial and viscous terms of momentum transport equation. For these 10 commercial printing papers the approximate relationships between the characteristic dimension for air through flow d_p , the permeability k and the mean pore size from mercury porosimetry were demonstrated. With the large

number of variables affecting the sheet structure of commercial paper there are no simple relationships between these properties. As an alternative to permeability, the relationship between Reynolds number and friction factor for dry PM paper was demonstrated. With limitation adopted for pressure drop and thus for air flow rate for through drying experiments it was not possible to calculate d_p for moist paper for the semi-permeable grades used.

- (9) From the complete drying rate curves determined for various types of machine formed paper, three drying periods are distinguishable, i.e. increasing, constant and falling rate drying periods. The parameters which characterizing the complete drying rate curve, X_i , n_i , R_c , X_c and n_f , were determined using established methods.
- (10) The relation between drying conditions and two key characteristics, the moisture content X_i at the end of the increasing drying rate period, and the through drying rate R_c for constant drying rate period, did not vary significantly between the types of paper used nor from the relations reported by previous investigation on kraft handsheets.
- (11) The extent of the constant rate and falling rate drying periods varied substantially between the 10 types of machine-produced paper because the critical moisture content, X_c , expressed as the ratio to the initial moisture content, X_c/X_0 , is specific to the type of paper.
- (12) When the paper-specific value of X_c/X_0 is used, the normalized drying rate curve with parameters reported by Chen, $n_i=3.6$ and $n_f=1.7$, for the curvature of the drying rate curves in the increasing and falling rate periods satisfactorily represents the entire through drying rate curve for the 10 types of papermachine paper.
- (13) As it is not possible to determine relations between papermaking parameters and through drying characteristics when using commercial grades due to the interrelationship of the effects of these parameters and to the variety of conditions used industrially, the effects of commercial papermaking parameters are investigated systematically using handsheets, the subject of the next chapter.

CHAPTER 3:

Effect of Papermaking Parameters

3.1 Introduction and Objectives

Possible extension of the industrial practice of through air drying from its current use for light weight papers, tissue and toweling, requires knowledge of the effects on through drying of papermaking parameters involved for printing and heavier grades. As these effects interact and the variables occur in only limited combinations for machine - produced paper, their influence cannot be extracted directly from measurements with papermachine sheets. Therefore experiments with handsheets are required to determine the impact on through drying characteristics of important commercial papermaking parameters such as beating, bleaching, wet pressing, formation and pulp blending. These variables affect the basic structure and local nonuniformity of machine-formed paper, thereby influencing the pressure drop - moisture content relationship as well as the drying rate curve. The effect of grammage on through air drying characteristics for handsheets made from one noncommercial furnish has been documented by Polat [1989] and Chen [1994].

3.2 Experimental Procedure

The experimental technique must enable measurement of four interrelated parameters of through drying - sheet permeability, moisture content, through flow rate and pressure drop. The laboratory unit that was previously used to accomplish this objective in through drying commercial sheets, section 2.3, with only the addition of a special design sheet holder for paper from beaten pulps due to the large drying stress for such paper under restraint drying. The criterion for the range of through flow rates of drying air was again to limit the maximum pressure drop to 40 - 50 kPa. Sheets 103 mm diameter of nominally 60g/m² were used. As the air permeability of moist paper changes with papermaking

parameters, the conditions which determine drying rates are correspondingly variable. Thus the drying rate-pressure drop-moisture content relationships were obtained simultaneously, with the ΔP -X lines showing an exponential decline while the R-X drying rate curves pass through the successive periods of increasing, constant and falling rate drying. As the effect of the initial moisture constant X_0 on through drying was included in the study by Polat [1989] this variable was not considered here. Between batches of the same type of pulp, differences in sheet permeability could be measured as these are a sensitive indicator of the pulp. However, all experiments for each papermaking parameter, but not for the entire study, were conducted with a single batch of pulp.

3.3 Pulping Process: Effect of Beating

In the standard stock preparation step of pulp beating, this mechanical action increases fibrillation and fines content, thereby producing a sheet which shrinks more while drying and dries to a paper of lower porosity, lower permeability. Typical levels of freeness of commercial pulp suspensions are 150 - 250 ml for TMP, 400 - 500 ml for beaten kraft. Handsheets were made from laboratory chemical pulps of various levels of freeness, 683 (unbeaten), 600, 435 and 258 ml. Four levels of both drying temperature, T_d , and air mass flow rate, G , were used. Table 3.1. A replicate experiment was made at every drying condition.

Table 3.1 Drying conditions for effect of beating

Air flow rate, $\text{kg/m}^2\text{s}$	0.025 - 0.051
Air temperature, $^{\circ}\text{C}$	21 - 85
Pulp suspension freeness, ml	258 - 683

The results indicate that at all values of moisture content, beating increases ΔP at constant G , i.e. sheet permeability decreases. But Figure 3.1 also introduces a curious effect of moisture content, not previously reported as the permeability such paper when moist has not until now been reported. Figure 3.1 shows that for sheets from beaten pulp, as drying proceeds below the fibre saturation point, 0.81 kg water/kg fibre in this case, ΔP increases,

i.e. sheet permeability decreases with decreasing moisture content. For paper from beaten fibres this reversal of the normal effect would result from the significant drying shrinkage of such paper, possibly with a contribution also from release into the pores of some fibrils which had been attached by surface tension to the wet fibres. A second remarkable finding is that in spite of the great sensitivity of permeability, the R-X drying rate curves are independent of beating.

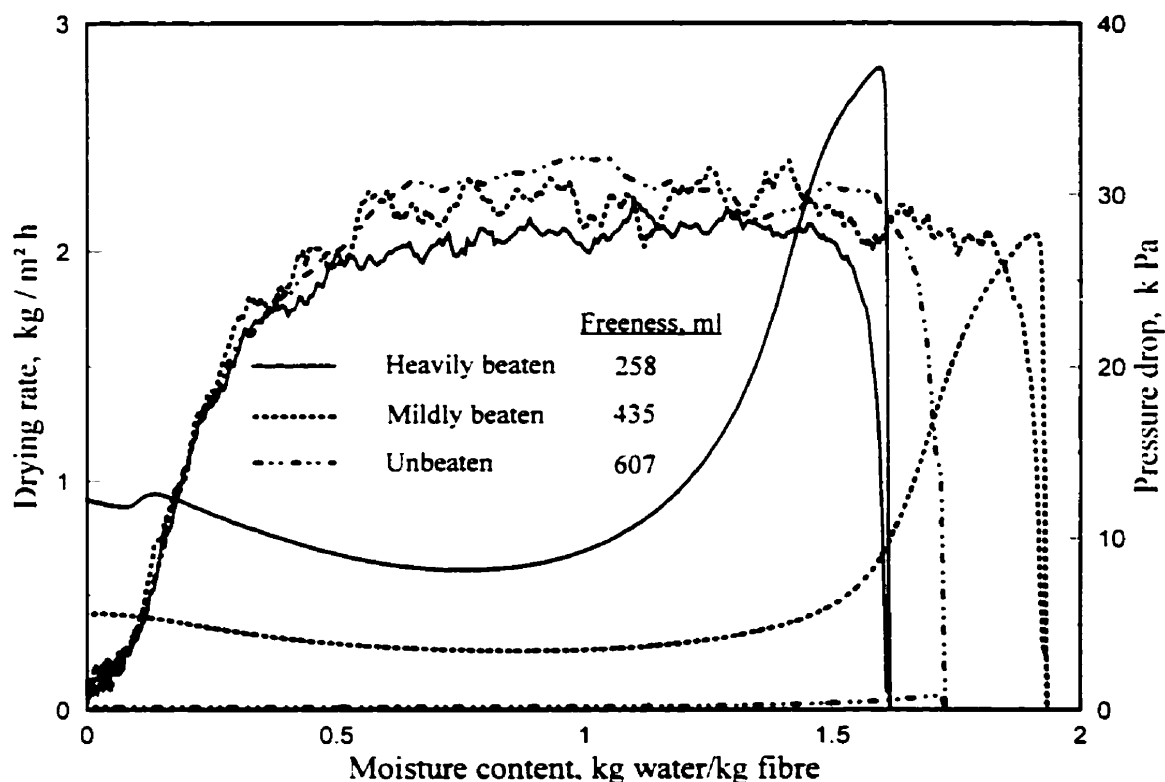


Fig. 3.1 Effect of beating on through drying behavior

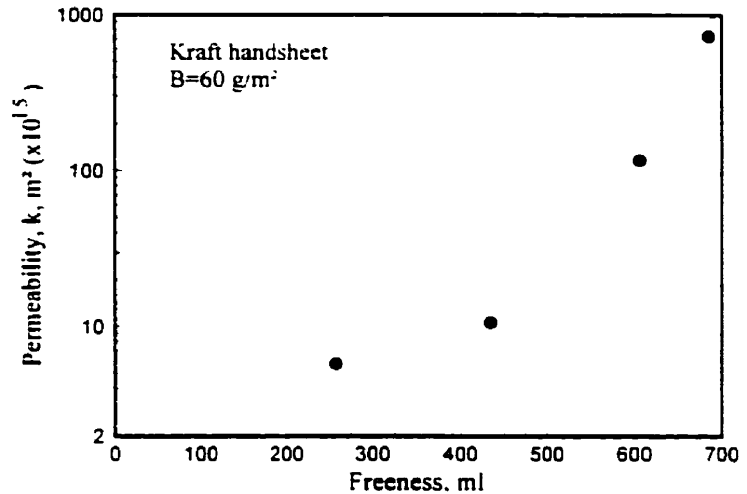
3.3.1 Effect of beating on momentum transport

The permeability of dry and moist paper was calculated using the appropriate form of the momentum transport equation by fitting the experimental results to the power law relation, eqn. 2.1. The absence of inertial effects ($n = 1$) gives Darcy's law, eqn. 2.3, while the presence of inertial effects ($n > 1$) requires use of the complete momentum transport equation, equation 2.6. For dry handsheets made from unbleached kraft pulp beaten to various freeness, Table 3.2 and Figure 3.2 show the extreme sensitivity of permeability to beating, as has been reported by Bliesner [1964] and Knauf and Doshi [1986].

Table 3.2 Permeability of dry handsheets made from beaten pulp

Freeness, ml	685 (unbeaten)	606	435	258
Permeability, m ²	732 x 10 ⁻¹⁵	117 x 10 ⁻¹⁵	10.6 x 10 ⁻¹⁵	5.6 x 10 ⁻¹⁵

In phenomenological approaches, the flow of fluids through porous media is considered to be analogous to flow through a system of capillaries, cylindrical or noncylindrical. The standard treatment for flow through porous media of noncylindrical capillaries is that of Kozeny and Carman, equation 2.10. Paper porosity may also be obtained by

**Fig. 3.2 Effect of beating on permeability**

$$\varepsilon = 1 - \frac{\rho_p}{\rho_f} \quad (3.1)$$

where ρ_p is paper apparent density, ρ_f is fibre density. Figure 3.3 shows the change in specific surface of dry paper with beating, using the Kozeny - Carman equation with $\kappa=5.555$. The reference data shown are those of Robertson and Mason [1949] for a pad of kraft pulp, of Ingmanson and Andrews [1959] using hydrodynamic permeability and by Knauf and Doshi [1986] using aerodynamic permeability for bleached kraft handsheets. Beating increases both fibrillation and fines content. The increase in air resistance depends greatly on fines content, as shown by Ingmanson et al. [1959]. Yasoshima et al. [1963] reported that the air resistance of a beaten pulp decreases from 34000 (s/100 cc by the Gurley technique) to 230 (s/100 cc) after classification of the pulp and removal of the fines, resulting in an increase in sheet permeability by a factor of more than 140. They showed that the beating technique used had almost no effect on increase in permeability after

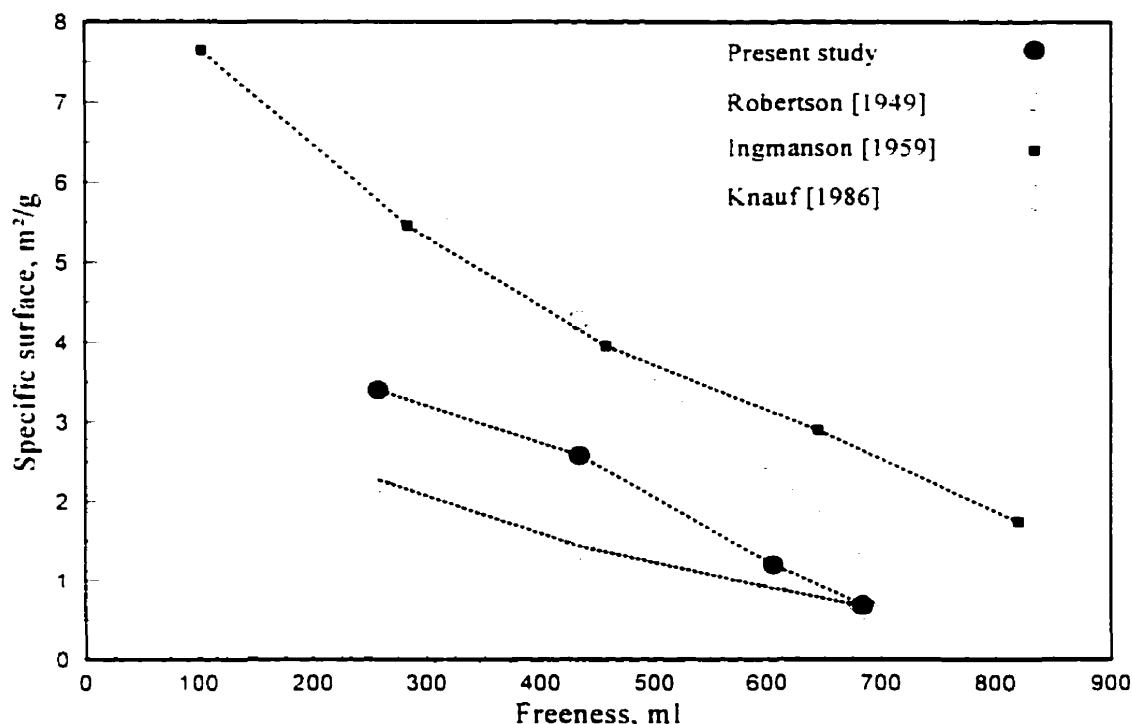


Fig. 3.3 Effect of beating on specific surface area

removal of fines. And also the effect of fibrillation or variation in fibre-length distribution on air resistance compare to the effects by fines is negligible.

For the effect of beating on the permeability of moist paper, no comparisons are possible because such measurements have not previously been reported. The modified permeability k/L of

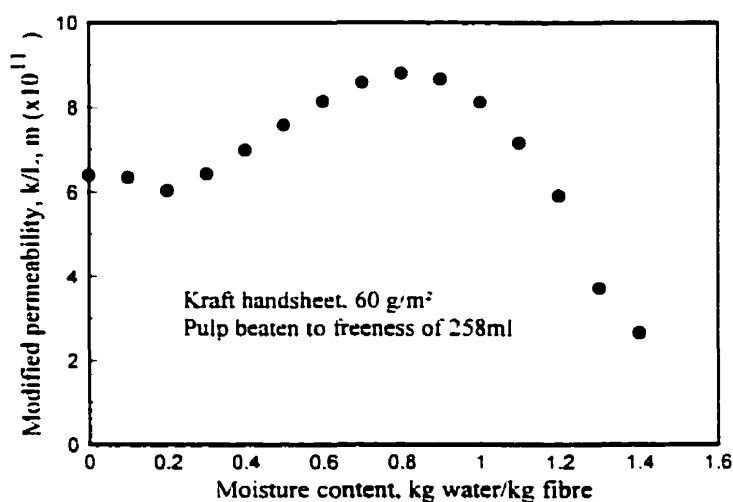


Fig. 3.4 Effect of moisture content on modified permeability of paper from beaten pulp

moist paper from beaten pulp recorded in Figure 3.4 shows a maximum at the fibre saturation point. The decrease in this permeability at lower moisture contents would be from sheet shrinkage, and at higher moisture contents because of water in the pores. The

practice of previous authors in reporting k/L rather than k for moist paper has been continued because of the lack of accepted standard conditions for determining the thickness of wet paper. The shrinkage of paper from beaten kraft pulp has been reported by Smook [1992]. An additional contribution to the reduction in permeability with decrease in moisture content below the fibre saturation point may come from release of fibrils from the fibres, as noted in connection with Figure 3.1. A very small increase in permeability occurs from a moisture content of 0.2 kg water/kg fibre to dryness. By 0.2 kg/kg moisture content the sheet structure is established by hydrogen bonding between the fibres, so there is negligible sheet shrinkage below this moisture content. However from 0.2 kg/kg to dryness individual fibres continue to shrink, thereby slightly increasing porosity and hence permeability. Figure 3.4 shows that this is a small effect.

The effect of beating on the permeability - moisture content relationship is seen on Figure 3.5, where the Figure 3.4 data appear for reference as the case for heavily beaten pulp. Even for the mildly beaten pulp, of freeness 435 ml, there is a substantial decrease.

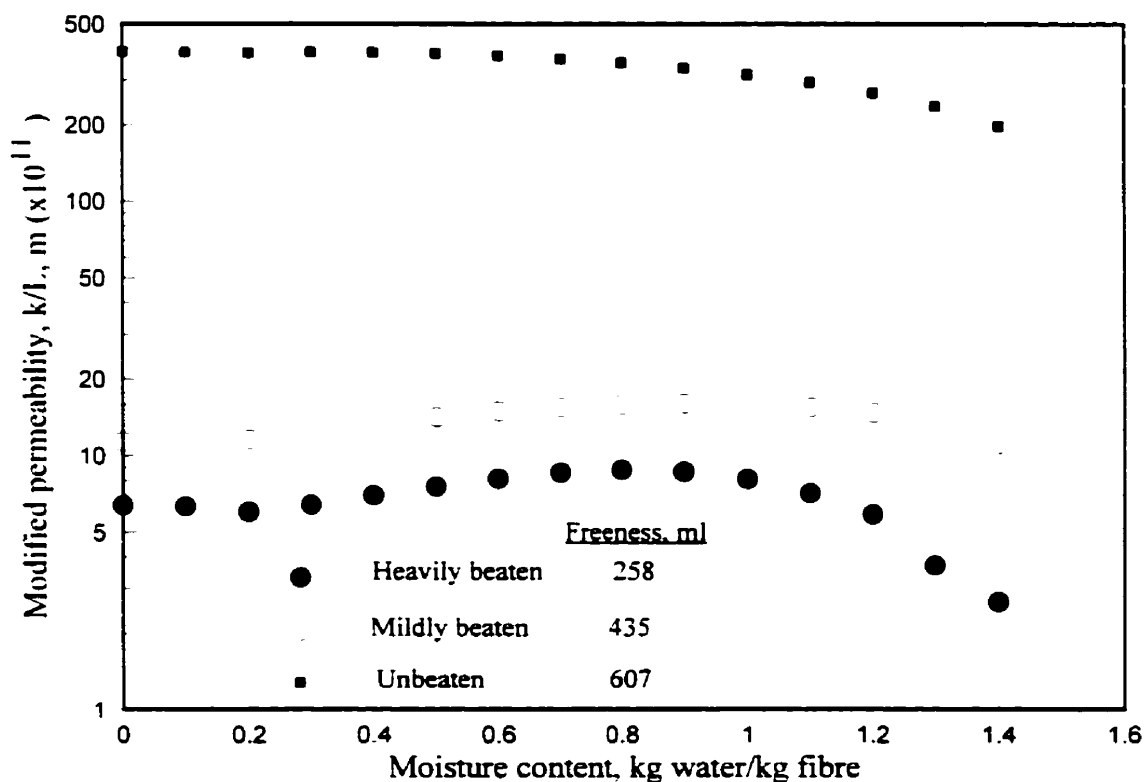


Fig. 3.5 Effect of beating on modified permeability of moist paper

about 30%, in the modified permeability from the maximum at the fibre saturation point, to the minimum. Because of sheet shrinkage below the fibre saturation point the relative effect is of course greater yet on permeability k than on modified permeability k/L . The effect of permeability decreasing as moisture content drops below the fibre saturation value is seen from Figure 3.5 to disappear completely for kraft paper made from unbeaten pulp.

3.3.2 Effect of beating on through drying characteristics

Because of the high sensitivity that the latter part of the falling rate period exerts on drying time and hence dryer size, determination of drying time for a particular initial and final moisture content provides a more critical test of differences in drying rate curves than does the inspection of $R - X$ curves. Therefore in Figure 3.6 is presented the drying time from a moisture content of 1.65 to 0.03 kg water/kg fibre for 41 sheets of 60 g/m² kraft paper made from furnishes beaten to two levels of freeness, 258 and 435 ml. It was difficult to obtain valid results for paper from the most highly beaten pulp because its shrinkage potential is so great that the sheets frequently slipped from the restraining rings, allowing air

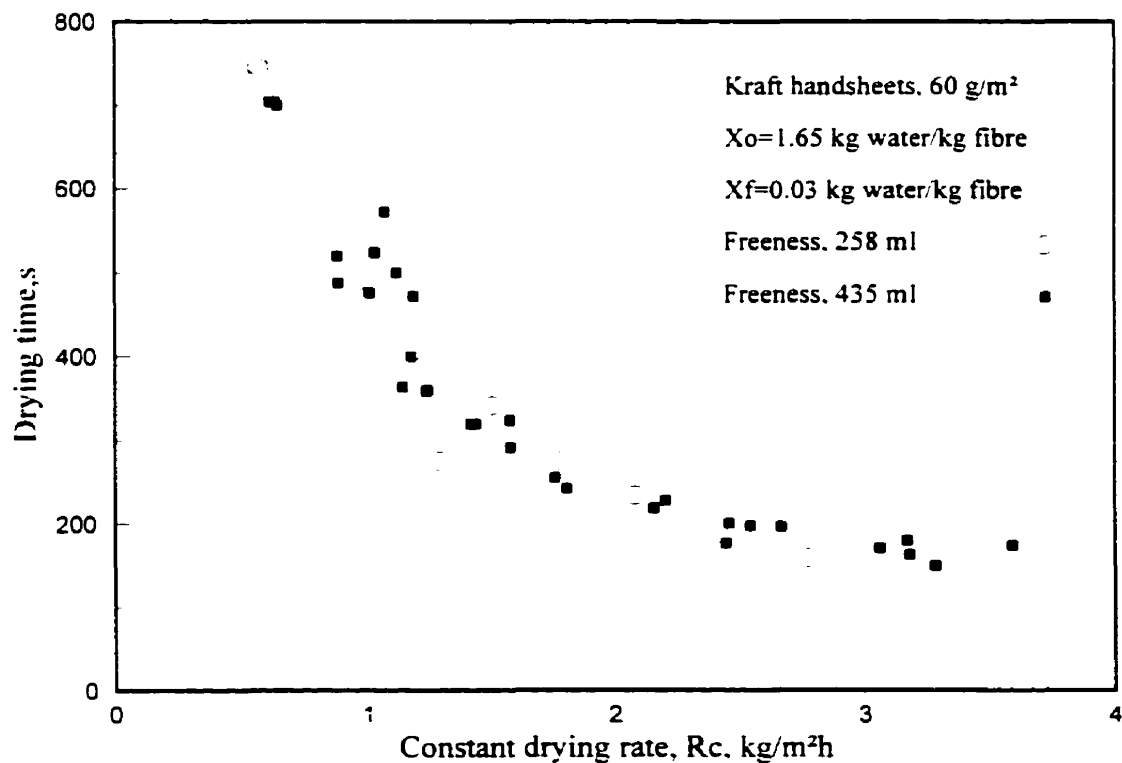


Fig. 3.6 Effect of beating on drying time

by-passing which invalidates the results. Figure 3.6 shows that, in spite of about a factor of two ratio in sheet permeability for this difference in pulp freeness, there is no significant difference in drying time for these papers. To provide another check, the length was determined for each drying period i.e. those of increasing, constant and falling rate. These results likewise showed no significant effect of beating on the end of the increasing rate period at X_i , the value of the constant drying rate, R_c , or on the onset of the falling rate drying period, X_c . Thus the present investigation indicates that the degree of beating of kraft pulps affects strongly the momentum transport aspects of through drying while leaving the drying rate characteristics quite unaffected.

3.4 Bleach Plant: Effect of Bleaching

The specifications of the two types of bleached and unbleached kraft pulps obtained from Domtar Inc. are listed in Table 3.3. The unbleached kraft pulp, designated Q30, is the standard reference pulp used at the Pulp and Paper Research Institute of Canada. The bleached pulp, Q90, comes from the same mill. With the drying conditions given in Table 3.4 at least 16 experiments were carried out with each type of paper, including a replicate experiment at each drying condition. The results for the through drying characteristics, of which Figure 3.7 shows a typical set, are analyzed first for the momentum transport aspects and then as to drying rate.

Table 3.3 Pulps used for effect of bleaching

Pulp	Type of pulp	Freeness, ml	Fines, %
Q 30	Unbleached kraft softwood	660	0.2
Q 90	Bleached kraft softwood	645	2.5

Table 3.4 Drying conditions for effect of bleaching

Air flow rate, kg/m ² s	0.207 - 0.402
Air Temperature, °C	20 - 89
Initial moisture content, kg water/kg fibre	1.7 - 1.9

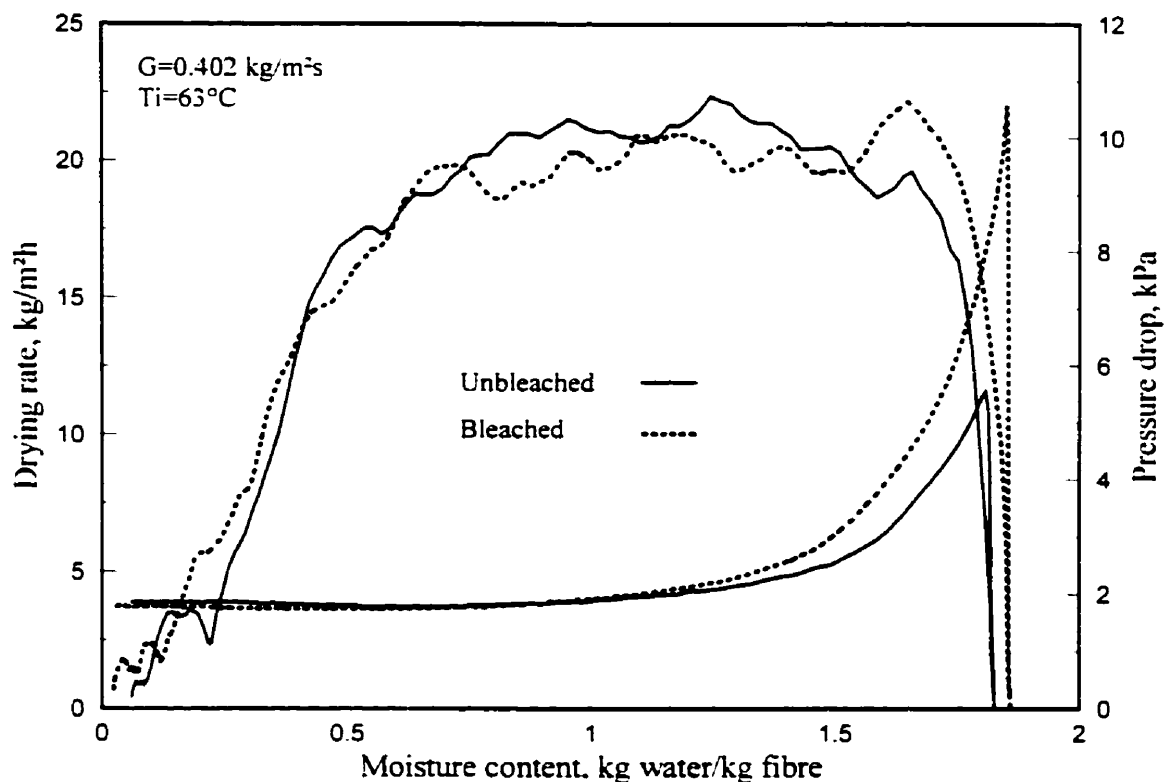


Fig. 3.7 Effect of bleaching on through drying behavior

Measurements on the dry sheets, Table 3.5, show that bleaching leads to a 25% reduction in permeability. Due to the extreme sensitivity of permeability to beating shown on Figure 3.5, the effect of bleaching was determined with unbeaten pulp in order to avoid confusing these two effects. Probably two consequences of bleaching are involved. The removal of lignin by bleaching leads to greater fibre flexibility, hence to a slightly denser, better bonded structure, and thereby a lower permeability. Also, mechanical action on the pulp suspension in passing through the bleach plant increases the fines content from 0.2% to 2.5%, and sheet permeability is very sensitive to fines content, as was demonstrated qualitatively in this chapter for the effect of beating, and quantitatively in the preceding chapter for the effect of fines.

Table 3.5 Effect of bleaching on permeability

Type of Paper	Unbleached	Bleached
Permeability, m^2	5.83×10^{-13}	4.36×10^{-13}

Because for through air drying it is the permeability of the moist sheet which controls the use of this technique, Figure 3.8 shows the relative effect over the full moisture content range from wet to dry. Bleaching results in a significant reduction in permeability over the moisture content range from the fibre saturation point to dryness. However in the range from 1.4 kg water/kg fibre down to the fibre saturation point the reduction in permeability is much greater, with the permeability of the sheet at the typical moisture content from the press section being reduced by bleaching by more than 50%. At moisture contents above that of the fibre saturation point the effect on air permeability of the sheet caused by even the modest increase in fines content in passing through the bleaching process, from 0.2 to 2.5%, is magnified by the fact that a substantial fraction of the pore volume is occupied by water. Thus in this range of moisture content the fines and the pore water combine to reduce substantially the air permeability of the sheet.

Because of the greater sensitivity of drying time than drying rate curves, the same type of drying time comparisons were made for unbleached and bleached kraft paper as previously as for the effect of beating. Again, the drying times for unbleached and bleached paper were similar, as were the values of X_i , R_c and X_c . Thus these measurements indicated that bleaching, like beating, had no significant effect on through drying rates.

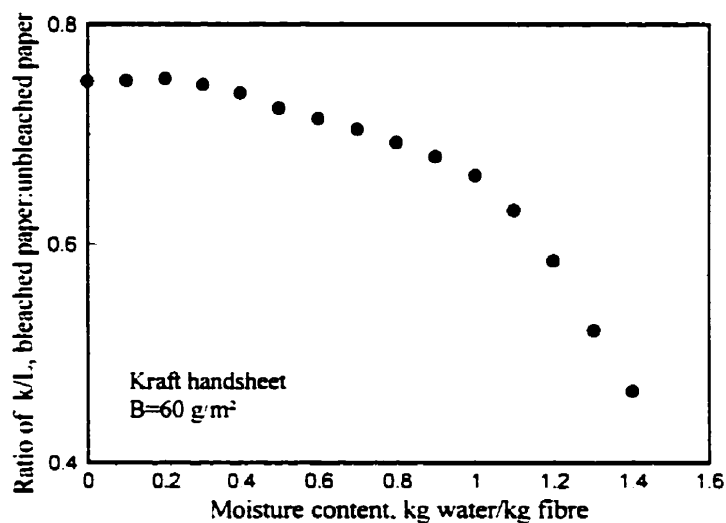


Fig. 3.8 Effect of bleaching on permeability of moist paper

3.5 Paper Mill: Effect of Wet Pressing

For standard handsheets the wet web is pressed at 50 psi first for 5 min., then for 2 minutes. To gain some understanding of through drying sensitivity to wet pressing, handsheets were also made with the use of pressures of 150, 300 and 600 psi. Although

these pressures are much lower than those in commercial wet pressing, this is compensated by the use of much longer times of applying the pressure. For the handsheets made from unbleached, unbeaten kraft pulp the drying conditions were as used for the effect of bleaching, Table 3.4. Inspection of the results for just the extremes in pressing, 50 and 600 psi, Figure 3.9, reveals that the ΔP -X curves are highly sensitive but the R - X curves show little effect. The momentum transport and the drying rate aspects are examined again in this order.

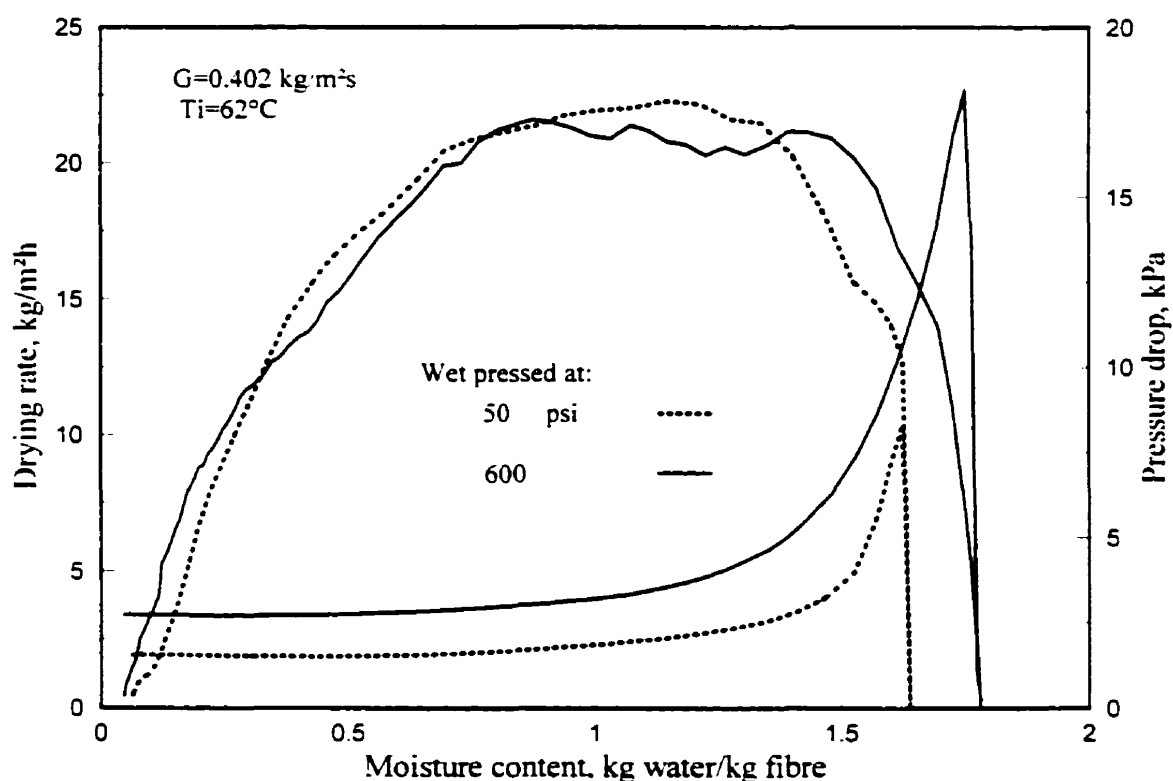


Fig. 3.9 Effect of wet pressing on through drying behavior

3.5.1 Effect of wet pressing on momentum transport

Comparison of the ΔP -X curves in Figure 3.10 shows that the high sensitivity of sheet permeability to wet pressing occurs over the entire range of pressing conditions used. For the dry paper, where sheet caliper can be determined by accepted standard procedures, Figure 3.11 shows the effect of wet pressing on the permeability of these kraft handsheets. The exponential reduction in permeability with increasing pressure in wet pressing

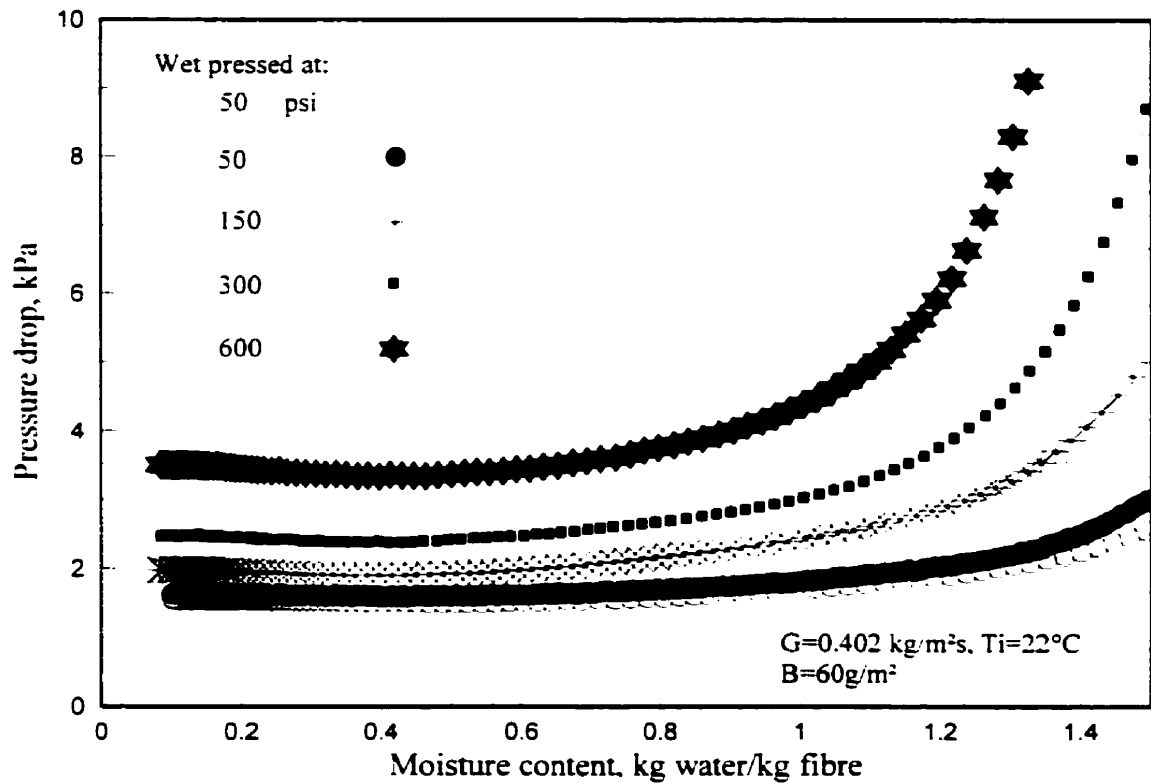


Fig. 3.10 Effect of wet pressing on pressure drop

corresponds to the reduction in specific volume of the paper and hence in its porosity. In their study of the effect of wet pressing for 200 g/m^2 handsheets made from pulp of various freeness, Knauf and Doshi [1986] have shown a linear relation between the permeability of dry paper and its apparent density. Knauf and Doshi measured the air permeability using the Gurley and Bendtsen testers, for which they showed Darcy's law could be used due to a negligible contribution of inertial effects in the momentum transport. For wet sheets Boerner and Orloff [1994] measured the hydrodynamic permeability of thick paper, 150 to 400 g/m^2 , made from pulps of 740 and 600 ml freeness. They represented permeability as a linear function of porosity.

Substitution of equation 3.1 into 2.10 and rearranging leads to:

$$(k\rho_p^2)^{1/3} = \left[\frac{1}{\kappa(a_p')^2} \right]^{1/3} \rho_p \quad (3.2)$$

where a_p' is the specific surface area per unit mass of dry fibres.

According to this equation a plot of $(k\rho_p^2)^{1/3}$ against ρ_p should be linear if the Kozeny-Carman equation 2.10 is applicable. Furthermore, in that case the value of a_p may be calculated from the slope of this plot. Figure 3.12 shows the nonlinearity of this relationship for 60 g/m² handsheets wet pressed over a range of 50 to 600

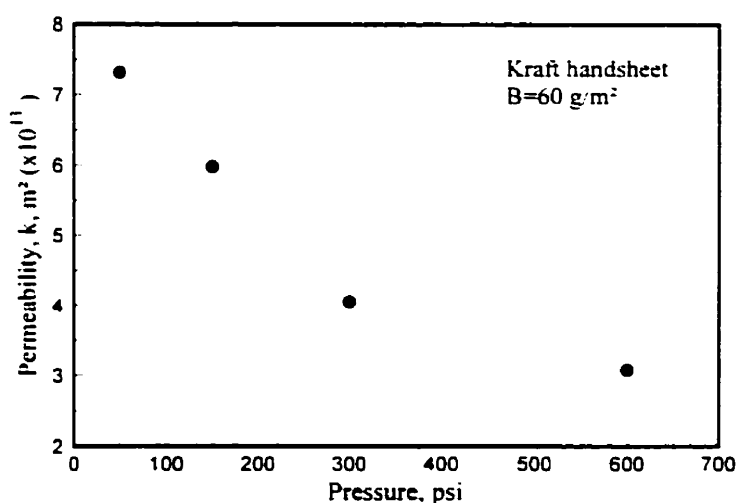


Fig. 3.11 Effect of wet pressing on permeability

psi. This finding indicates that when paper porosity is reduced to this extent by wet pressing, the Kozeny-Carman equation relating specific surface, porosity and permeability does not apply over this full range.

With 60 and 200 g/m² handsheets from bleached kraft pulp Knauf and Doshi [1986] showed the applicability of this equation, with the Kozeny constant $\kappa = 5.55$, for paper having porosity in the range from 0.39 to 0.65. Fowler and Hertel [1940] reported that the Kozeny-Carman equation could be applied to fibrous beds in the porosity range 0.55 to 0.86. However it has since been found that the Kozeny constant is a strong function of sheet porosity, Ingmanson and Andrews [1963], Chen [1982]. Both Brown [1949] and Sanborn [1962] reported that the Kozeny-Carman relationship is not applicable to paper. Bliesner [1964] documented that it could

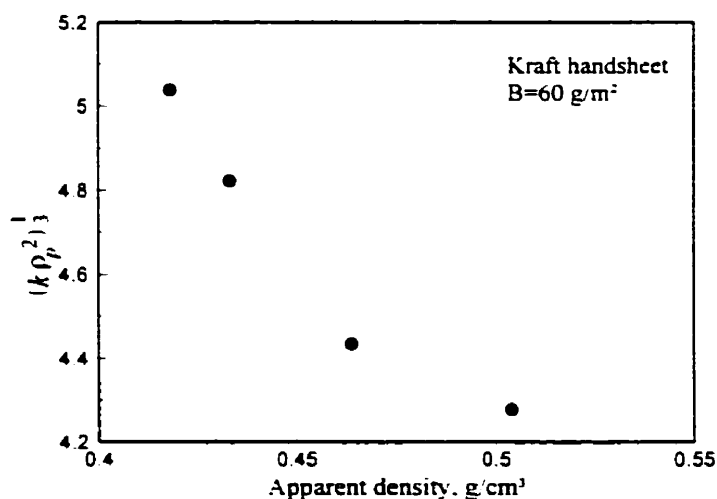


Fig. 3.12 Effect of wet pressing on applicability of Kozeny-Carman eqn.

not be used to predict the specific surface of dry paper of 100 g/m² basis weight made from unbeaten, bleached sulphate pulp when the porosity of the dry sheet was changed from 0.788 to 0.714 by changing the wet pressing pressure from 10 to 100 psi. However Polat [1989] used very extensive data to establish the applicability of the Kozeny-Carman equation with a Kozeny constant $\kappa=5.55$ for kraft handsheets of 25 to 150 g/m² and porosity over the range of 0.6 to 0.7. For handsheets made from kraft pulp and pressed at the standard pressure of 50 psi. Table 3.6, both Polat's and the present results show good agreement between the Kozeny-Carman equation and other techniques. By increasing the wet pressing from 50 to 600 psi the specific surface area estimated using the Kozeny-Carman equation increases while that calculated using the light scattering coefficient decreases. Wet pressing increases the bonding area, hence leading to the lower specific surface area predicted from the optical measurement, but the results obtained by the Kozeny-Carman equation indicate just the contrary. Bliesner [1964] believed that the failure of the Kozeny-Carman approach when applied to his handsheets could be attributed to the broad pore size distribution of the sheets and to the fact that the Kozeny factor κ changes with the amount of pressure applied to the sheet in wet pressing. As increasing the intensity of pressing should not make the pore size distribution wider, the conclusion from the present work is that the Kozeny parameter κ must not be a constant.

Table 3.6 Effect of wet pressing on specific surface area

Wet Pressing, psi	50	150	300	600
a'_p , from equation 2.10, m ² /g	0.68	0.77	0.84	0.86
a'_p , from light scattering, m ² /g	0.71	0.69	0.68	0.66

Polat et al. [1989] showed that with the momentum transport equation expressed here in equation 2.6, and with Reynolds number being the ratio of the inertial term to the viscous term, i.e. $Re = \beta \rho u^2 / \alpha \rho u = \beta \rho u / \alpha \mu$, it follows that the characteristic dimension for Reynolds number and for all nondimensional numbers in convective transport phenomena is therefore $d_p = \beta / \alpha$. In the present study it was for practical reasons not possible to determine d_p over the entire range of moisture content from wet to dry. With wet paper the low flow rates, required by the limitation on pressure drop, were insufficient to produce an

inertial contribution to ΔP large enough that β could be determined accurately. However this restriction did not apply for the more permeable dry sheets, for which the values of d_p determined here using the method of Polat et al. are listed in Table 3.7. The decrease in d_p with increasing wet pressing seen here is due to the corresponding decrease in paper specific volume and porosity. This trend follows that observed by Bliesner [1964] for the effect of wet pressing on the mean hydraulic radius of paper. As our d_p derives directly from momentum transport measurements it is therefore the characteristic dimension for Reynolds, Nusselt, Sherwood and Peclet numbers.

Table 3.7 Effect of wet pressing on characteristic dimension d_p

Wet pressing, psi	50	150	300	600
d_p , μm	4.6 ± 0.3	3.3 ± 0.3	3.05 ± 0.3	3.0 ± 0.25

While the above effects relate only to dry paper the special contribution of the present study is in providing the first information on the effect of wet pressing on the permeability of paper in through drying, i.e. for the paper when wet. Figure 3.13 shows the effect of wet pressing on the modified permeability of moist paper. Increasing the pressure applied in a wet press section of a papermachine reduces the permeability substantially over the entire range of moisture content from wet to dry. The modified permeability-moisture content relation expressed in either exponential or power law form, equation 2.1, was used. As the value of R^2 for the results given in Table 3.8 was always higher than 0.99 for both forms, either one could be used.

Table 3.8 Effect of wet pressing on modified permeability of moist paper

Pressure, psi	Exponential model			Power law model		
	$a \times 10^9$	$b \times 10^7$	c	$A \times 10^9$	$B \times 10^8$	C
50*	0.124	0.10	1.86	0.140	0.496	3.06
150	0.252	0.193	3.13	0.257	0.394	3.92
300	0.340	0.214	3.48	0.347	0.616	4.38
600	0.412	0.189	3.92	0.414	0.999	4.41

* From Polat's [1989] results for 50 g/m² handsheets.

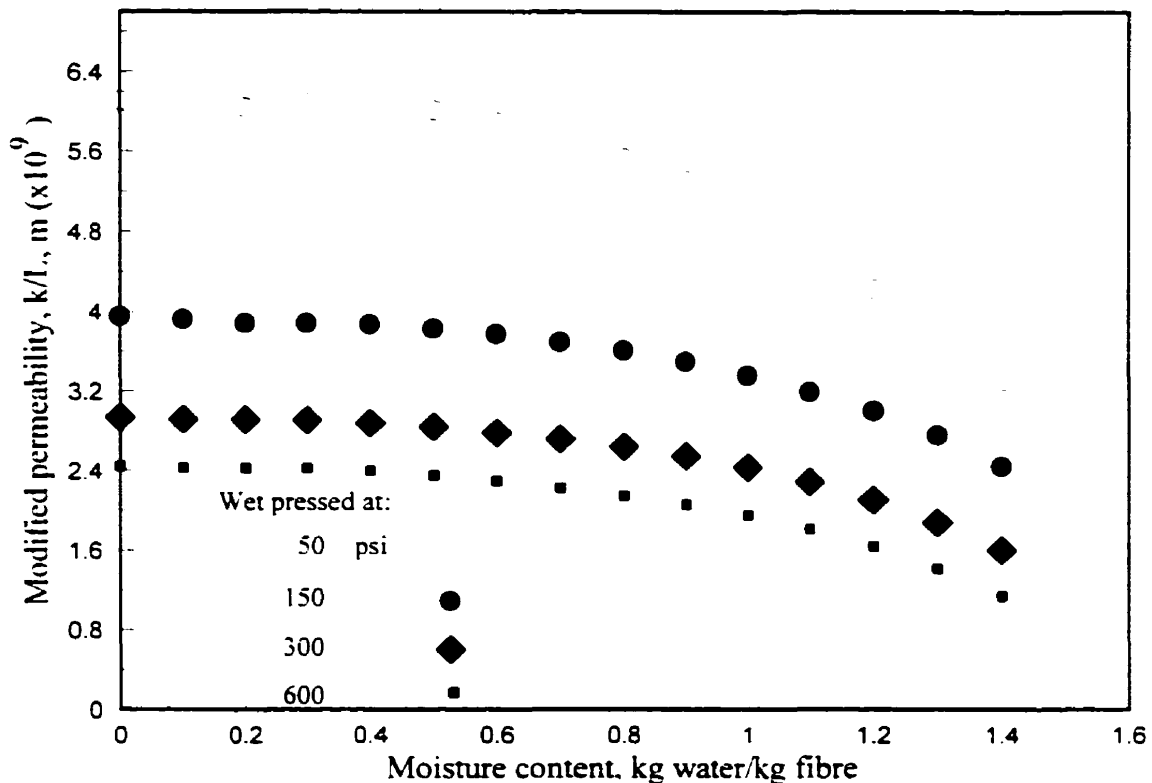


Fig. 3.13 Effect of wet pressing on permeability of moist paper

3.5.2 Effect of wet pressing on through drying characteristics

Figure 3.14 shows that there is no relation between the drying time of paper and a wide range of conditions of wet pressing. The ratio R_c/R_s was found to be nearly independent of the pressure of wet pressing. At the highest drying intensity conditions used, $G = 0.402 \text{ kg/m}^2\text{s}$ and $T_1 = 86^\circ\text{C}$, R_c was reduced by 1.0, 1.8 and 2.5% for sheets pressed at 150, 300 and 600 psi, effects so small as to be just measurable. With increased wet pressing it would be expected that there would be closer air-fibre contacting but shorter air residence time in the sheet. These compensating effects almost cancel. For the four levels of wet pressing pressure the value of the X_c/X_0 ratio of critical to initial moisture content was found to be 0.44 ± 0.03 , varying randomly. Thus for the case of a wide variation in the wet pressing condition, again the general conclusion is that the through drying rate characteristics are essentially unaffected.

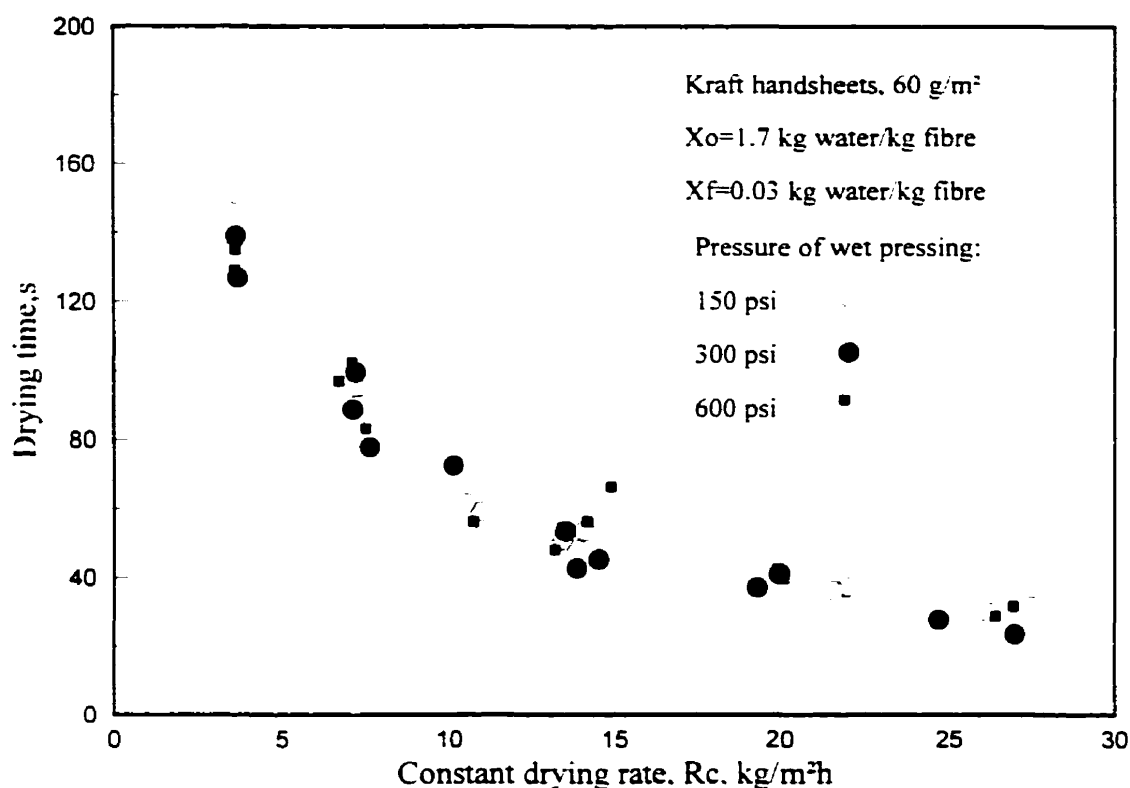


Fig. 3.14 Effect of wet pressing on drying time

3.6 Paper Mill: Effect of Formation

In studies of through drying previous investigations have not considered the fact that paper is locally nonuniform with respect to grammage, thickness, density and porosity, in short, is nonuniform in structure. As the essential local nonuniformity of sheet structure should be expected to be important when the drying is by air flow through the sheet, this aspect was explored using experimental conditions similar to those given in Table 3.4. The formation of handsheets was varied by allowing the pulp suspension to flocculate for times of 10s and 100s in addition to the standard value of about 1s. The results, a sample of which are shown in Figure 3.15, are analyzed below.

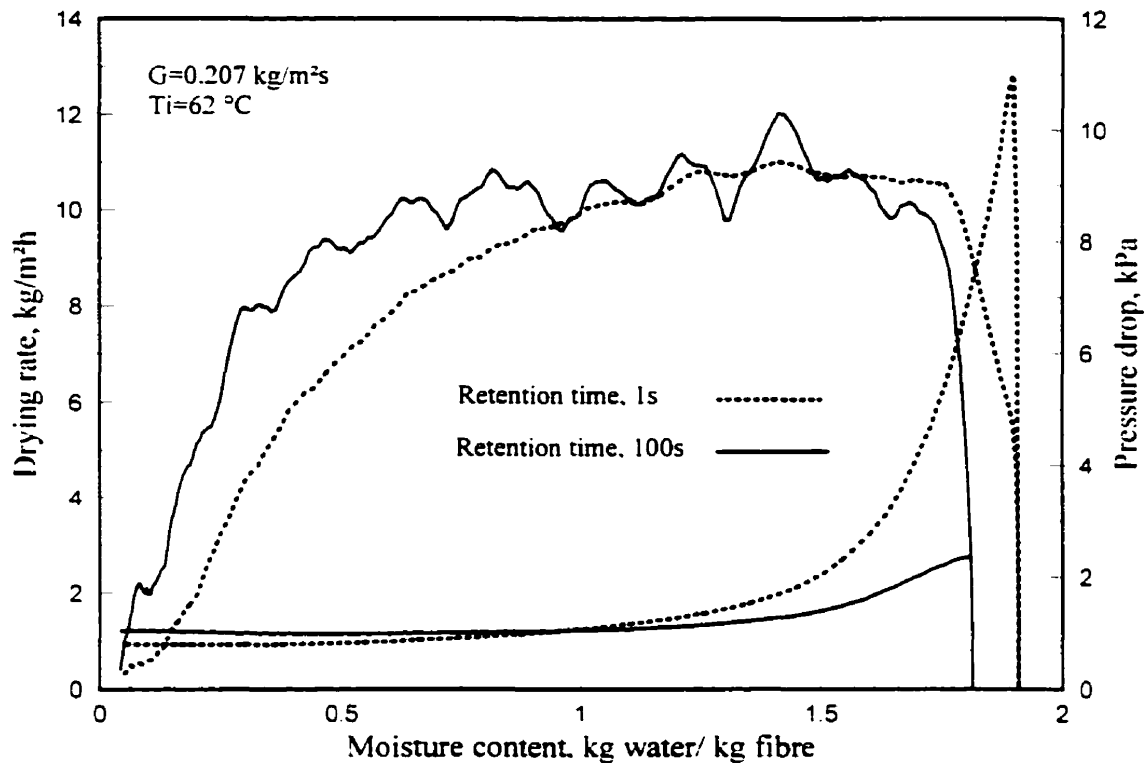


Fig. 3.15 Effect of formation on through drying behavior

3.6.1 Effect of formation on momentum transport

As the drying of printing and heavier papers typically starts with moisture contents from the wet press in the range 1.3 - 1.5 kg water/kg fibre, this is the range examined in detail. Sheet permeability was determined without assuming in advance that Darcy's law applied, i.e. with the appropriate momentum transport equation. For two sheets which differ only as to local nonuniformity of formation, the sheet average permeability measured would be independent of formation only if

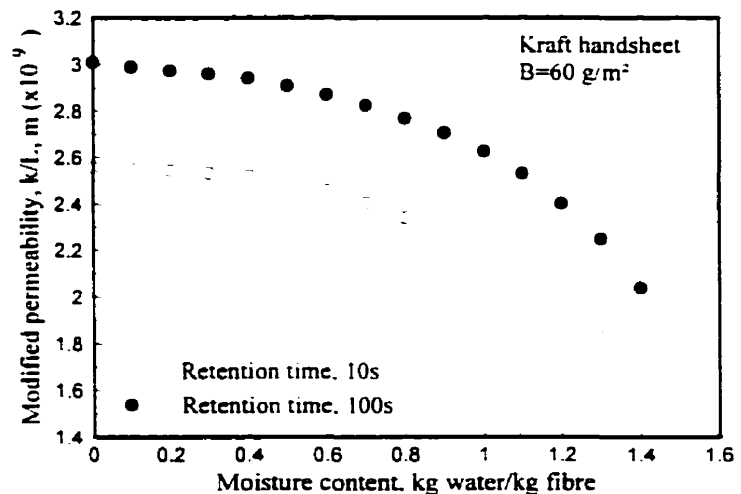


Fig. 16 Effect of formation on permeability of moist paper

all aspects of momentum transport were linear, which is far from true. With nonlinearity it is predictable that the greater the nonuniformity in formation, the higher the sheet average permeability. An extreme limit would be a sheet with many holes between regions of locally high grammage, a structure giving a much higher sheet average permeability than the equivalent sheet of uniform local grammage. The results determined here, Figure 3.16, for the permeability of a sheet of average quality formation (10s retention) and for one of much worse formation (100s retention) than obtained with the forming section of an industrial papermachine, show that the difference in permeability is only about 25% or less. Thus relative to the large effects on sheet permeability from both wet pressing and beating, the effects on air permeability for the range of sheet formation found in practice are small by comparison.

3.6.2 Effect of formation on through drying characteristics

The only previous investigation was that by Gomes et al. [1992] who simulated the effect on through drying of nonuniformity in sheet formation. That simulation, based on the experimental results of Polat [1989] and Polat et al. [1991, b], indicated that paper of poor formation would have a substantially longer drying time. The present experimental results with sheets of various formation provide the first measurements of the extent of this effect. Figure 3.17 shows that the paper with a poor quality of formation has significantly longer drying time than a well formed sheet. Analysis of the $R - X$ data revealed that there was no effect of formation on either the length of the increasing rate drying period, i.e. on X_i , or on the rate of drying during the constant rate period, R_c . But clearly the length of both the constant and falling rate drying periods are a function of sheet formation quality. With poorer formation the constant rate period ends sooner, i.e. at a higher X_c , and the drying rate is lower during the falling rate period. Going from good to poor formation (retention time from 1s to 10s to 100s) the ratio X_c/X_0 increased from 0.42 to 0.45 to 0.49. Also, the sensitivity of drying time to quality of formation increased with drying intensity. Thus the increase in drying time for sheets formed at 100s retention time relative to those formed at 1s retention is 20% at $R_c = 5\text{kg/m}^2\text{h}$ but about 40% at the highest R_c used here, $28\text{kg/m}^2\text{h}$. The mechanisms involved in the local nonuniformity effect is the subject of an intensive investigation reported in next chapters.

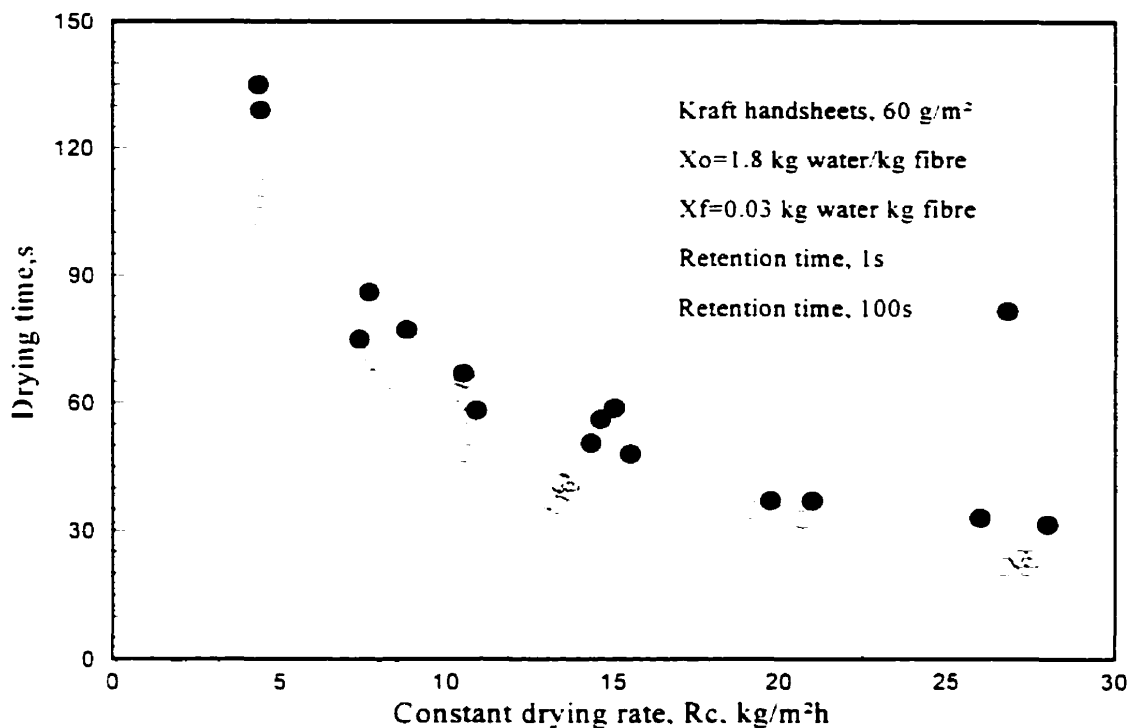


Fig. 3.17 Effect of formation on drying time

3.7 Paper from Pulp Blends

Newsprint and related papers are made from a furnish of exclusively mechanical pulp or from blends incorporating chemical pulp. Therefore the objective here was to characterize the momentum transport and drying rate aspects of through air drying for sheets of basis weight in the printing grade range and made from TMP or blends of TMP with kraft pulp. Standard 60 g/m² handsheets were dried under a constant air mass flow rate G , and inlet air temperature T_i , in the experimental facility described in previous chapter. The pulp furnishes used were pure TMP and pure kraft pulp, as specified in Table 3.9, and their blends. The handsheets were made according to CPPA standard C.4. As is common in laboratory drying experiments the sheets were rewetted prior to drying.

Table 3.10 shows the experimental conditions. The maximum through flow rate used was that giving a pressure drop of about 40 kPa across the wet sheet at the start of drying. The cost of providing a higher pressure drop is probably not economic, and this

Table 3.9 Pulp specifications

Type of pulp	Specifications
TMP	100% mechanical pulp, 26.4% fines content, CSF 168ml, FSP 0.72 kg/kg
Kraft	Unbleached, unbeaten, kraft pulp, black spruce, CSF 685ml, FSP 0.87kg/kg

Table 3.10 Drying conditions

Mass flow rate, G , kg/m ² s	0.0246, 0.0362, 0.044, 0.051
Inlet air temperature, T_i , °C	20, 42, 62
Initial moisture content, X_0 , kg water/kg fibre	1.5-1.8

ΔP is also near the limit to avoid marking the paper with the wire mesh support. The initial moisture content was in the range 1.5 - 1.8 kg water/kg fibre, thus including typical values in a paper mill for paper entering the dryer section after wet pressing. Variation in basis weight and initial moisture content was not a priority for this investigation as these effects were investigated by Polat [1989], but a few experiments were carried out with sheets of different initial moisture content. Generally each experiment was replicated, leading to 24 tests for each type of paper (4 values of G , at 3 values of T_i , replicated

Figure 3.18 shows typical results. The three drying periods are distinguishable, those of increasing rate, constant rate and falling rate. The pressure drop curve consists of a nearly instantaneous pressure build up when the sheet enters the drying chamber, then the drop in ΔP at constant G as sheet permeability increases with decreasing sheet moisture content. The exit air temperature drops for the constant drying rate period to a constant minimum value, near or below the adiabatic saturation temperature, then increases during the falling rate period to approach the temperature of the drying air as the sheet approaches dryness.

The two most comprehensive studies of through air drying, by Polat [1989] and Chen [1994], were limited to unfilled handsheets from kraft pulp. Those studies documented the effects on drying characteristics of key parameters - basis weight B , initial moisture content X_0 , drying air temperature T_i , air through flow rate G , and the nature of the air flow pattern to the wet sheet. The focus here is to examine the effect on

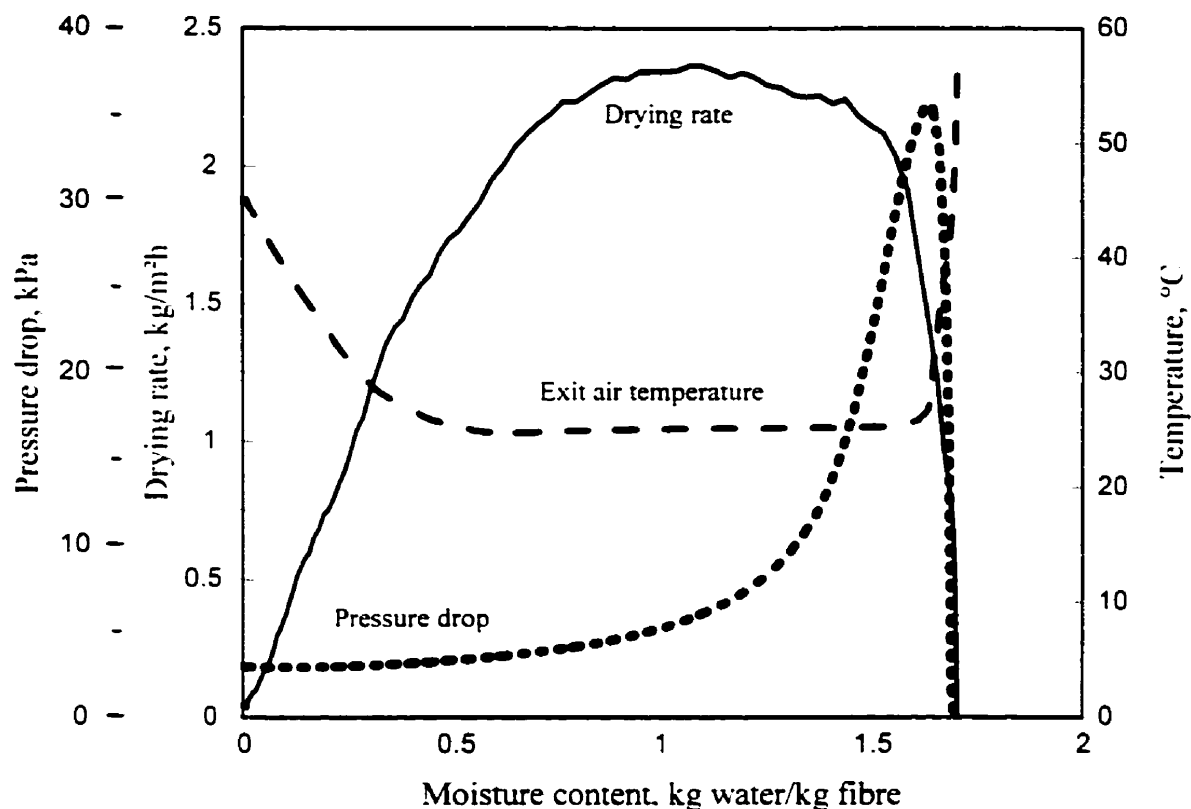


Fig. 3.18 Typical results for a TMP handsheet

through drying characteristics for paper made from TMP and of TMP-kraft pulp mixtures, thereby extending the results of previous studies with a single furnish.

3.8 Drying Rate Characteristics of Paper From Blends

Due to the much lower permeability of paper from TMP than from unfilled kraft pulp the through flow rate in the present study was correspondingly much lower. The low through flow rate combined with the use of drying air temperatures in the range 25-90°C gives drying rates which bear no relation to those effective in the industrial through drying of tissue and toweling where 200-400°C air may be used at large flow rates through high permeability sheets. The present study is however oriented not to current industrial practice for tissue drying but to examining of the through drying characteristics of semi-permeable paper.

In the Figure 3.19 presentation of drying rate curves it is not possible to detect significant differences related to the composition of the pulp furnish. As drying time provides a more sensitive test of differences in drying rate characteristics. Figure 3.20 shows the same data converted to the equivalent drying time from initial to final moisture contents of 1.8 and 0.05 kg water/kg fibre. As drying time relates directly to dryer size, the differences on the Figure 3.20 type plot provide a direct interpretation of the significance of the results. Drying time is seen to be the highest for the standard TMP paper and the lowest for the blend with the lowest TMP content, 25%. However the degree of experimental scatter in the data indicates that this tendency for a higher TMP content to lead to somewhat longer drying time is not a strong effect.

From the experimental R-X data of each run the method of Chen [1994] was used to obtain the five parameters, R_c , X_i , X_c , n_i , and n_f , reported in Appendix E, which he showed were sufficient to describe the through drying rate curves as these pass through

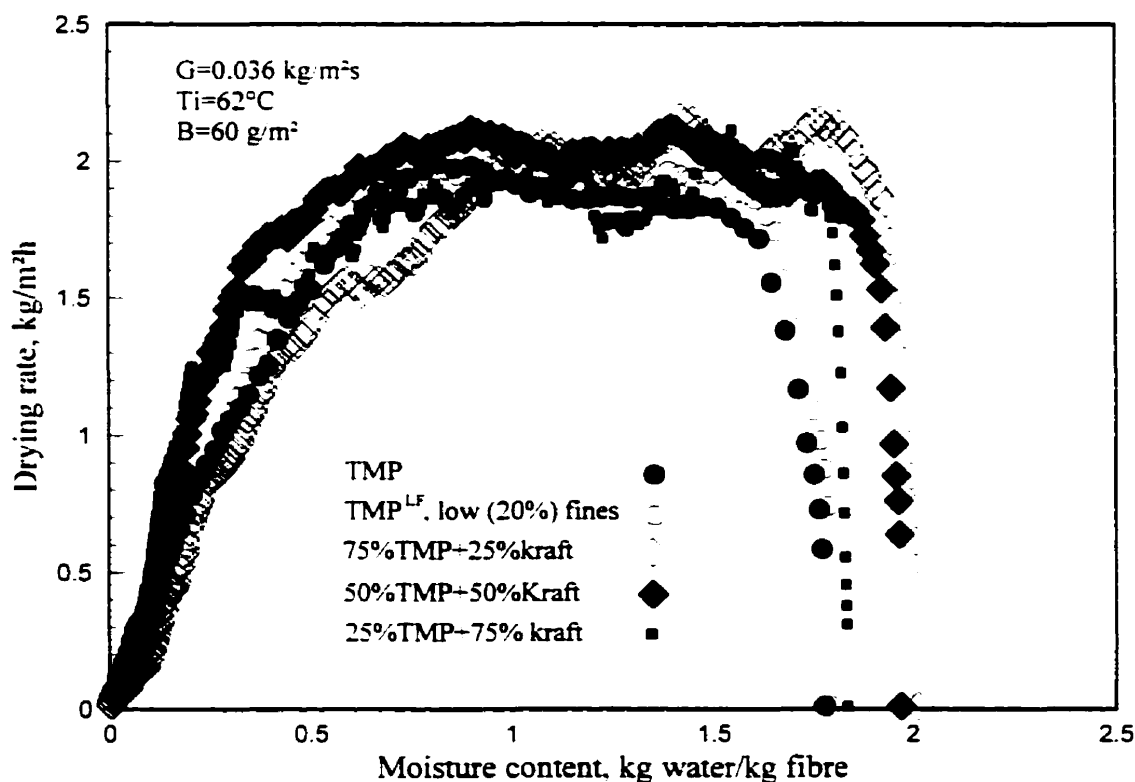


Fig. 3.19 Drying rate curves for paper from TMP-kraft pulp blends

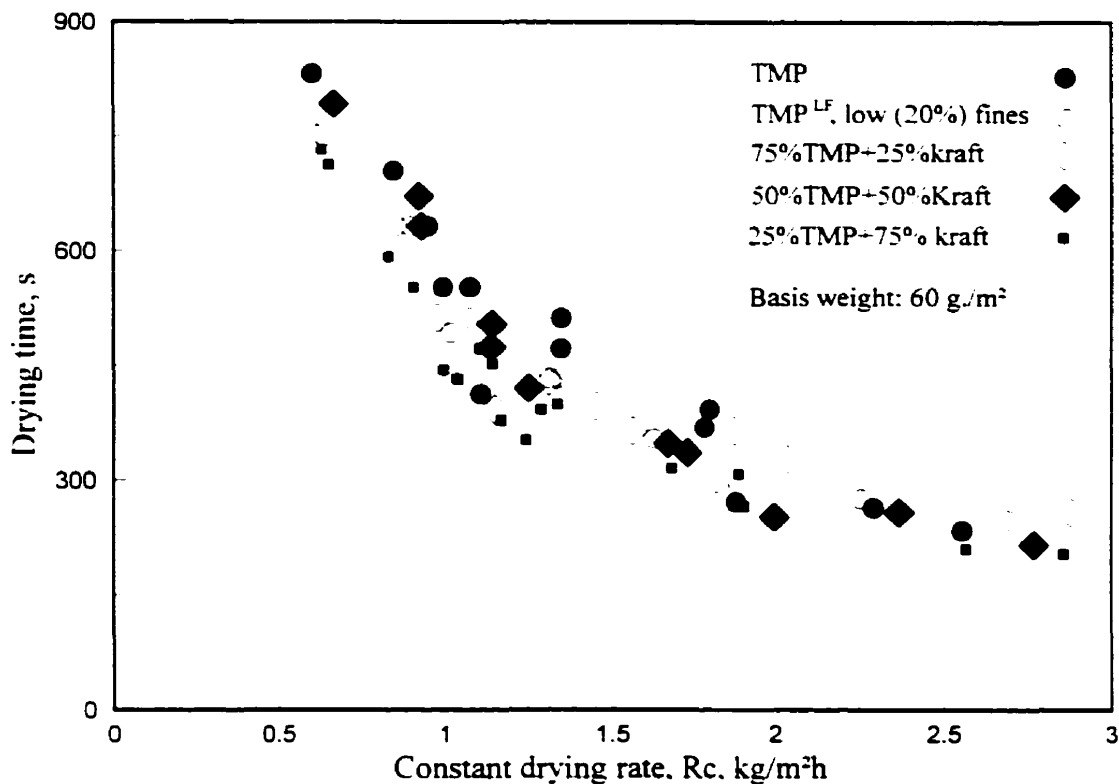


Fig. 3.20 Effect of furnish on drying time

the increasing, constant and falling rate drying periods. An example of the close agreement between the R-X curve for the five parameters obtained and the experimental R-X data appears in Appendix C. The most comprehensive test for the effect of pulp furnish composition on through drying is to examine effect of furnish on these parameters.

As discussed in chapter 2, the increasing rate period ends when sufficient interfacial transfer area has been developed within the sheet by removal of water from the pores that the drying rate reaches the limit of the constant drying rate, R_c . Application of the correlation of Chen [1994] for the extent of the increasing rate period, $X_o - X_i = aG^b(T_i - T_r)^c B^d$, enables calculation of the average value of the proportionality factor, a , for each of the furnishes used, as listed in Table 3.11. A strong trend of this proportionality constant with furnish composition is evident. Thus the extent of the increasing rate period is two to three times higher with paper made from TMP than from this kraft pulp, with the blends indicating a proportionate behavior. The mechanism for

this significant change may reflect a combination of effects. For the development of transfer area the pore size distribution would be important, and this would certainly be changed in going from a paper of approximately 0.65 porosity made from flexible kraft pulp fibres, to the 0.8 porosity TMP paper of stiff fibres. Also, where the large amount of fines

(26.4%) of the standard TMP are located within the sheet, the local value of porosity will be low, leaving less pore space for free water at the start of drying. With a high fines furnish therefore, in order to generate the amount of transfer area needed to bring R up to R_c it would require more drying, i.e. a higher value of $X_0 - X_i$, thus a higher value of the parameter "a" in Table 3.11. The values of X_i calculated with the average value of "a" from Table 3.11 relate well with the X_i values determined from individual drying experiments (see Appendix C for the case of pure TMP).

The difference in sheet structure between TMP and unfilled kraft paper should lead to differences in through drying rate behavior. For example, a TMP sheet is much bulkier, giving a thicker paper at the same basis weight which, with the mechanism of air through flow, would suggest a higher value of the constant drying rate R_c . However, for the form of R_c correlation used by Polat [1989] and Chen [1994], $R_c = aG^b \Delta T^c B^d$, the values of the correlation parameters given in Table 3.12 show no trend with furnish

Table 3.11 Correlation parameter for increasing rate period

Paper type	a
TMP	0.83
TMP ^{LF}	0.56
75%TMP+25%kraft	0.41
50%TMP+50%kraft	0.40
25%TMP+75%kraft	0.23
kraft	0.30

TMP^{LF}: TMP pulp with low (20%) fines content

Table 3.12 Correlation parameters for R_c

Paper type	a	σ_a	b	σ_b	c	σ_c	d
TMP and TMP ^{LF}	1.16	0.15	1.01	0.08	1.03	0.06	0.01
75%TMP+25%kraft	1.26	0.03	0.96	0.01	1.01	0.01	0.01
50%TMP+50%kraft	1.20	0.04	0.97	0.01	0.99	0.01	0.01
25%TMP+75%kraft	1.25	0.02	0.96	0.01	1.00	0.01	0.01
kraft	1.24	0.2	0.96	0.02	1.00	0.02	0.01

TMP^{LF}: TMP pulp with low (20%) fines content

composition. The experimental data and correlation for R_c are recorded in the two graphs of Appendix C. With the low intensity drying conditions of these experiments, R_c is 75 - 98 % of the saturation drying rate, R_s . As $R_c \rightarrow R_s$, then the correlation parameters $b \rightarrow 1$, $c \rightarrow 1$ and $d \rightarrow 0$. The Table 3.12 values confirm that in the present experiments R_c is controlled by an approach to equilibrium within the sheet, not by rate effects where the variation in sheet structure with furnish composition could become important.

The critical moisture content X_c , the moisture content at which the drying rate can no longer be maintained constant, i.e. purely heat transfer controlled, found by Polat [1989] to be $X_c/X_o=c=0.45$, accurate within 10%. Chen [1994] reported that the slope of the R-X curve in the falling rate period could be represented as a power law, equation 2.17, with $n_f=1.7$. From the Table C1 in Appendix C listing of values of these two parameters, c and n_f , it is apparent that there is no trend in these parameters with composition of the furnish, again with the reservation that at higher drying intensities the variation in sheet structure may influence these falling rate period parameters. Appendix C provides for one furnish, pure TMP, two examples of good fitting of the R-X values to Chen's form of correlation. One R-X curve is the best possible, using X_i , n_i , R_c , X_c and n_f for the individual sheet. The other drying rate curve derives from the individual value of R_c but Chen's universal values of n_i and n_f . The latter curve is seen to be almost as good.

3.9 Permeability of Paper From Blends

3.9.1 Momentum transport and paper properties

The pressure drop for flow through paper may be analyzed not only by the standard permeability procedure but also through use of the nondimensional Reynolds number- friction factor approach. For the permeability alternative it is important to use the correct momentum transport equation to calculate permeability, while for the latter approach a characteristic dimension is required. The type of flow regime determines the proper momentum equation, while the appropriate characteristic dimension must derive directly from the flow phenomena through the paper. To establish the regime of the flow, the power law equation 2.1 was used.

3.9.2 Flow through dry paper before and after a wetting-drying cycle

The type of flow through handsheets made from TMP or blends of TMP and kraft pulp was determined with equation 2.1 and the permeability calculated using the proper momentum transport equation. For the low range of through flow rate used here the exponent n reveals that in most cases the contribution of inertial effects to momentum transport is negligible. Hence Darcy's law, equation 2.3, could be used to calculate the permeability of dry sheets before and after a wetting-drying cycle, Table 3.13. The sheet thickness used to calculate permeability was the average thickness of the 24 sheets used. The change in the thickness of paper from blends of TMP and kraft pulp, measured after the sheets were through dried, is shown on Figure 3.21 along with the related dependence of paper density on composition of the blend. When paper functions as a packed bed, as in through drying, its thickness is fundamental to the process.

The permeability obtained here for dry 60 g/m² kraft handsheets, Figure 3.22, agrees well with values obtained by interpolation between those of Polat et al. [1993]. Their permeability for 45 g/m² newsprint, 7.8×10^{-14} m², compares with 5.6×10^{-14} m² obtained here. Several effects contribute to this difference. The fines content is significantly different, 20.5% for their Papriformer newsprint, 26.4% for the TMP used here. There is the basis weight difference. Finally, there is the difference in formation. As standard handsheets have less nonuniformity than machine-formed paper, the latter should be expected to have a higher permeability. Polat et al. observed that Papriformer sheets

Table 3.13: Permeability of dry paper before and after a wetting-drying cycle

Paper type	Before wetting-drying		After wetting-drying		%Increase in permeability
	$k, \text{m}^2 \cdot \text{s} / \text{N} \cdot \text{m}$	$\sigma_k, \times 10^{14}$	$k, \text{m}^2 \cdot \text{s} / \text{N} \cdot \text{m}$	$\sigma_k, \times 10^{14}$	
100%TMP	4.0	0.4	5.6	0.7	41
100%TMP ^{LF}	-	-	7.6	0.9	-
75%TMP+25%Kraft	6.45	0.4	11.7	1.2	82
50%TMP+50%Kraft	11.1	0.7	26.3	2.4	137
25%TMP+75%Kraft	12.6	0.5	38.6	3.1	205
100%kraft	26.2	0.6	73.2	5.1	280

TMP^{LF}: TMP pulp with low (20%) fines content

usually have a higher permeability than the corresponding handsheet.

Table 3.13 shows that before a wetting-drying cycle the permeability of unfilled kraft paper is about seven times that of a TMP sheet of the same basis weight. The high fines content of mechanical pulp would be the source of the

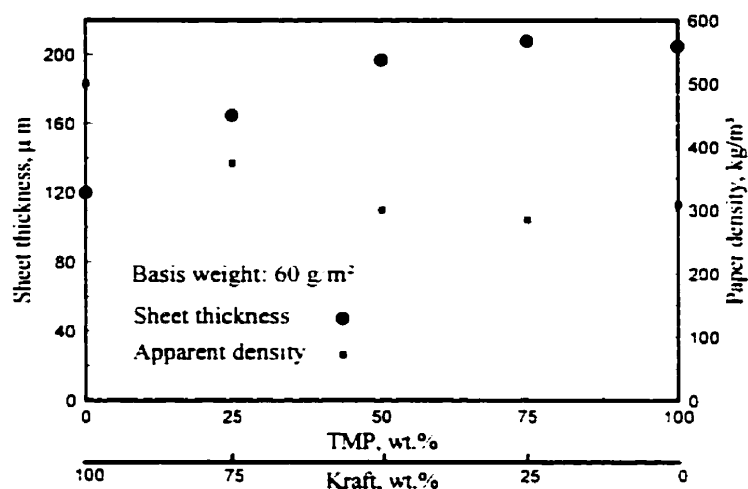


Fig. 3.21 Thickness and density of dry paper from TMP-kraft blends

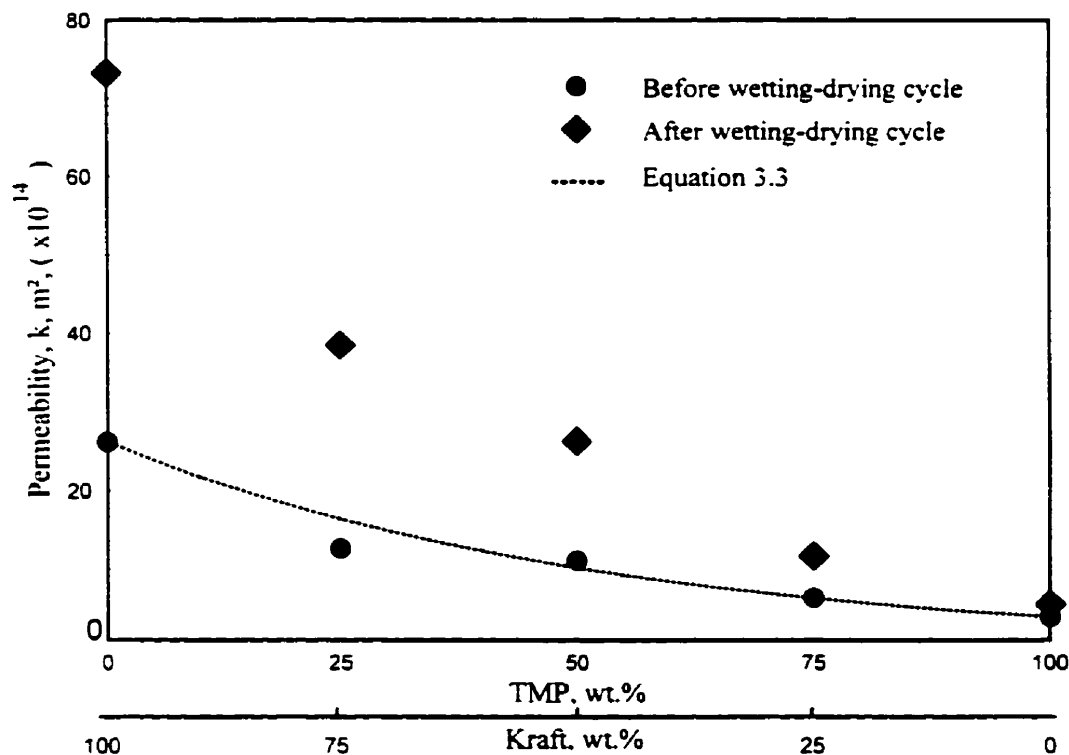


Fig. 3.22 Permeability of dry paper from TMP-kraft blends

lower permeability than for kraft paper with its negligible fines content. Table 3.13 shows that when the fines content of TMP was reduced by washing from 26.4% just to 20.0%, the permeability increased by more than one-third. Note however the kraft pulp used here was unbeaten, while it was shown in section 3.1 that the permeability of paper from

beaten kraft pulp can be lower by a factor of 100 relative to that from the unbeaten pulp. In view of the important commercial practice of adding some kraft pulp to predominantly mechanical pulp furnishes to increase paper strength, it should be noted from Figure 3.22 that the permeability of a 25% kraft-75% TMP paper is only increased by about 10% of the permeability difference between pure kraft and pure TMP paper. Thus the high nonlinearity in the permeability - furnish composition relationship is unfavorable when high permeability is advantageous, as in through drying.

Polat et al. [1993] showed that the increase in permeability of dry kraft handsheets after a wetting-drying cycle is due to the effect of wetting, not the drying. This behavior is important for through drying research. In laboratory drying work, initially dry paper is wetted, then dried under some test conditions whereas in a paper mill it is never - dried sheets that are dried. Thus the wetting of dry paper prior to laboratory through drying means that such sheets benefit from having a higher permeability than for the equivalent never - dried sheets in industrial practice. This effect is much less important for TMP than for kraft paper, the results in Table 3.13 showing that after a wetting-drying cycle the permeability of TMP increased by 40% while that for kraft paper was over 2.5 times higher.

3.9.3 Permeability of moist paper

Although the experimental plan given in section 3.8.1 included one replicate experiment for each test condition the inclusion of 3 levels of inlet air temperature, a variable for drying rate but not for momentum transfer, thereby provided not one but four replicate sets of pressure drop-flow rate-moisture content data for each furnish. For moist paper the values of ΔP were obtained at selected common values of moisture content X . Air viscosity was determined as a function of X at the average of inlet and outlet air humidity and temperature. The use of equation 2.1 showed that in the range of flow rates used the inertial effects were negligible, hence Darcy's law could be used to determine sheet permeability. As sheet thickness is not known as a function of moisture content, the practice of previous research was followed and a modified permeability, k/L , was calculated at each moisture content, as recorded in Table 3.14.

Table 3.14 Modified permeability of moist paper

Moisture content kg water/kg fibre	TMP $\text{m}^2 \times 10^{11}$	TMP ^{LF} Low Fines $\text{m}^2 \times 10^{11}$	75% TMP + 25% Kraft $\text{m}^2 \times 10^{11}$	50% TMP + 50% Kraft $\text{m}^2 \times 10^{11}$	25% TMP + 75% Kraft $\text{m}^2 \times 10^{11}$
0	27.4	37.0	56.3	133	234
0.1	27.3	36.8	56.2	133	233
0.2	26.8	36.4	56.0	133	232
0.3	26.0	35.5	55.6	133	232
0.4	25.3	34.5	55.0	132	231
0.5	24.2	33.2	53.9	130	229
0.6	22.9	31.7	52.6	128	225
0.7	21.5	29.9	50.8	125	220
0.8	20.0	27.9	48.7	121	214
0.9	18.3	25.8	46.3	116	205
1.0	16.6	23.4	43.6	110	194
1.1	14.6	20.8	40.5	103	179
1.2	12.6	18.1	37.0	95	162
1.3	10.5	15.3	33.3	86	141
1.4	8.14	12.3	29.3	76	117
1.5	5.71	9.04	25.0	75	92

TMP^{LF} : TMP with fines content reduced from 26.4% to 20.0%

The values of R^2 and σ_{KL} for every furnish were determined. For more than 95% of the results R^2 was higher than 0.95, the lowest of about 75 values of R^2 being 0.7. The maximum value of σ_{KL} , expressed as coefficient of variation, was 6.7%. The main source of experimental variability is the difference in structure between sheets of the same type of paper. As is well known this variability is higher for handsheets made from TMP or blended pulps with a high portion of TMP because of the sensitivity of permeability to the distribution of fines. Table 3.14 provides the first comprehensive set of data for the permeability of moist paper made from TMP or blends of TMP and kraft pulp.

Figures 3.23 and 3.24 show that with respect to the dependence of modified permeability on moisture content, this sensitivity is highest for the lowest permeability paper, that from the 26.4% fines TMP. this sensitivity being substantially reduced by the addition of as little as 25% kraft pulp. Thus as the moisture content drops during drying over the range from 1.6 down to 0.7 kg water/kg fibre, the modified permeability increases by a factor of 4-5 times for pure TMP paper, but only by 2-3 times for blends of TMP with from 25% to 75% kraft pulp. When the moisture content has dropped to about 0.7 kg/kg the modified permeability is approaching that of the dry sheet. For pure kraft paper Polat [1989] reported this permeability ratio, wet to dry, to be about 5-6. When through drying is started at about 1.5 kg water/kg fibre, permeability to through flow is low because much of the pore volume is occupied not by air but by free water. Most of the total increase in sheet permeability during drying has occurred when the moisture content has been reduced to just that of fibre saturation point, 0.72 and 0.87 kg/kg for TMP and kraft paper respectively. Table 3.9, with removal of all of the pore water. From the FSP

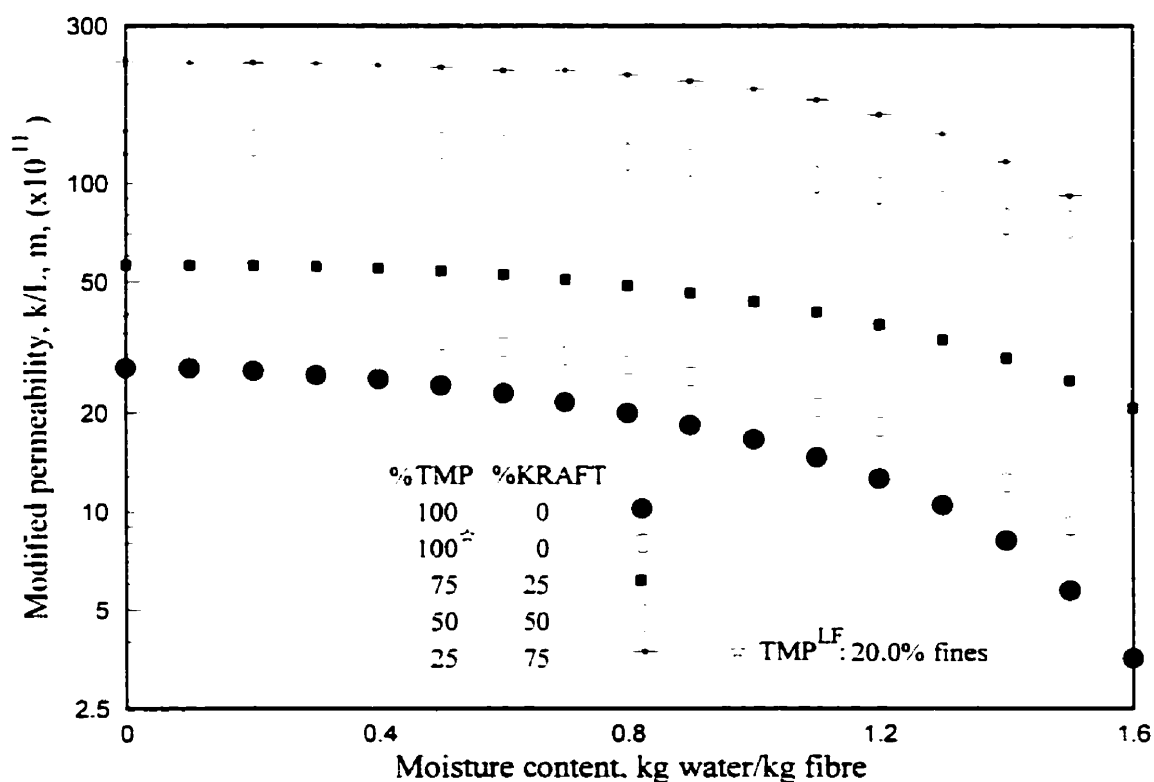


Fig. 3.23 Effect of moisture content on permeability of paper from TMP-kraft blends

moisture content to dryness the small increase in sheet permeability apparent on Figure 3.23 would occur from the shrinkage of fibres, which increases the sheet porosity, having a more significant effect than the opposing effect of sheet shrinkage which decreases porosity and permeability.

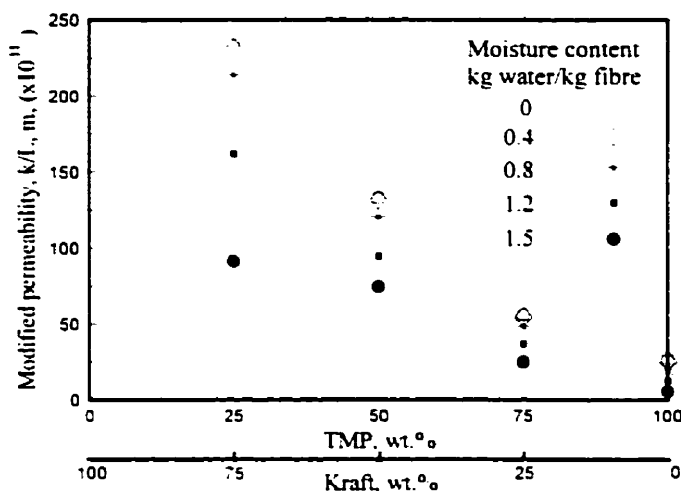


Fig. 3.24 Effect of furnish on permeability of paper from TMP-kraft blends

After a wetting-drying cycle the ratio of modified permeability, k/L, between these kraft and TMP

papers is seen from Figure 3.23 to be about 8:1, considerably smaller than the corresponding ratio of about 13:1 for permeability, k, between the kraft and TMP sheets after a wetting-drying cycle from Table 3.13. This difference between ratios of k/L reflects the fact that, as shown by Figure 3.21, these kraft sheets are about 40% thinner than the TMP paper. Thus for these kraft and TMP sheets the differences in permeability k are substantially greater than those in modified permeability.

Polat [1989] studied extensively the modified permeability of moist handsheets, but only from pure kraft pulp. Brundrett and Baines [1966] measured the effect of moisture content on modified permeability for laboratory handsheets of basis weight 47.5 to 85 g/m² made from newsprint and chemical pulp. However he used Darcy's law although their flow rate was sufficiently high that inertial effects were present, invalidating the use of Darcy's law and making their values of modified permeability too small. White and Marceau [1962] measured the permeability of wet paper in the range of 0.25 kg water/kg fibre down to dry sheets but their furnish contained no TMP and their moisture content range is too limited.

The measurements of Burgess et al. [1972 a,b] indicate k/L-X curves similar to those obtained here, but their k/L value for 50 g/m² newsprint is somewhat lower than that obtained here for 60 g/m² handsheets. Assuming a linear relationship between k/L and

basis weight, from the present results one may estimate k/L for 52 g/m² TMP paper to be 23.7×10^{-11} m, whereas they reported 17.7×10^{-11} m, about one-third lower. Through use of Darcy's law their neglect of the effect of the inertial term in the momentum transport equation leads to underestimating the true permeability. For the range of through flow rate used by Burgess et al., Polat [1989] estimated this error to be about 40%. With that correction, the results are in good agreement.

The k/L -X relation may be expressed in either a power law or exponential form, equations 2.7 and 2.8. Table 3.15

indicates that the two forms are equally satisfactory. For one of the blends a comparison of the data with the equation 2.7 representation is shown in Figure 3.25. This study for the first time provides a complete relationship of air permeability for moist TMP and blends of TMP and kraft paper.

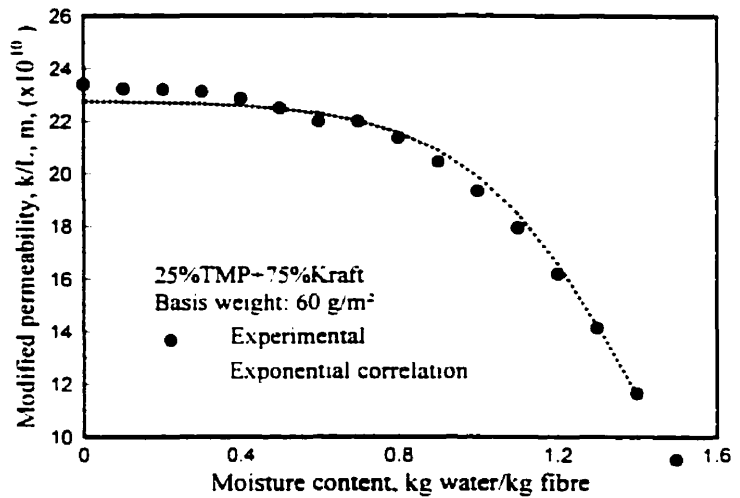


Fig. 3.25 Effect of moisture content on k/L of a sheet of blended furnish

Table 3.15 Parameters of modified permeability-moisture content relation

Paper Type	Exponential form				Power Law form			
	a $\times 10^9$	b $\times 10^6$	c	R^2	A' $\times 10^{10}$	B' $\times 10^9$	C'	R^2
TMP	4.15	8.95	4.92	0.99	0.436	0.733	7.33	0.99
TMP ^{LF}	2.97	11.16	4.44	0.99	0.312	0.611	6.56	0.99
75% TMP-25% Kraft	1.75	27.85	2.94	0.99	0.183	0.407	4.20	0.99
50% TMP-50% Kraft	0.72	17.46	2.45	0.99	0.075	0.160	3.49	0.99
25% TMP-75% Kraft	0.44	0.54	4.76	0.99	0.045	0.040	7.02	0.99

TMP^{LF} : TMP with fines content reduced from 26.4% to 20.0%

3.10 Specific Surface and Porosity of Paper From Blends

As reported by Hashemi et al. [1995], Table 3.16 documents the porosity of these papers as well as their specific surface calculated both by the Kozeny-Carman equation and, according to Scallan and Borch [1974], from the light scattering coefficient. Comparison of a_p and a_{pLS} data of Table 3.16 shows that for kraft paper the results by the two methods agree satisfactorily but that the Kozeny-Carman equation yields unrealistic results for the specific surface of paper from TMP and blends with kraft pulp containing as little as 25% TMP, i.e. 6.6% fines. Thus the Kozeny-Carman equation fails to predict the specific surface of paper if fines are a significant component of the sheet structure. With TMP and TMP-kraft blends therefore, only values calculated from scattering coefficient are considered reliable. For TMP containing sheets, results obtained with the Kozeny-Carman equation before and after a wetting-drying cycle do however provide a measure of the relative reduction of paper internal surface area (in order of 10–40%) due to the collapse of fibrils on to the fibres from wetting. Thus after a wetting-drying cycle, the collapse of fibrils is the mechanism for both the reduction of specific surface and, as seen on Figure 3.22, the increase in permeability. The specific surface of TMP paper is almost double that of kraft paper, this difference being also attributable to the fines content of mechanical pulp.

Table 3.16 Specific surface area of paper from TMP-kraft blends

Paper type	Before wetting-drying			After wetting-drying			
	$\epsilon_{\text{Caliper}}$	a_p $\text{m}^2/\text{m}^3 \cdot 10^6$	a_p m^2/g	$\epsilon_{\text{Caliper}}$	a_p $\text{m}^2/\text{m}^3 \cdot 10^6$	a_p m^2/g	a_{pLS} m^2/g
TMP	0.80	7.61	4.91	0.81	6.92	4.47	1.29
TMP ^{LF}	0.80	-	-	0.81	6.01	3.88	1.38
75%TMP-25%kraft	0.82	6.69	4.32	0.81	4.89	3.15	1.20
50%TMP-50%kraft	0.81	4.78	3.09	0.80	3.04	1.96	1.12
25%TMP-75%kraft	0.76	3.28	2.11	0.77	1.95	1.26	0.84
kraft	0.65	1.22	0.79	0.72	1.06	0.68	0.71

TMP^{LF}: TMP with fines content reduced from 26.4% to 20.0%

a_{pLS} : specific surface calculated from light scattering coefficient

3.11 Effects of Pulp Mixtures on Permeability, Specific Surface and Density

The structure dependent parameters involved in transport phenomena for the through air drying process are air permeability, specific surface and paper density. In practice, however, for paper made from blends of pulps there is much more concern about other aspects such as strength and surface properties. The numerous empirical treatments of the effect of composition on the properties of paper from pulp blends, Levlin and Paulapuro [1987], are based either on the principle of property additivity, Brecht [1963], on regression analysis, Ryti [1971], or on mechanistic models. Mohlin and Wennberg [1984], Mohlin [1987] and Lindholm [1981] provide reviews of this extensive literature. Additivity models consider properties of a sheet made from a pulp mixture to vary linearly with the weight percentage of the components, rarely applicable, as noted by Brecht [1963] and Mohlin and Wennberg [1984]. Regression analysis has been used in the choice of linear and non-linear relations for the properties of blends. Mechanistic models predict sheet properties from fibre properties and the parameters involved in papermaking.

As kraft pulp is added to TMP, the permeability of dry paper from the blends is seen from Figure 3.22 to increase relatively little until the furnish is more than 75% kraft pulp, and may be represented with R^2 of 0.98 by the equation:

$$k_m = e^{(w_T \ln k_T + w_K \ln k_K)} \quad (3.3)$$

where k_T , k_K and k_m are the permeabilities of paper from TMP, kraft and the blend, while w_T and w_K are the weight fraction of TMP and kraft in mixture. The only treatment of the nonlinear dependence of air permeability on blend composition is that given by equation 3.3. Brecht [1963] reported a graph which shows a similar dependency for the air permeability of a paper made from a mixture of spruce sulfite pulp (65°SR) and bleached beech sulfite pulp (22°SR), but without presenting any supporting data. Subsequent discussion will show that an equation which does not allow for the interaction between pulp types in the sheet structure is not adequate.

Figure 3.26 shows that for paper from mixtures of TMP and kraft pulps, specific surface area determined from scattering coefficient changes linearly with furnish

composition. The specific surface - light scattering coefficient relation is linear and a linear additive correlation was also found between the light scattering coefficient of paper made from these blends and from the pure pulps, as has been reported in the literature cited earlier.

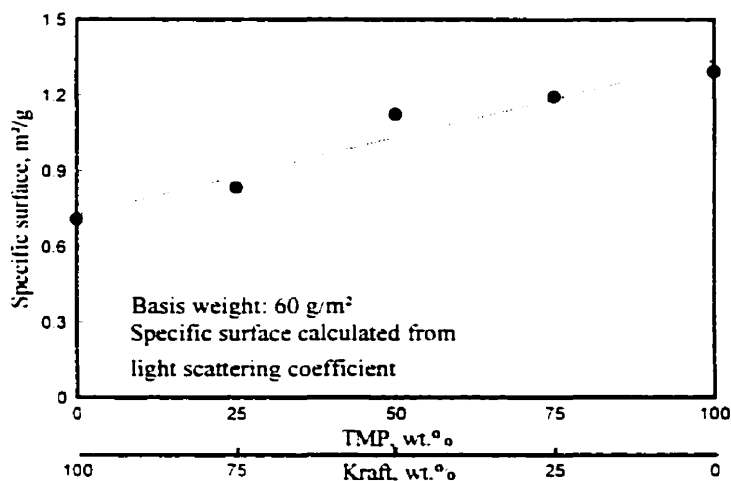


Fig. 3.26 Effect of furnish on specific surface

To explain nonlinearity in properties of paper made from mixtures of mechanical and chemical pulps, Mohlin and Wennberg [1984] proposed the speculative view that in the mixture there is little bonding between fibres of these two types of pulps. They suggested that the pulps form two independent networks, and proposed the high shrinkage and twisting tendency of chemical pulp on drying as a major cause for the low interaction between chemical and mechanical networks. Other theories include the view of Fernandez and Young [1994] that variable collapse of kraft pulp fibres in such blends is the major cause of this nonlinear relation for various paper properties.

For the density and porosity of paper made from TMP-kraft pulp blended furnishes, Figure 3.21 and Table 3.16 show that for a blend containing only 25wt.% of TMP, paper density and porosity are already dominated by the low bulk density given by the stiff fibres of the mechanical pulp. Viewed from the 100% TMP limit, Figure 3.21 and Table 3.16 show that stiff TMP fibres effectively control the density and porosity of the paper until the TMP content has been reduced to less than 50%. Retulainen [1991] also reported a similar deviation for blends of mechanical and chemical pulp. The form of the dependence of the permeability of blends of TMP and kraft pulp, Figure 3.22, derives from the same source as that seen for paper density on Figure 3.21. Thus when stiff TMP fibres plus fines are blended with flexible kraft pulp fibres without fines, it is the TMP furnish which exerts the dominant control on the sheet structure aspects controlling both sheet density and sheet permeability. Thus in both cases, as kraft pulp is added to TMP it

is the property of pure TMP paper which remains dominant until the furnish is more than half kraft. while only a small proportion of TMP added to kraft pulp gives a blended furnish paper of properties greatly changed from those of pure kraft paper. The stiff fibres and the high fines content of TMP exert a disproportionate influence on the density and permeability of paper from TMP-kraft pulp blends.

3.12 Characteristic Dimension for Flow Through Paper From Blends

The treatment for momentum transport through paper alternative to permeability is to characterize the fluid flow as for a packed bed with the nondimensional Reynolds number-friction factor model, described in chapter 2. Polat et al. [1989] initiated this approach, applying it to unfilled kraft paper, the most permeable sheet. To determine d_p for paper by the present method one needs two independent pieces of information for the mass flow rate-pressure drop relation in the region of significant inertial effects. However, as the flow rates used here to through dry the paper were limited to a low range in order to keep the maximum pressure drop to about 40 kPa, a consequence was that the inertial effects in the flow were too small to enable calculating d_p for moist paper by this method. As there is no problem for using higher air flow rates with dry paper, d_p was calculated in this way for dry sheets.

For this purpose two mass flow rates of air, 0.419 and 0.207 kg/m²s were used with equation 2.6. The selection of the lower flow rate as one-half of the upper value is because this choice provides the most accurate determination of d_p from just two through flow rates. The values of the characteristic dimension of the dry sheet as determined after a wetting-drying cycle are listed in Table 3.17 and plotted on Figure 3.27. The value of 4.6 μm obtained for 60 g/m² paper from the pure unfilled, unbeaten kraft pulp in this study is close to the 5.0 μm value of reported by Polat et al. [1989] for 50 g/m² paper made from this type of pulp. This excellent agreement is also consistent with their claim that, although d_p decreases as the basis weight of the paper increases over the range of 25-50 g/m² due to the change in pore size, this trend is very small above 50 g/m².

Table 3.17 Characteristic dimension for dry paper

Paper type	d_p , μm	σ_{dp} , μm
TMP	6.2	0.4
75%TMP+25%kraft	5.5	0.4
50%TMP+50%kraft	2.8	0.4
25%TMP+75%kraft	2.3	0.5
kraft	4.6	0.3

Table 3.17 and Figure 3.27 show the highly nonlinear relationship between the characteristic dimension d_p of a blend and the composition of the TMP-kraft blend. Because the completely different structure of TMP and kraft sheets, nonlinearity is expected. For

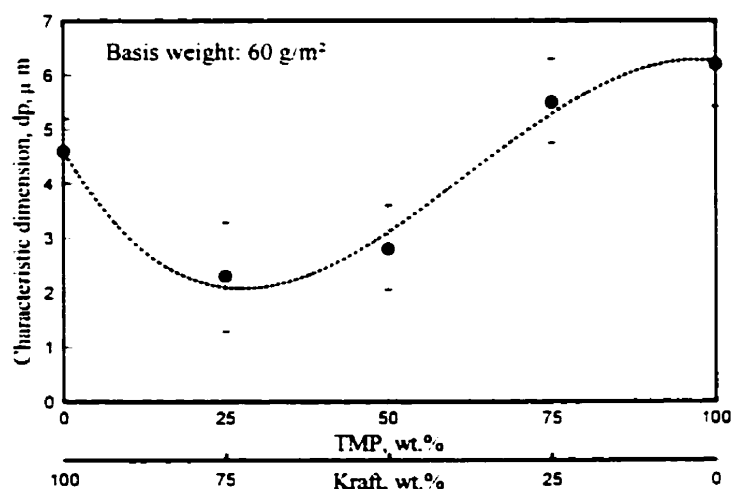


Fig. 3.27 Characteristic dimension for paper made from TMP-kraft blends

[1984]. Retulainen [1991] and Fernandez and Young [1994] among others have discussed nonlinearity for other sheet properties, as noted earlier. As the characteristic dimension for flow in the sheet, d_p , is influenced most sensitively by the interaction of the TMP and kraft pulps in forming the structure of a sheet from a blended pulp, it is not surprising to find that the dimension which characterizes flow through this structure shows a higher nonlinearity than any other paper property. The big drop in d_p going from pure kraft paper to a sheet with just 25% TMP would result from the addition of TMP fines to the pores of kraft paper with its low porosity, 0.65 compared to 0.8 porosity of TMP paper, Table 3.16. As noted in the previous section, the fact that TMP pulp consists of a mixture of stiff fibres and fines leads to the TMP content in blends exerting a dominant influence on the properties such as paper density (Figure 3.21), porosity (Table 3.16) and permeability

(Figure 3.22). This is seen again on Figure 3.27 for d_p . Because of its fines content a small amount of TMP in a predominantly (75%) kraft pulp blend reduces d_p sharply, while a predominantly (75%) TMP blend remains with d_p little changed from that for a pure TMP paper.

With reference to the momentum transport equation 2.6, $k=1/\alpha$ while $d_p=\beta/\alpha$, it is apparent that the characteristic dimension d_p is a basically different property than permeability k . As $d_p=\beta/\alpha$, the nonlinearity in d_p with the composition of TMP-kraft pulp blends reflects the nonlinearity with composition of both α and β , of which that for α appears (for $1/\alpha$) on Figure 3.22. As this study presents the first reported measurements of the effect of pulp mixtures on the characteristic dimension for flow through paper, no other comparisons for d_p can be made. A complex, highly nonlinear interaction of sheet structure properties on the characteristic dimension for flow through the sheet is evident.

As all of the above relates to dry paper, the d_p -X relations are now considered for moist paper. Because it was not possible in the present study to determine d_p for moist paper, this relation for kraft paper by Polat et al. [1989] provides the only basis available. Thus, their d_p -X relation for 50 g/m² unfilled kraft paper has been used as the basis for indicating the possible form of the d_p -X relation for pure TMP paper. With the experimental value, $d_p=6.2\mu\text{m}$, for dry TMP paper from Table 3.17 being not far from the $d_p=5.0\mu\text{m}$ value for pure kraft paper of Polat et al., a d_p -X curve for TMP paper was projected by applying this 6.2/5.0 ratio to their d_p -X curve for kraft paper. Figure 3.28 shows the two d_p -X curves, that determined experimentally for unfilled kraft paper, that projected for pure TMP paper. As Figure 3.23 indicates that the modified permeability k/L of TMP paper shows about twice the sensitivity to moisture content as kraft paper, one may expect that the ratio of d_p between wet and dry TMP paper may also be greater than that projected on Figure 3.28. In the absence of the experimental basis for the d_p -X curve for TMP paper, this analysis was not taken further. As the dependence of d_p on the composition of TMP-kraft blends is highly nonlinear even for dry paper, Figure 3.27, one can appreciate the complexity that is probable for d_p -X curves as a function of composition for the case of paper made from blended furnishes of TMP and kraft pulp.

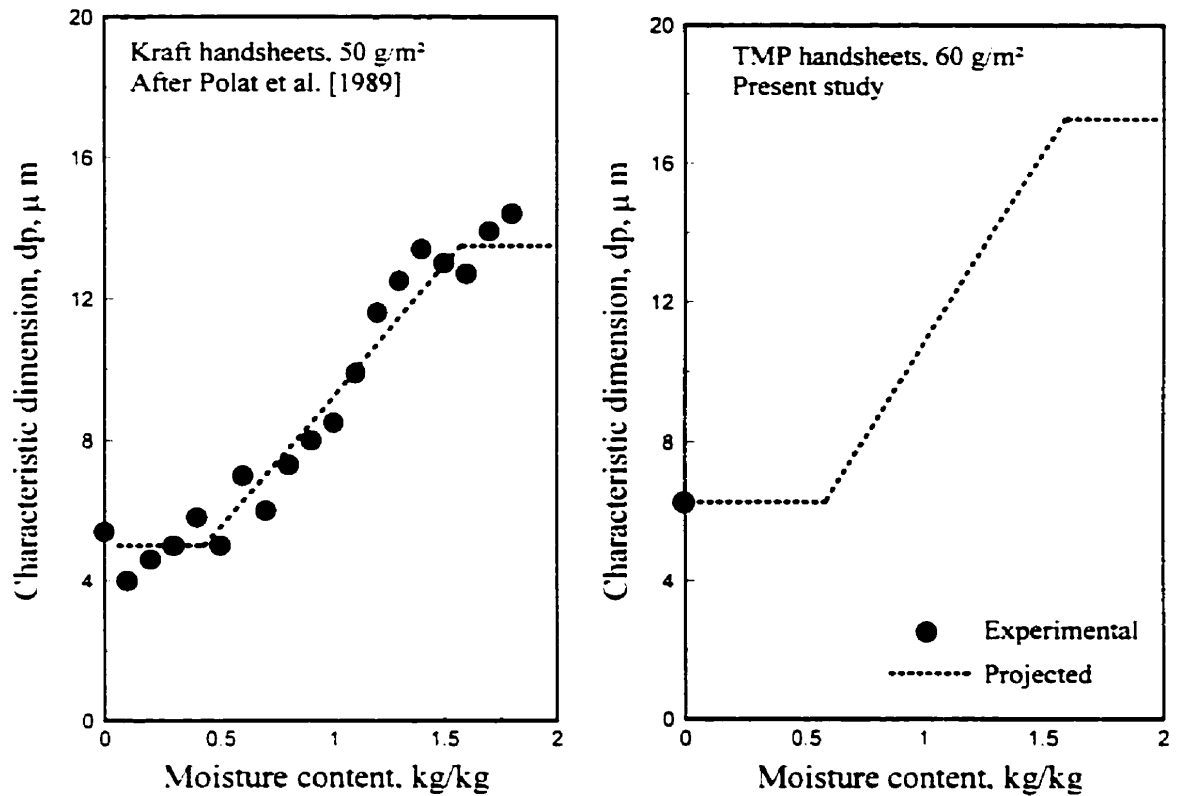


Fig. 3.28 Characteristic dimension for flow through moist paper

In summary, the momentum transport aspect of through air drying of paper made from mixtures of mechanical and chemical pulp is complicated first by the fact that for a blend of any particular composition the characteristic dimension d_p is influenced by paper density, porosity and pore size distribution, next by the nonlinear relations between such properties and the proportion of the various pulps in the blended furnish, and finally by the dependence of sheet structure on moisture content.

3.13 Reynolds Number - Friction Factor Relationship

The pressure drop - air flow rate relation that is central to the through drying process involves the relation between pressure drop and the sheet characteristic dimension d_p in terms of the friction factor. There are various definitions of friction factor, a nondimensional parameter related to the energy loss from flow through a porous media

and which is expressed as a function of Reynolds number, the nondimensional ratio of the inertial to viscous terms of the momentum transport equation. For paper the most fundamental basis of analyzing the flow rate-pressure drop relations for flow through this thin packed bed is via the Re - f relation, equations 2.13 and 2.14 in chapter 2. When the flow rate is sufficiently low that the inertial term becomes negligible, i.e. for the Darcy's law simplification, equation 2.14 reduces to equation 3.4

$$f = \frac{1}{Re} \quad (3.4)$$

Figure 3.29 shows the lines for equation 2.14 and 3.4 and the data for flow through dry TMP paper expressed in terms of Reynolds number and friction factor. For the range of flow rate used here for drying experiments the contribution of the inertial term is seen to be negligible. An advantage of the Re - f - d_p method for paper is that one may calculate ΔP at any G without the need to determine, as for a permeability calculation, whether the inertial effect is sufficiently small that Darcy's law may be used. In current industrial use

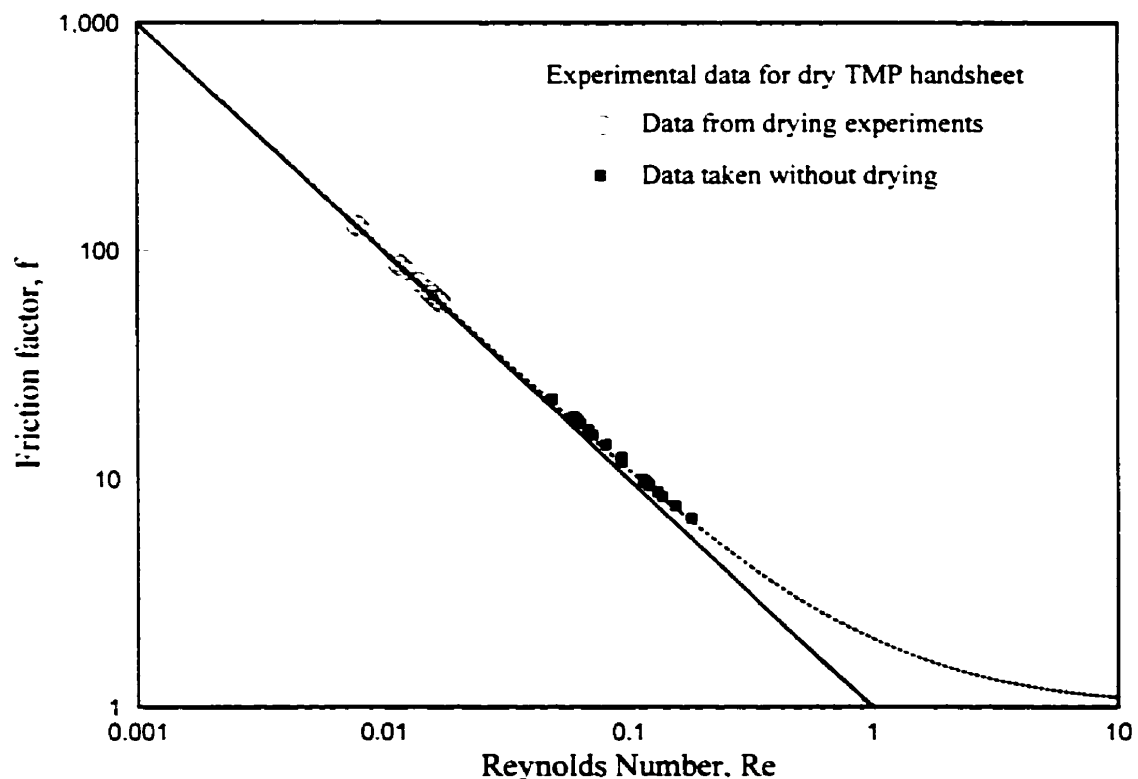


Fig. 3.29 Reynolds number - friction factor relation

of through air drying for tissue and toweling air flow rates may be up to $G=4 \text{ kg/m}^2\text{s}$, corresponding to about $Re=6$, so the flow is dominated by inertial effects but if through drying were extended to heavier papers such as those studied here, this might not be the case.

Unfortunately this analysis cannot be yet applied with the through drying measurements of the present study because of the inability to determine experimentally the d_p -X curve for the types of paper used. Even if that were possible, there is the additional problem that the large nonlinearity of d_p for dry paper with the composition of blends of TMP and kraft pulp would make these d_p -X curves an even more complex function of the composition of the blend. However, the theoretical structure of this analysis has been clarified by the present study, to be put into effect in the future when the momentum transport characteristics of moist paper made from pulp mixture have been sufficiently determined.

3.14 Summary and Conclusions

- (1) Of four papermaking parameters tested, only bleaching was found to have no effect on either the momentum transport or drying rate aspects. Beating of kraft pulp and increased wet pressing both lead to large reductions in permeability to air through flow. The resulting denser, lower porosity sheets that give these much lower permeabilities could lead to either higher or lower drying rates but the measured rates were not measurably affected, indicating that the advantage of smaller pores and the disadvantage of a thinner sheet effectively compensate.
- (2) Poorer sheet formation provides a slightly higher permeability but a significant increase in drying time, an important consideration as this effect translates directly as increased dryer size.

The sensitivity to papermaking parameters of the characteristics of through drying paper may be summarized as follows:

<u>Papermaking parameters</u>	<u>Sensitivity of the parameter for</u>	
	<u>Momentum transport</u>	<u>Drying rate</u>
Bleaching	very small	not measurable
Beating	very high	not measurable
Wet pressing	high	not measurable
Formation	small	high

- (3) The effect of furnish composition on through air drying characteristics was investigated with sheets made from TMP, unfilled kraft pulp and their blends. The only aspect of the drying rate characteristics that was found to be a function of the ratio of TMP and kraft pulp in the furnish was the extent of the increasing rate period, determined to be two to three times higher for paper made from TMP than for unfilled paper from the kraft pulp used, with blends giving a proportionate behavior. This large effect is believed related to various consequences of the high fines content of TMP, including the sensitivity of pore size distribution to fines content and to the low porosity and hence low pore water content of local regions of high fines content.
- (4) The permeability of TMP paper is only about 1/7 that of kraft paper, with again the fines content believed to be the determining factor. For blended furnishes the dominant influence is exerted by the stiff fibres and high fines content of TMP, as is the case also for paper density and porosity. Thus relative to the property for pure TMP paper, the sheet density, porosity and permeability change is disproportionately low as the fraction of kraft pulp is increased. For the same reason, relative to the property for pure kraft paper, the change in sheet permeability, porosity and density is disproportionately high in the region of small to moderate percentage of TMP in the blend.
- (5) The increase of paper permeability after a wetting-drying cycle is important in interpreting laboratory results with rewetted paper, relative to the industrial case of the through drying of never-dried sheets. This effect from a wetting-drying cycle is very furnish dependent, the permeability increase being 40% for TMP paper but 280% for the kraft paper used.

- (6) The complete relationship for the air permeability of moist paper from blends of mechanical and chemical pulp were determined for the first time. The permeability of TMP paper with its high fines content is much more sensitive to moisture content over the range typical of papermachine dryer section. Thus going from wet to dry, the modified permeability, k/L , increases by a factor of 4-5 times for pure TMP paper but only by 2-3 times for blends of TMP with from 25 to 75% kraft pulp. Most of this increase in permeability during drying has occurred when the moisture content has been reduced to the fibre saturation point value. Correlations were presented for the effect of moisture content on modified permeability of paper from these pulp blends.
- (7) For paper from TMP and its blends with kraft pulp containing as little as 25% TMP, it was shown that specific surface must be calculated from the light scattering coefficient, not from the Kozeny-Carman equation, as the latter method becomes invalid in the presence of any significant fines content. The fines content of TMP paper gives it about twice the specific surface of the kraft paper tested.
- (8) For paper from blended furnishes of TMP and kraft pulp the effect of furnish composition on the value of the characteristic dimension d_p required for Reynolds, Sherwood, Nusselt and Peclet numbers was determined for the first time. The finding of $d_p=4.6 \mu\text{m}$ for 60 g/m^2 kraft paper obtained here agrees well with the $d_p=5.0 \mu\text{m}$ value of Polat et al. for 50 g/m^2 paper from the same type of furnish. The value of d_p could not be determined here for moist paper because of pressure drop limitations with the semi-permeable grades of paper used. As a function of furnish composition, d_p was found to be a highly nonlinear function, passing through a minimum, with the biggest change being a drop from 4.6 to $2.3 \mu\text{m}$ from adding only 25% of TMP to a kraft pulp furnish while by contrast, adding 25% of kraft pulp to a TMP furnish changes d_p relatively little. Thus as is the case for paper density, porosity and permeability, the TMP content of blended furnishes exerts a disproportionate influence on d_p because of the control of the macrostructure by the stiff TMP fibres and of the microstructure by its high fines content.

CHAPTER 4:

Nonuniformity in Through Air Drying and Lateral Moisture Transport in Moist Paper

4.1 Introduction

Nonuniformity of moisture content in drying is doubly disadvantageous. From the process point of view, nonuniformity in moisture reduces drying efficiency and increases drying cost. From the perspective of product quality, nonuniformity of moisture during drying may decrease the quality of paper for printing through effects such as cockling. The present study therefore examines the general phenomenon of nonuniformity in through drying. The association of drying nonuniformity with nonuniformity of paper formation, with process conditions affecting drying nonuniformity, and implications for minimizing the cost of providing the flow of drying air through semipermeable grades of paper are explored.

4.2 Effect of Formation

In the first study of this effect, the simulation results of Gomes et al. [1992] indicated that the quality of sheet formation could be a significant factor for the effectiveness of through drying. Because it is not possible to obtain machine-formed paper of a particular furnish at controlled levels of quality of formation, the present exploration of the effect of formation on local nonuniformity of drying was carried out using handsheets where such control is possible. Variation in formation was obtained by changing the retention time of the pulp suspension prior to forming the sheet, as quality of formation decreases as the time for fibres to flocculate increases. This retention time was varied from 1 to 100s. The formation was characterized quantitatively as the Floc Formation Index, FFI, obtained with the image analysis technique of Bernié and Douglas [1996].

In a set of experiments with five replicate sheets for each of three retention times, kraft handsheets of basis weight 60 g/m² were dried with 62°C air at a through flow rate G of 0.21 kg/m²s. For pairs of sheets closely matched as to initial moisture content, Figures 4.1 and 4.2 show some degradation of the drying rate curve in the falling rate period as formation

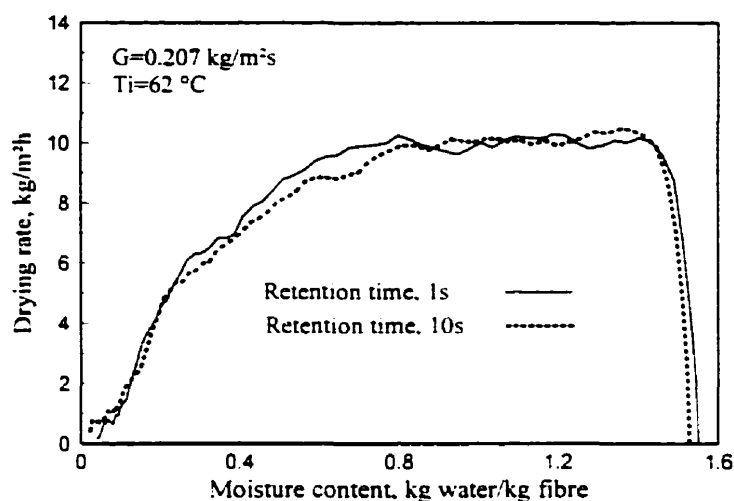


Fig. 4.1 Effect of small degradation in formation on drying rate curve

retention time is increased from 1 to 10s, substantial degradation for the retention time increased to 100s. Table 4.1 shows that as formation retention time is increased there is a corresponding degradation in both formation and drying rate. Here the decrease in quality of formation is indicated by the increase in FFI values, and the degradation in drying rate curves appears as the increase in critical moisture content X_c , expressed as the ratio X_c/X_0 . As the transition from constant rate to falling rate drying is gradual, the value of X_c must be determined by a standardized technique. For this purpose the method of Polat [1989] for determining drying rate parameters from R-X data was used.

The critical moisture content at the transition from constant to falling rate drying marks the point where the drying rate ceases to be purely heat transfer controlled. As moisture

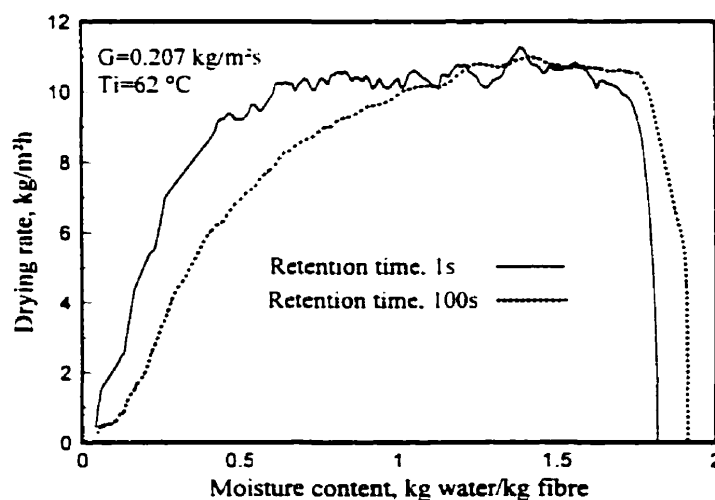


Fig. 4.2 Effect of large degradation in formation on drying rate curve

content decreases in a perfectly uniform sheet, factors involved in the onset of the falling rate period can include the decrease in vapour pressure of water, the increase in heat of desorption of water, the increase in distance over which moisture must diffuse and the decrease in value of the diffusivity of moisture in paper. Each of these effects acts to make the drying rate controlled by some factor in addition to heat transfer.

Table 4.1 Formation index and critical moisture content

Retention time, s	Floc formation index, FFI	X_c / X_o
1	8.8	0.42
10	9.8	0.45
100	16.5	0.49

That all paper is to some extent locally nonuniform in structure constitutes another factor controlling the R-X curve during the falling rate drying period, including the value of the critical moisture content at which the falling rate starts. Locally nonuniform sheet structure results in local nonuniformity in permeability, in through flow rate, in drying rate, and hence in local nonuniformity for the onset of the falling rate period. Thus some local regions of the sheet enter the falling rate period while the remainder of the sheet is still in the constant rate drying period. The poorer the quality of sheet formation, the greater would be these consequences of drying local nonuniformity. With drying mechanisms coupled to the local nonuniformity in sheet structure, for which the "floc formation index" (FFI) provides a particularly sensitive measure, the direct relation in Table 4.1 between these FFI values and the sheet average values of critical moisture content now demonstrates quantitatively this characteristic of through drying.

4.3 Drying Nonuniformity from Local Exhaust Air Temperature

As the R-X curves of Figures 4.1 and 4.2 and the critical moisture contents X_c of Table 4.1 are sheet average values, these provide only indirect evidence for the hypothesis of local nonuniformity effects. In order to obtain direct evidence of local nonuniformity,

measurements were made of the local air exhaust temperature directly below the sheet. Because of the local air exit temperature being independent of any local nonuniformity in drying during the constant rate period, this temperature can detect drying nonuniformity only after the element of sheet being monitored has entered the falling rate period. Until the critical moisture content is reached the air exit temperature is slightly or substantially less than the adiabatic saturation temperature, depending on conditions, but this exhaust temperature starts to rise as soon as that specific region enters the falling rate drying period. Hence monitoring local exit air temperature should test directly the validity of the drying nonuniformity hypothesis.

For this test, four thermocouples 0.5 mm diameter were positioned at exactly 15 mm beneath the sheet. Because the Reynolds number for 25°C air at $G = 0.2 \text{ kg/m}^2\text{s}$ in the 103 mm diameter duct is well within the laminar flow range, at about $Re = 1000$, there would be relatively little radial mixing in the flow over the short distance between the sheet and the monitoring thermocouples. Thus the local air temperatures measured were very close to the values exiting the sheet.

The results for a standard handsheet made with 1s retention time. Figure 4.3, show that during the constant drying rate period the local exit temperatures are constant within the accuracy of the measurement. Each of these temperatures is seen subsequently to enter the falling rate period at a different time, with the range of local exhaust

temperatures growing to an impressive 20°C. Thus these particular four local regions of the sheet are seen to enter the falling rate period at widely different values of the sheet average moisture content, from about 0.7 down to 0.25 kg water/kg fibre. These values determined by a local criterion for the switch from constant rate to falling rate drying are considerably

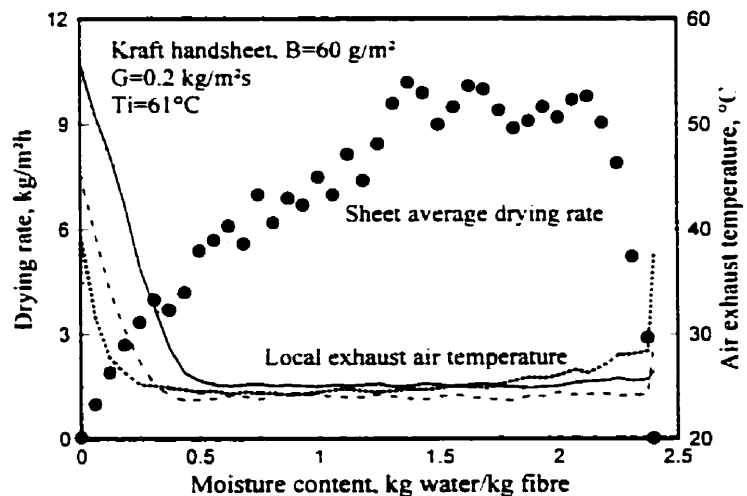


Fig. 4.3 Local exhaust air temperature

lower than the sheet average value of critical moisture content, about 1.5 kg/kg according to the R-X curve of Figure 4.3. However in order to have a statistically significant sample of local exhaust air temperatures it would clearly be necessary to monitor considerably more than four local sheet positions.

Differences in sheet structure such as nonuniformity in grammage and density, which lead to differences in local sheet permeability, establish the level of nonuniform through flow and nonuniform drying rate which exist at the moment through drying starts. As drying proceeds, this initial level is amplified by the coupling between through flow rate and through drying rate. This coupling results in an increase in local nonuniformity as drying proceeds. With local exhaust air temperature a sensitive indicator of local nonuniformity during the falling rate period, this increasing nonuniformity is manifested as the increasing spread between local exhaust air temperatures in Figure 4.3, once these are monitoring conditions which locally are in the falling rate period.

4.4 In-Plane Diffusivity of Moisture in Paper

Any nonuniformity in local moisture content of paper which develops during drying because of locally nonuniform drying rates provides a driving force for in-plane diffusion of moisture, which in turn acts to reduce this moisture nonuniformity. No data have appeared for the in-plane diffusivity of moisture during desorption from paper for the range of conditions existing during papermachine drying. An investigation was therefore undertaken to obtain such information relevant to the role of in-plane moisture diffusion in drying nonuniformity.

4.5 Literature Review of Moisture Transport

Investigations of the transport of water in paper can be divided in two major categories according to the direction of transport, in-plane or thickness dimension, as the microstructure of the sheet is quite different between these directions. In each of these cases

the transport can be again divided into two categories according to whether or not the system includes liquid water as a boundary condition establishing the gradient for moisture transport. The presence of liquid water as a boundary condition may affect the mechanism of transport and hence its rate. For the case of absorption Marmur [1992] summarized the effects of a boundary condition of liquid water as either a limited or unlimited source. Thus studies with liquid water as a boundary condition are reviewed first, termed "water transport", then those without the presence of liquid water, as "moisture transport".

4.5.1 Water transport in paper

Water transport into paper is of importance in the manufacture and use of paper, in operations such as coating, surface sizing, packaging and printing. As this literature is therefore extensive, it is only summarized here as background for the choice of an appropriate experimental method for determination of the in-plane moisture transport occurring during drying. A comprehensive review, including mechanisms of transport, is given by Hoyland and Field [1976-77, 1, 2, 3, 4, 5]. Subsequent treatments, again including the aspect of transport mechanisms, are provided by Eklund and Salminen [1986, 1987], Salminen [1988] and Sandas and Salminen [1987].

The two fundamental approaches for treating water movement in paper are Lucas - Washburn kinetics [1918 and 1921] and Fickian diffusion. The Lucas - Washburn model for liquid penetration into pores leads to a penetration distance proportional to the square root of time

$$l^2 = \frac{r\sigma \cos\theta}{2\mu} t \quad (4.1)$$

where l = depth of penetration in time t , r = pore radius, σ = surface tension, θ = contact angle and μ = viscosity. This model is used for systems with either a limited or unlimited source of water. The case for transport in a porous medium with a distribution of pore size has been treated for paper chromatography by Ruoff et al. [1959] and Denton [1965], for fine filter paper by Ruoff et al. [1960] and for a fine sand bed by Gardner and Mayhugh [1958]. For paper as the porous medium, Marmur [1992] treated the aspects of thickness and pore size distribution.

When water transport is characterized by the Fickian-diffusion approach the classic reference is the treatment by Crank [1975] of the theory and application of transport by diffusion for a wide range of materials. The diffusion model is commonly applied to systems where the effective transport mechanism is not the random molecular diffusion for which Fick's law was derived, in which case such diffusion coefficients should be called apparent or effective diffusivity. With a diffusivity coefficient independent of moisture content, the transport equation is

$$\frac{\partial X}{\partial t} = \Delta \cdot (D \nabla X) \quad (4.2)$$

where X is moisture content. With the diffusion coefficient D constant, Haishi and Mokuzai [1981] proposed a solution with the diffusion initially proportional to the square root of time.

Denton [1965] showed that in any homogenous porous material with transport described by the equation of continuity and in which Darcy's law is obeyed, liquids will be sorbed at a rate determined by the square root relationship, with no assumption needed as to the structure of the porous material and no particular model required for the capillary system. Marmur [1988 a, b] proposed further refinements in modeling the penetration into porous media, particularly relative to paper structure.

While the above studies deal exclusively with advancing modes, i.e. filling up pores, the process of removing water from a wet spot during drainage, which has been called "exsorption", was treated by Burgeni and Kapur [1967]. Because of sorption hysteresis, exsorption and absorption have different characteristics. When paper is absorbing moisture from

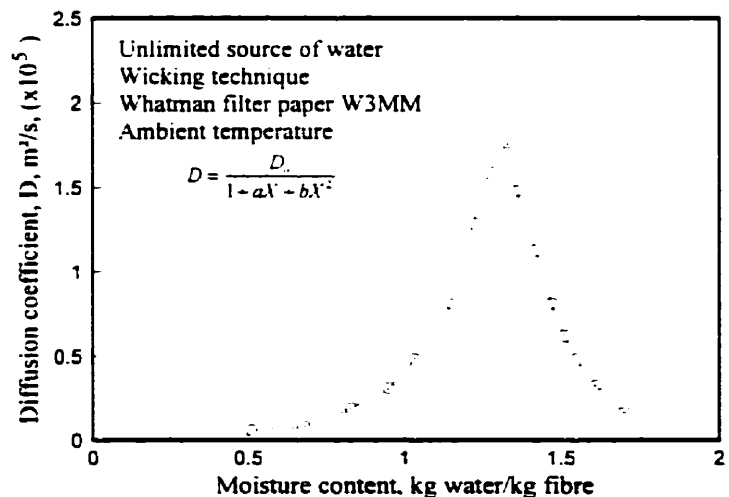


Fig. 4.4 In-plane diffusion coefficient for water into paper: Ruoff [1959]

liquid water. a concentration gradient has been observed between the source and the advancing liquid front. Wood and Strain [1954], Ackerman and Cassidy [1954], Gillespie [1959]. While some authors derived equations for capillary system based models, Ruoff et al. [1959] treated the water transport as occurring by diffusion. Figure 4.4 shows Ruoff's results for in-plane diffusion of water from an unlimited source into filter paper. Oliver [1982] with aqueous ink, and Hoyland [1978] for the penetration of various aqueous liquids into paper found diffusivity in the range 10^{-8} to 10^{-11} m²/s. Oliver [1994] derived a diffusion model for the penetration of microscopic ink droplets into paper, with moisture diffusivity as an exponential function of moisture content, i.e. $D = D_0 e^{2.5C}$, with D_0 in the range 10^{-8} to 10^{-11} m²/s. Li and Henriksson [1992] measured water diffusion into cellulose fibres derived from wood pulp. They divided the diffusion coefficient into two components, one independent of diffusion time, called the self-diffusion coefficient D_1 , and the other dependent on diffusion time, called the apparent diffusion coefficient D_2 . They attributed these two coefficients respectively to the bulk water between fibres, and to the water in pores within fibres. For kraft pulp pads and paper they reported values of D_1 and D_2 in the range 0.1 to 1×10^{-9} m²/s, with D_1 significantly larger than D_2 .

4.5.2 Moisture diffusion in paper

Techniques of determining moisture diffusivity in various materials are reviewed by Fulford [1969], Keey [1980], Van Brakel [1980], Fortes and Okos [1980], Chirife [1983] and Rosen [1987]. In a general review of drying models Wananen et al. [1993] provide a detailed discussion of the mechanisms of moisture diffusion in porous media. Moisture diffusivity estimation methods were examined critically by Zogzas et al. [1993]. For moisture diffusivity in paper there is dependence on both temperature and moisture content and, as paper is not an isotropic medium, the direction of diffusion is a fundamental parameter as well as the type of paper. With all reported experimental work for moisture diffusion in paper having been for transport in the thickness dimension of the sheet the extent of the difference between diffusivity in the thickness and the in-plane dimension has not been established.

Hartley and Richard [1974], based on experimental work by Dreshfield [1956], reported a value of a coefficient for diffusivity of moisture in paper as $\beta = 3.0 \times 10^{-8} \text{ gcm/s}^2$, independent of moisture content, from which one may obtain

$$D = \frac{\beta}{\mu} = \frac{3 \times 10^{-13}}{\mu} \quad (4.3)$$

where μ is water viscosity, Pa s . They claimed agreement between this value and the $D = 10^{-11} \text{ m}^2/\text{s}$ value reported by Crank [1956] for diffusion of water in wood fibre. The temperature dependence of the Hartley and Richard diffusivity is that of water viscosity.

Lee and Hinds [1982] determined the moisture diffusivity for paper by delaminating six-ply sheets of total basis weight 600 g/m^2 after various times of drying on a hot surface at 105°C . They did not report a dependency of diffusivity on temperature. For moisture content in the range from 2 down to 0.15 kg water/kg fibre they indicated the diffusivity increase with moisture content to follow a power law as

$$D = 1.40 \times 10^{-10} (X - 0.15)^{2.2} \quad (4.4)$$

while for $X < 0.15 \text{ kg/kg}$ they took $D = 0$.

Kobari [1985] included a dependence of moisture diffusivity on porosity, ϵ , as:

$$D = e^{(3.19 \frac{X}{\epsilon} - 27.04)} \quad (4.5)$$

This correlation provides no temperature dependence, and the exponential increase of D with moisture content X does not possess an acceptable asymptotic limit.

Lin [1990 and 1991] studied moisture absorption and desorption for cellulosic material. Based on data published in internal reports of the General Electric Co., not in the public domain, he reported the moisture diffusivity during desorption from kraft paper as

$$D(X, T) = D_0 e^{\frac{X}{2}} e^{\frac{E_a}{R} \left(\frac{1}{T_0} - \frac{1}{T} \right)} \quad (4.6)$$

for $0 < X < 0.15 \text{ kg water/kg fibre}$, where E_a is the activation energy, $16100 \text{ cal / g-mol}$; D_0 is the base diffusion coefficient, $2.616 \times 10^{-11} \text{ m}^2/\text{s}$; R the gas constant and T_0 and T are respectively the 298K base and the measurement temperature. Due to the paper thickness used, not recorded, drying times were 20 to 50 days.

With a steady-state absorption measurement technique Lescanne and Moyne [1992] reported the moisture diffusivity of 120 and 300 g/m^2 paper using 25°C air of various

relative humidity. They did not present a correlation, reporting only the moisture diffusivity at $X = 0.05, 0.11$ and 0.17 kg water/kg fibre for 120 g/m^2 paper as $0.92, 0.50, 0.45 \times 10^{-14} \text{ m}^2/\text{s}$, and for 300 g/m^2 paper as $1.00, 0.52$ and $0.36 \times 10^{-14} \text{ m}^2/\text{s}$ respectively. Their finding that diffusivity increases as X decreases is in contradiction with all other measurements.

4.5.3 Mechanisms of transport

Four mechanisms for the absorption of water in paper proposed by Nissan, as reported by Hoyland [1976], are:

- Diffusion transport of vapour in the pores
- Capillary transport of liquid in the pores
- Surface diffusion in the pores
- Water transport through the fibres

Salminen [1988] summarized studies of the mechanism of transport of water into paper from either an unlimited or limited source. Water absorption is complicated by the possibility of multiple mechanisms for transport.

In a general review of work on the drying of porous materials Bruin and Luyben [1980] list the mechanisms involved in the desorption of moisture as: Knudsen diffusion, Stefan diffusion, mutual diffusion, Poiseuille flow, condensation - evaporation, capillary flow, liquid diffusion and surface diffusion. In the most recent review of moisture diffusion during drying paper, Liang et al. [1990] added Knudsen diffusion. Included among the component mechanisms in most recent investigations are moisture diffusion through the fibres and, when the moisture content is above the fibre saturation point, capillary movement of water in the pores. Table 4.2 records all mass transfer mechanisms which have been proposed.

Table 4.2 Mass transfer mechanisms in drying porous material

<u>Vapor Phase</u>	<u>Liquid-Solid Phase</u>
Mutual diffusion	Diffusion
Knudson diffusion	Capillary flow
Slip flow	Surface diffusion
Hydrodynamic flow	Hydrodynamic flow
Stefan diffusion	
Poiseuille flow	
Evaporation - condensation	

There is no general agreement concerning which mechanisms operate or how they contribute.

4.5.4 Comparisons and evaluation

For water transport into paper from a limited or unlimited source, various experimental techniques have been used and the data have been interpreted by approaches as different as the Lucas - Washburn equation and diffusion - type models. For the case when liquid water is not present as a boundary condition, moisture transport is generally represented by the moisture diffusivity model, and all studies have been for diffusion in the thickness dimension of the sheet. For these studies Figure 4.5 shows the substantial disagreement concerning both the moisture content dependence of moisture diffusivity and the level of moisture diffusivity values, with the reported diffusivities differing by about one order of magnitude for wet paper and by up to a factor of 10^5 for nearly dry paper.

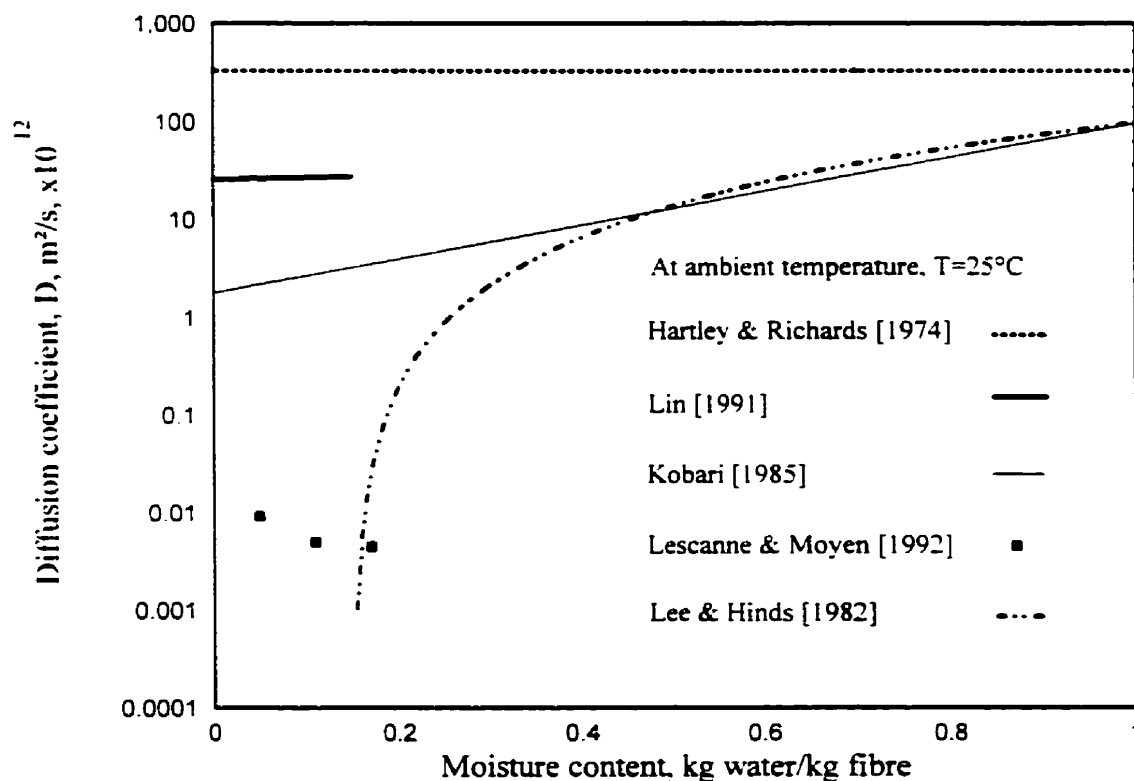


Fig. 4.5 Thickness-direction diffusion coefficient for moisture in paper

Sources of such diversity include the experimental techniques, the method of evaluation of diffusivity and the variety of types of paper and pulp used. With use of the Fick's law approach it is assumed that the ratio of the transport flux to the moisture gradient driving force, i.e. the diffusion coefficient, is independent of the driving force. However for transport in a medium with the wide pore size distribution of paper, this definition of diffusion coefficient may give different values between conditions of low and high gradient in moisture content. The great variability in results evident in Figure 4.5 suggests that the values of diffusivity used for a specific application should derive from an experimental technique with conditions of the same type as for the intended use. For relevance to local nonuniformity of drying paper the interest is in the in-plane rate of moisture transport from regions of higher to lower moisture content. The technique which results in the most complex combination of transport mechanisms is the sorption of liquid water into dry paper because the local values of the moisture content, kg water/kg fibre, range from ∞ down to zero, so that every mechanism listed in Table 4.2 may be effective over some part of the paper - water system. Results from such experiments may not be relevant to a system involving moisture transport just between regions of moist paper of different moisture content. Therefore the perspective of the present study is now narrowed to the case of transport by diffusion in paper between regions of different moisture content, with moisture diffusion in the in-plane direction because all reported work is for transport in the thickness dimension of paper.

4.6 Objectives for In-Plane Moisture Diffusion

To be relevant to the lateral transport of moisture during locally nonuniform drying, the in-plane moisture diffusivity must be determined using initial and boundary conditions that maintain the sheet within the range of moisture contents found in dryer sections of paper mills. The objective then was to develop a transient technique, including lateral scanning of the sheet for measurement of local moisture content, for determination of the in-plane moisture diffusivity.

4.7 Measurement Technique for In-Plane Moisture Transport

4.7.1 Overall design concept

A moist sheet, 105 mm diameter, was clamped in a sheet holder with a radial moisture gradient established from a moisture sink provided by sandwiching the test sheet between two 20 mm wide rings of super-absorber paper at the

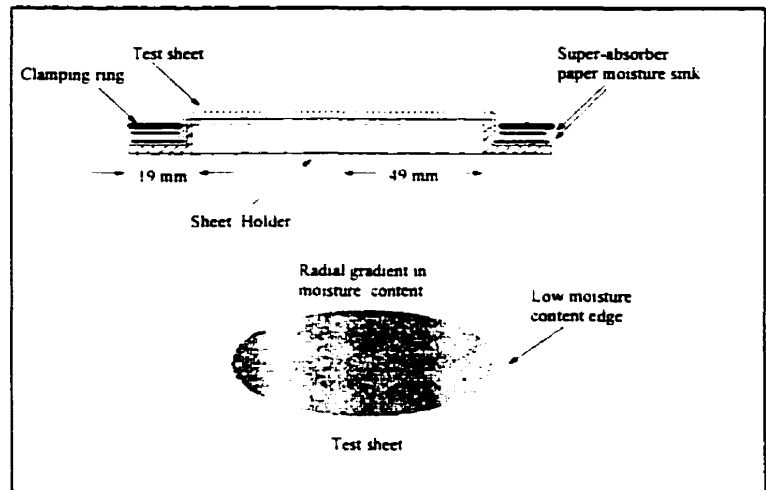


Fig. 4.6 Sheet holder for moisture diffusivity measurement

periphery. Figure 4.6. A

capability for determining the local moisture content of paper as a function of time and radial position was developed. The experimental rig, Figure 4.7, consisted of three parts: an

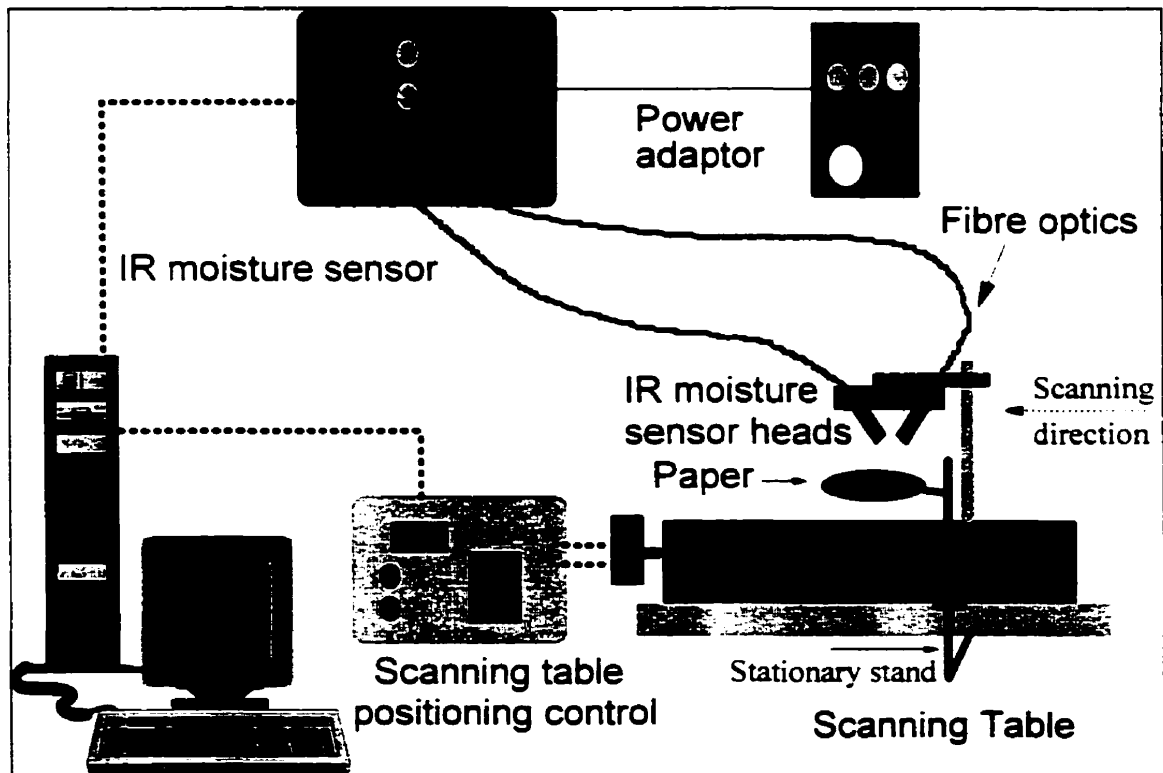


Fig. 4.7 Experimental setup

IR moisture sensor of high accuracy, a positioning table for scanning the sheet with this sensor, and a computer control integrating these elements. Integration of the IR moisture sensor with this positioning stage provides rapid scanning of the sheet at controlled positions, as is needed to determine profiles of local moisture content as a precise function of time and position. The most critical requirements concerned the accuracy of the moisture sensor and the precise, reproducible location of the measuring spots for the scanning.

4.7.2 IR Moisture Sensor

Use of the absorption of infrared light to measure moisture content, Pande [1974], reviewed by Spiro and Schlessinger [1989], has been widely used to determine paper moisture content, Chu and Ball [1977], Pugh [1980], Edgar and Hindle [1980]. IR moisture sensors work on the basis of selective absorption by water of specific wavelengths between red light and radio waves, i.e. from 1 to 10^4 microns. The wavelength at $1.94\text{ }\mu\text{m}$ is strongly absorbed by water, as well as that at 1.2, 1.45 and $2.95\text{ }\mu\text{m}$. Typically the sheet is exposed to narrow-band radiation of two wavelengths, i.e. a measurement wavelength, usually $1.94\text{ }\mu\text{m}$, and a reference wavelength relatively insensitive to absorption by water, usually 1.7 or $2.1\text{ }\mu\text{m}$. This exposure is in rapid alternation through the action of a chopper disc equipped with spike pass filters. The radiation is collected in a receiver, an integrating sphere, where it activates a lead sulphide detector. The amount of moisture is proportional to the difference in intensity of response between $1.94\text{ }\mu\text{m}$ and the reference wavelength.

The absorption and scattering of light is affected by several factors in addition to the moisture - the composition of the material other than its water content, its color and surface condition, the measurement distance and angle. The reference wavelength is therefore measured at the same time in order to minimize the effects of all factors other than moisture content. Moreover, all water in paper does not behave in absorption as free water. Thode [1964] treated the mechanism of IR absorption by bound and free water. The equilibrium between free and bound water depends on temperature and free water concentration. The result of this interplay is a nonlinearity in the relation between electronic properties and moisture content, so that a single electronic measurement is not directly proportional to moisture content. A further practical problem is that moisture measurement by this

technique is sensitive to variation in both scattering coefficient and paper basis weight, g/m². Therefore, in order to obtain data of the high precision required by the presence of first and second order derivatives of moisture content in the diffusion equations it is necessary to calibrate the IR sensor using each time the same type of paper used for the experiment.

The specific infrared moisture sensor was a custom - made version, developed to our specifications by the Fujitechnica company, Model IM. 3SCV. 1900. The production of this sensor required a long period of development between this laboratory and Fujitechnica in order to satisfy our stringent requirements for precision. While standard IR moisture measurement instruments use one reference wavelength, as noted above, this instrument obtains high precision in part by the use of two reference wavelengths, 1.8 and 1.21 μm , in addition to the base measurement at 1.94 μm . The signal from the lead sulfide detector, after processing and conversion to voltage, gives:

$$Voltage = K \log \frac{E_1 - E_3}{2E_2} \quad (4.7)$$

where E_1 and E_3 are from the reference wavelengths and E_2 from the measurement wavelength. Instead of the common lens of IR moisture sensors for a 10 mm diameter measurement area, the optics of this sensor permit measurement of an 8 mm diameter area and a 2.5 mm spot, the latter being used in the present study. Also, this sensor has fibre optics cables to the emitting and receiving heads for signal transmission, which gives the flexibility required here for the scanning of multiple positions. This instrument can be used in either transmission or reflectance mode, the latter being appropriate for the determination of in-plane diffusivity with negligible moisture gradients in the thickness dimension of the sheet.

4.7.3 Sensor calibration, positioning and data acquisition

To achieve maximum accuracy the IR sensor with the lens for 2.5 mm spot measurements was calibrated in reflectance mode against the moisture content of sheets of identical specifications to those used for the determination of diffusivity. The local nonuniformity of paper formation is such that there is significant variability in the local

grammage of 2.5 mm diameter spots which, for the precision required in the present work, affects the calibration. Therefore seven sheets of identical specifications were used, the final calibration curve being obtained by averaging those sets of results. The reference moisture content for calibration was obtained gravimetrically. As the orientation distance between the IR heads and the paper is critically important for high accuracy measurements, the same care and techniques were used during calibration as during diffusivity experiments, including use of a precision adjustment device for positioning the IR heads. The voltage outputs from the IR sensor and the electronic balance, of accuracy 0.001 g, were connected to the computer for precision monitoring. The same data acquisition board was used for calibration as during diffusivity measurement. For one paper type Figure 4.8 shows the mean calibration and the data for individual sheets which were furthest from the mean curve. The moisture sensor loses sensitivity as paper moisture content exceeds 1.4 kg water/kg fibre for this type of paper, but for the determination of in-plane moisture diffusivity relevant for drying this characteristic is not a problem. With a response time of less than 85 ms, Figure 4.9, there was no constraint on obtaining reliable data with rapid scanning.

The IR heads moved over the stationary paper, carried by a very accurate positioning stage. This computer controlled stage was programmable as to its transiting speed (10 to 100 mm/s), distance between each measurement station (2.5 to 100 mm), time spent at each station (0.1 to 1s) and number of scanning points. Although the positioning stage could scan either continuously or incrementally, the latter mode was used here to accommodate the 85 ms response time of the IR sensor. At maximum transiting speed, the maximum error in position of the sensor is 0.005 mm.

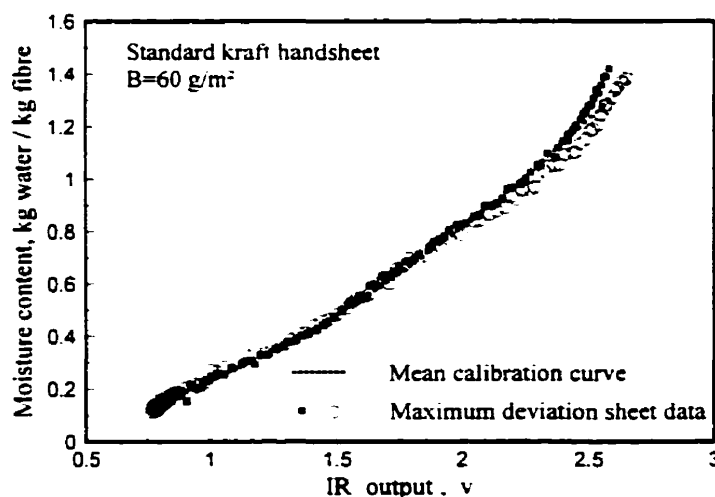


Fig. 4.8 IR moisture sensor calibration curve

The positioning stage and IR moisture sensor were integrated and computer controlled using a 486 PC computer with a data acquisition board. Obtaining a satisfactory data acquisition program was a major challenge due to the complexity of the process and the high accuracy required. Appendix A contains the summarized algorithm of the data acquisition program.

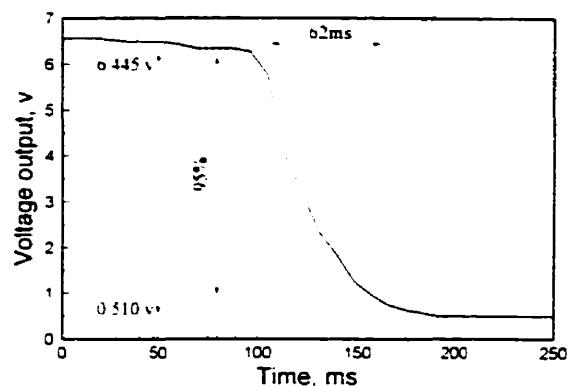


Fig. 4.9 Response time of IR sensor to a step change in moisture content

4.8 Experimental Procedure for Moisture Diffusion

The sheet was first equilibrated to the desired moisture content, then weighed very quickly on a honeycomb support, then clamped in the sheet holder between two annular rings of dry super - absorber paper. The IR sensor scanning started after a radial moisture profile had developed across the region to be scanned. The sheet radius was 52 mm, exclusive of the edge sandwiched between the absorbing paper.

Figure 4.10 illustrates a set of moisture content - time profiles for five radial positions, where position R1 is closest to the centre, position R5 closest to the moisture sink at the periphery. For the Figure 4.10 case, total radial distance between the R1 and R5 positions was 10 mm, giving the distance between centrelines of each of the 2.5 mm diameter measurement spots as 2.5 mm, the time stopped at each measurement station was 1.0s, the time of transit between successive measurement stations was 0.4s, so that each complete cycle of 5 stations was completed in 7s.

A complication is that moisture content is decreased not only by the moisture sink at the periphery but also by natural convection drying to the ambient air. This effect cannot be eliminated by control of the ambient air humidity because sheet moisture content varies with both time and position. However this effect may be corrected for by measuring the rate of natural convection drying of such sheets as a function of sheet moisture content, and

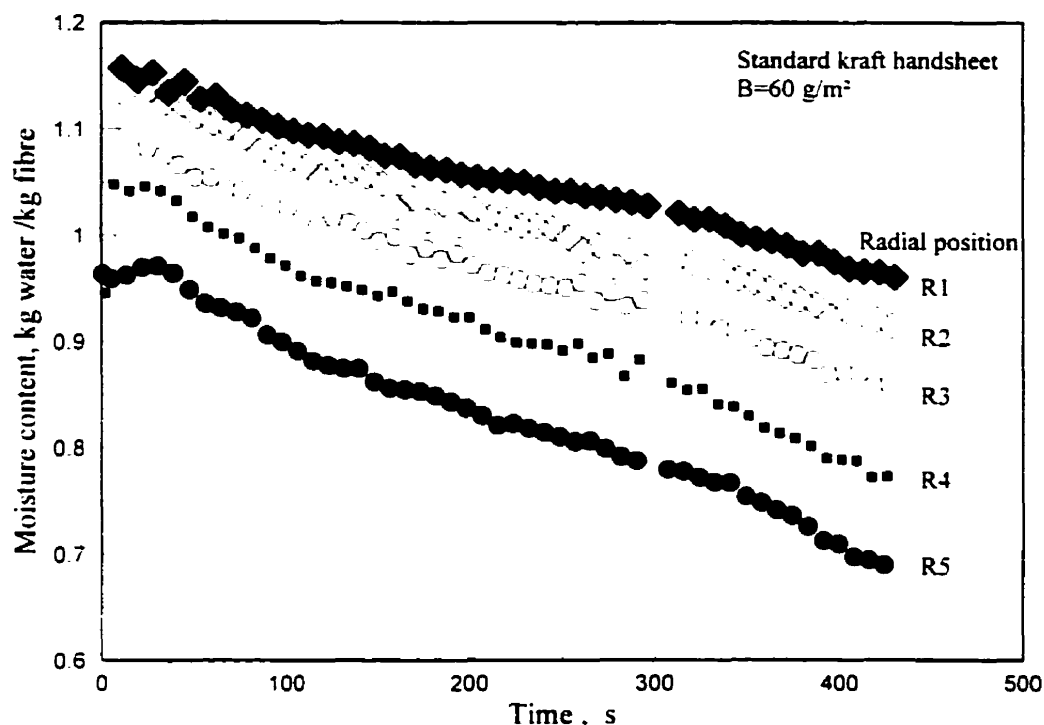


Fig. 4.10 Moisture profiles for five radial positions

adjusting the measured local values of moisture content for ambient drying. Figure 4.11 illustrates for one sample profile the data before and after this adjustment for ambient drying. To minimize the adjustment for ambient drying only the minimum of 3 cycles of scanning for the five radial positions were made, thereby reducing scanning time as much as possible. With each cycle of five measurements completed in 7s, this procedure reduced the total scanning time to about 20s, for which the adjustment for ambient drying was very small.

This data is sufficient for an accurate determination of moisture diffusion at one value of sheet moisture content by solution of Fick's second law. Solution of Fick's law for a variety of geometries and of initial and boundary conditions is exhaustively described by Crank [1976]. Strumillo and Kudra [1986] describe a related use of Fick's second law for the calculation of drying time while Pakowski and Mujumdar [1987] describe its use in calculating drying rate, in both cases with moisture content dependent diffusivities. The experiment described above was repeated for 135 sheets of paper, of initial moisture content ranging from 1.4 down to 0.2 kg water/kg fibre.

As a gravimetric check on accuracy, the weight of the sheet was determined before and after scanning, thereby establishing the precise amount of water loss due to absorption by the super - absorber paper and by ambient drying. Thus the correction for ambient drying during the scanning could be made consistent with this gravimetric check. As a test of

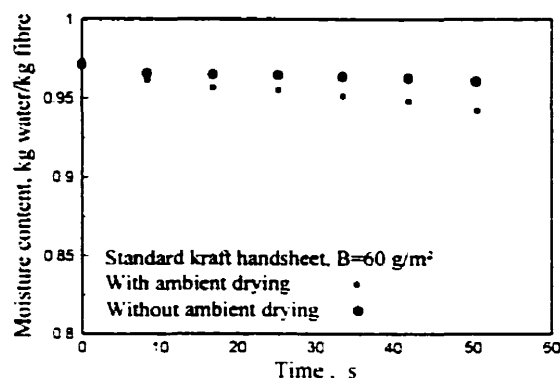


Fig. 4.11 Effect of natural convection drying

reproducibility of the measurement Figure 4.12 shows the results of three 24-point scans at identical positions of a sheet well equilibrated at a moisture content of about 0.6 kg/kg. Reproducibility of the measurement is very good, with the three repetitions superimposing. It is seen also that even for equilibrated moist paper, local moisture content is not completely uniform. This local nonuniformity in equilibrium moisture content reflects local nonuniformity in the grammage and structure of paper.

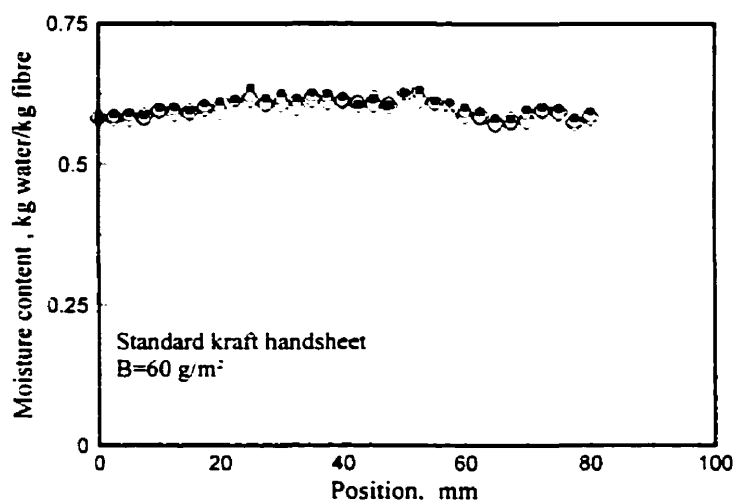


Fig. 4.12 Reproducibility of moisture measurement

4.9 Moisture Diffusivity Results

As written for the transient conditions used here, referred to as Fick's second law, the transport equation is:

$$\frac{\partial X}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(r D \frac{\partial X}{\partial r} \right) \quad (4.8)$$

where X is the dry basis moisture content, D moisture diffusivity, r radial in-plane distance and t is time. The integral data obtained here, $X = f(r, t)$, is numerically differentiated to

obtain values of $\partial X/\partial t$, $\partial X/\partial r$ and $\partial^2 X/\partial r^2$. Each of the 135 experiments covered only a small range of the total moisture content range between the limits of 1.4 kg/kg to nearly dry paper.

An iterative procedure was used to calculate diffusivity. The first estimate of diffusivity, determined as if independent of moisture content, was found to be a very sensitive function of moisture content, as was expected. The parameters of this dependency were estimated by fitting the first trial diffusivity values to a suitable function. This process was repeated iteratively, with the moisture dependent function thus obtained then being used to calculate new estimates of moisture diffusivity and a new moisture dependent function. This procedure was continued until there was no further significant change in diffusivity.

In-plane moisture diffusivity, D , at ambient temperature was thus determined as a function of sheet moisture content. Figure 4.13a indicates an impressive sensitivity of this

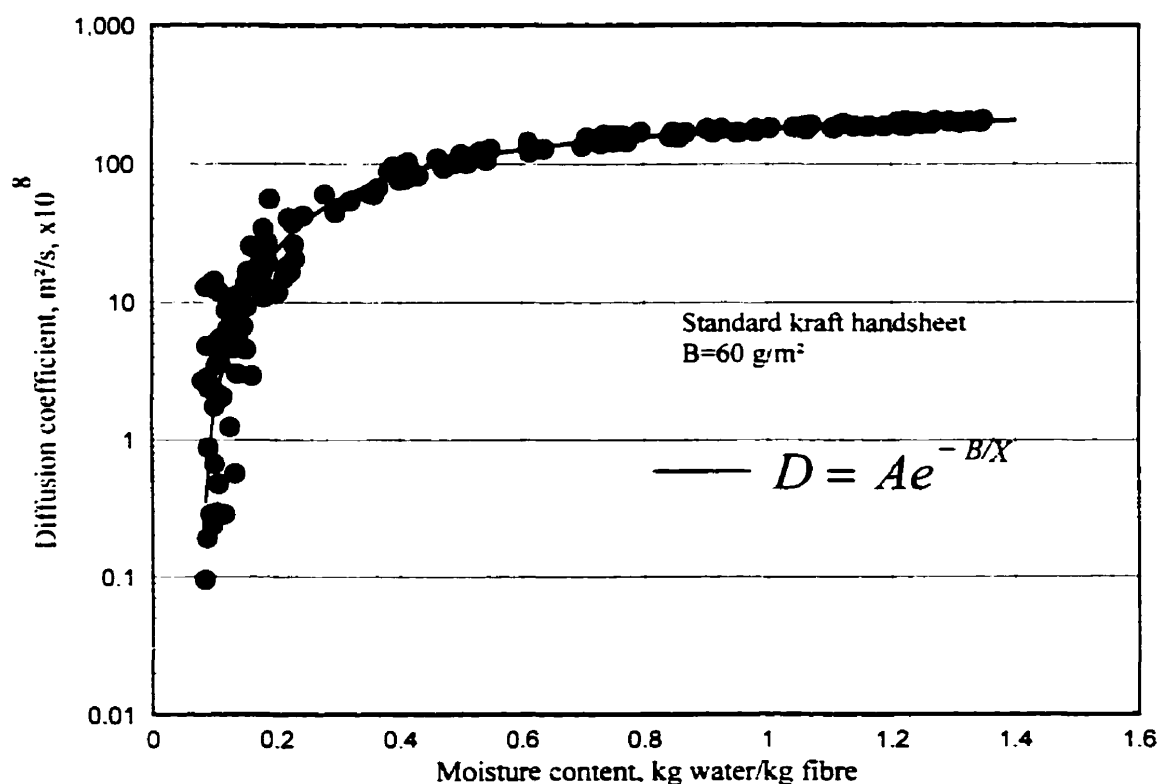


Fig. 4.13a Effect of moisture content on in-plane moisture diffusivity in paper

moisture diffusivity to moisture content, which can be represented in exponential form by:

$$D = Ae^{-\frac{B}{X}} \quad (4.9)$$

For standard kraft handsheets of 60 g/m² at ambient temperature the best fit values of these parameters are $A = 2.95 \times 10^{-6}$, $B = 0.505$.

With these parameters, equation 4.8 is valid down to a paper moisture content of 0.08 kg water/kg fibre, the lower limit of the present experimental measurements, which is adequate for application to the drying of paper. Although the sensitivity of diffusivity is much less at higher moisture contents, the dependence in that range is obscured by the logarithmic scale of Figure 4.13a. Thus presentation of the same results on the linear scale of Figure 4.13b shows that, over the moisture content range 1.4 down to 0.4 kg water/kg fibre, a range important in papermachine dryer sections, the diffusivity of moisture decreases substantially, by more than a factor of 2.5. The representation of Figure 4.13b demonstrates why Lee and Hinds [1982] presented a correlation in which they took $D=0$ for

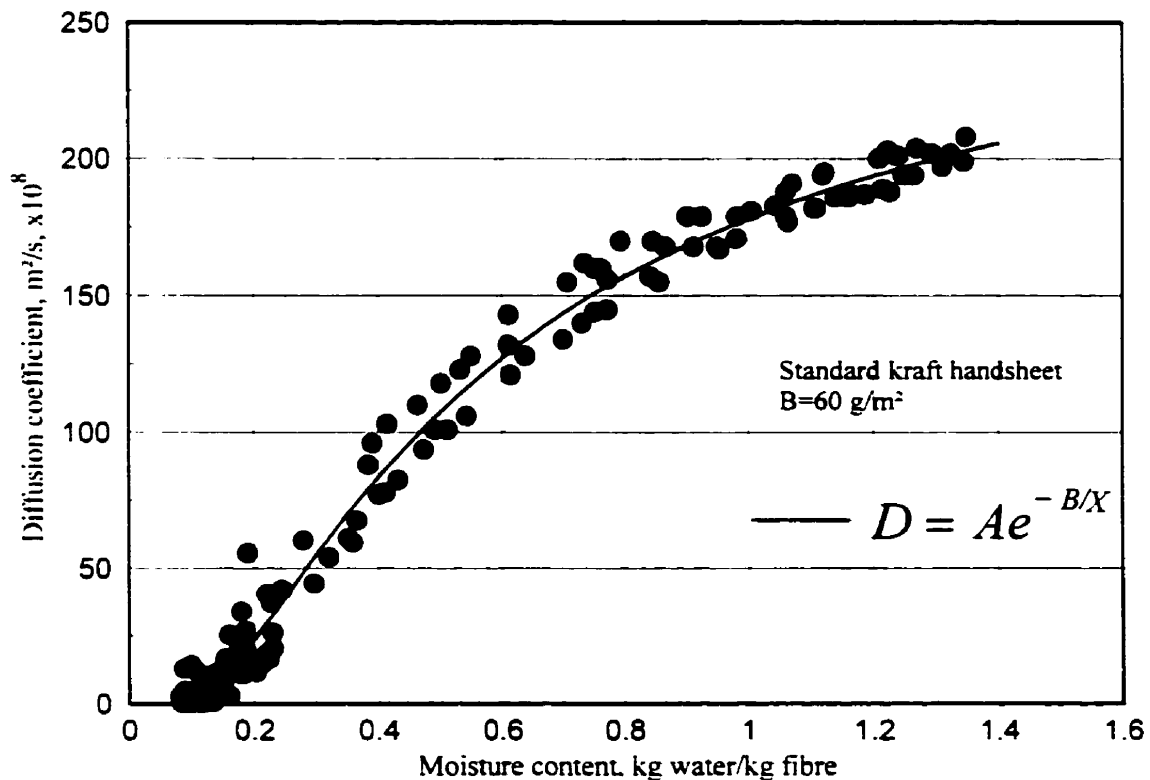


Fig. 4.13b Effect of moisture content on in-plane moisture diffusivity in paper

$X < 0.15$ kg/kg. Figure 4.13b also shows that there is no perceptible change in the D-X relationship around the fibre saturation point (FSP) moisture content, about 0.8 kg water/kg fibre for the paper used here, in spite of the fact that at moisture contents higher than the FSP free water is present in the pores of the sheet.

4.10 Analysis of Moisture Diffusivity Results

As noted at the outset, three basic considerations are whether moisture transport is in the in-plane or thickness dimension of paper, whether the concentration gradient involves the presence of liquid water as a boundary condition and whether it is moisture absorption or desorption that is occurring. For moisture diffusivity in the in-plane direction the present results, for desorption and without liquid water as a boundary condition, may be compared with those of Ruoff et al. on Figure 4.4, determined with sorption from an unlimited source of liquid water. At the low end of the range of moisture contents common to these studies the diffusivity determined here is higher than that of Figure 4.4 while in the upper range of moisture content the reverse is true, the cross-over occurring at about $X = 0.8$ kg water/kg fibre, $D = 0.16 \times 10^{-5} \text{ m}^2/\text{s}$.

An interpretation of these diffusivities being sufficiently close that a cross-over occurs is that, at least in the range of moisture contents common to these studies (from 1.35 down to 0.5 kg/kg), the difference in diffusivity between absorption and desorption and between the presence or absence of liquid water as a boundary condition may be within the limits of accuracy of the difficult measurement of moisture diffusivity. There is also the aspect of the nature of the paper used, where indications are that under the same conditions the diffusivity of moisture may be higher for our kraft handsheets than for the paper used by Ruoff et al.

Although the presence or absence of liquid water as a boundary condition may affect moisture diffusivity when there is water in the pores, for paper without water in the pores there is not agreement as to whether any difference in moisture diffusivity can be attributable to whether a boundary condition involved liquid water. With the fibre saturation point for the paper used here of about 0.8 kg water/kg fibre, this perspective suggests that the higher diffusivity by Ruoff et al. for the moisture content range above that value could

be related to their use of an unlimited source of water as a boundary condition. For the moisture content region without water in the pores it is considered that the diffusivity for moisture absorption is greater than for moisture desorption. However below 0.8 kg/kg moisture content the diffusivity of Ruoff et al. for moisture absorption is in fact less than that for moisture desorption obtained here. The difference between these two sets of measurements could be due to the difference between the types of paper used, as it was noted above that the kraft paper used here appears to give higher moisture diffusivity than that used by Ruoff et al.

Moving to the other basic difference, i.e. the direction of moisture transport in paper, comparison of the present results for in-plane diffusivity with the thickness dimension diffusivities of Figure 4.5 indicates that the direction of moisture transport in paper may be of very great importance, with in-plane diffusivity being much greater than that in the thickness direction. In this connection it is relevant to note that Lindsay [1994] reported the in-plane permeability of liquid water in paper can be 40 times higher than that in the thickness direction. Although the mechanisms for the flow of water in paper and the diffusion of moisture are fundamentally different, Lindsay's measurements none the less confirm that rates of transport in the in-plane direction can be very much higher than in the thickness dimension, due no doubt to the in-plane alignment of pulp fibers in a sheet of paper.

4.11 Summary for Moisture Diffusivity

As an overview, Figure 4.14 provides a comprehensive comparison of previous results, those of Figures 4.4 and 4.5, with the present results from Figures 4.13a and 4.13b. On the larger scale of Figure 4.14 the comparison of in-plane diffusivities with and without the presence of liquid water as a boundary condition, the two top curves, one for absorption, the other for desorption, suggests that these two differences may be of secondary consideration. By contrast, there is an impressive difference between the two sets of results for in-plane diffusivity relative to all other results, i.e. to the many determinations reported for thickness dimension diffusivity. The magnitude of this difference suggests that the non-isotropic nature of paper structure is of overriding importance.

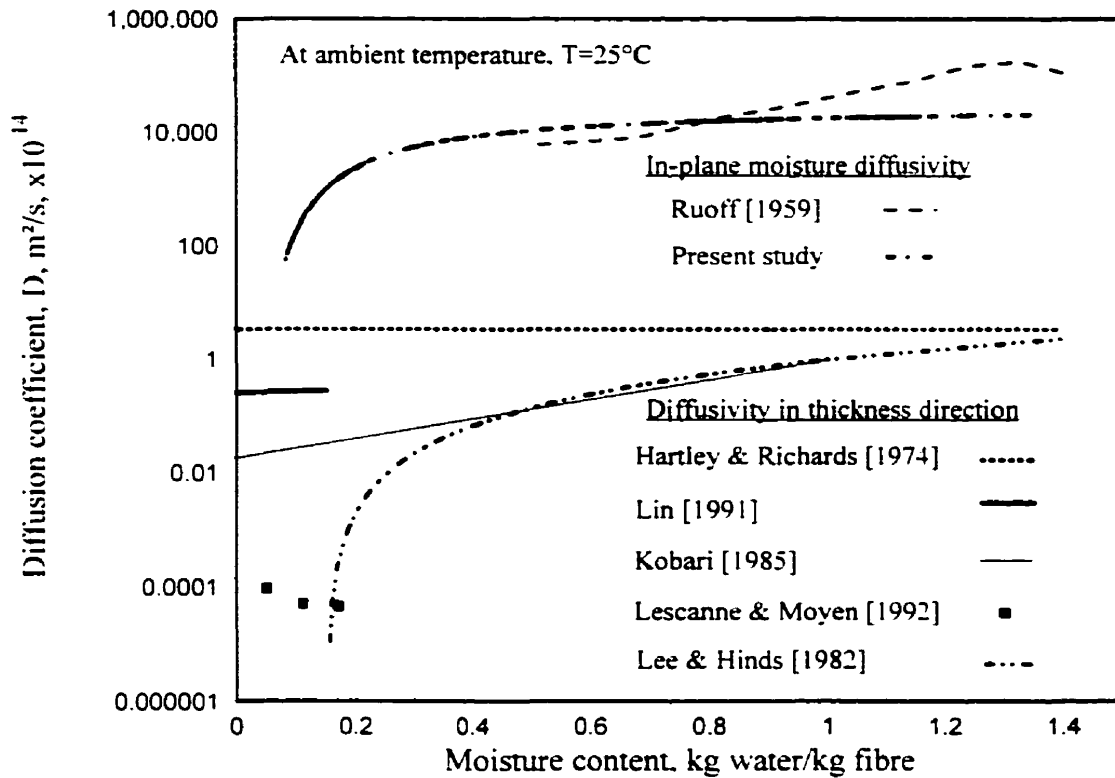


Fig. 4.14 In-plane and thickness-direction moisture diffusivity in paper

If the transport rates were controlled by any combination of the vapor transport mechanisms listed in Table 4.2, then there could not be such large differences between in-plane and thickness direction effective diffusivity because vapor phase transport is isotropic. Thus it appears that vapor phase transport is not important. Of the other mechanisms in Table 4.2, for the moisture content range below the fibre saturation point, which is where most of the sensitivity to moisture content occurs, there can be no liquid phase transport with no water in the pores. By this analysis, for the moisture content range below the fibre saturation point the only remaining mechanism of those listed in Table 4.2 would be moisture diffusion through moist fibres.

As paper porosity is in the range 65-80%, when transport through the vapor phase is not important it is evident that below the fibre saturation point the opportunities for moisture transport in the thickness direction are highly constrained. Fibres of the type in the kraft paper used in the present study are ribbons in the order of 3 mm long, 4-8 μm thick

and 40 μm wide, and in the sheet are located roughly parallel to the in-plane dimension. With moisture transport being by diffusion through fibres, then all thickness direction diffusion must pass through the small areas of contact between adjacent fibres which are at a different level in the thickness direction. The resulting path for diffusion in the thickness direction of paper must be extremely long and circuitous. Between each opportunity to diffuse by one fibre thickness, 4-8 μm , progress is interrupted because moisture must then diffuse a substantial distance laterally along the fibre to reach the next small area of contact to the adjacent fibre in the sheet thickness direction of diffusion. The tortuosity for air flow through paper is known to be high, but the effective "tortuosity" for moisture diffusion in the thickness direction could be orders of magnitude higher yet. By contrast, for diffusion in the in-plane direction there would be little tortuosity in the actual diffusion path. In this case moisture can travel in the order of millimeters along 3 mm long fibres between interruptions of path when passing to an adjacent parallel fibre. Thus for in-plane transport the actual diffusion path has little tortuosity with infrequent small shifts in path between parallel fibres while that for thickness direction transport is highly tortuous with large lateral displacements required about every 4-8 μm of diffusion in the thickness direction.

This micro-scale view of the mechanics of moisture diffusion is also consistent with the precipitous drop seen in Figure 4.14 for both the in-plane and thickness direction diffusivity as the moisture content drops below about 0.3 kg water/kg fibre. Sheet shrinkage is known to be very small below that level of moisture content because the web structure is then fixed by hydrogen bonding. However as the moisture content drops below about 0.3 kg/kg, individual fibres still continue to shrink. That fibre shrinkage is greater than sheet shrinkage in this range of moisture content is confirmed by the well documented increase in air permeability as paper is through dried from about 0.3 kg/kg to dryness. Fibre shrinkage without sheet shrinkage would decrease greatly the area of contact between fibres. Only a small shrinkage of a fibre could result in the loss of an area of contact between fibres, which is where all moisture must pass. This then could be the mechanism whereby the moisture diffusivity both in the in-plane and thickness direction drops by about a factor of 100 for a decrease in moisture content from about 0.3 to 0.1 kg water/kg fibre.

Moreover, with the much greater importance of these areas of fibre-to-fibre contact for moisture diffusion in the thickness direction than for in-plane diffusion, it should be expected that as the moisture content decreases, the reduction of diffusivity in the thickness direction would be substantially greater than for in-plane transport. Using the most complete and credible results, those of Lee and Hinds, Figure 4.14 shows that for moisture contents above about 0.6 kg water/kg fibre, in-plane diffusivity as measured here is higher than that in the thickness direction by about 10^4 , while at a moisture content of 0.2 kg/kg this ratio of in-plane to thickness direction diffusivity has increased to about 10^6 . This extra factor of about 10^2 in the difference between these diffusivities is consistent with the greater sensitivity of thickness direction transport to the loss of the limited amount of fibre-to-fibre contact area for moisture transport.

Aside from the great importance of direction of moisture transport in paper because of the non-isotropic sheet structure, Figure 4.14 also records the enormous variability between reported measurements, thus highlighting the great difficulty in determination of moisture diffusivity in moist paper.

4.12 Equalization of In-Plane Moisture Nonuniformity

To examine whether the time scale of the equalization by in-plane diffusion is sufficiently short to help reduce moisture content nonuniformity, this effect was investigated with experiments involving the interruption of through drying with a controlled time of equalization of the in-plane moisture profile, then completion of drying. As drying was interrupted at a moisture content near that of the fibre saturation point, the vapor pressure of water for such sheets would be near that of liquid water. The temperature of the drying air was selected at 61°C, for which the adiabatic saturation temperature is 21°C, which would be the paper temperature at the time of interruption. For the moisture equalization test the incompletely dried paper from the interrupted drying was placed immediately in a desiccator where the air was saturated with water vapor at room temperature. In this way there would be negligible transfer of moisture to or from the sheet during the short interruption of drying.

Figures 4.15 and 4.16 show drying rate curves with TMP paper through dried with such interruptions of 120 and 270s duration. Inspection of these drying rate curves, as well as comparison of the total drying time with and without the drying interruption, showed that there was no measurable effect of the interruption. Thus in-plane

diffusion of moisture is slow enough that, even after 270s for moisture equilibration, the improvement in sheet local moisture profile is not sufficient to improve the drying behavior measurably. The message is therefore clear that the local moisture nonuniformity developed while a sheet is through dried from 1.5 - 1.6 kg water/kg fibre to about 0.6 - 0.7 kg/kg is not appreciably decreased by allowing even up to 5 minutes for equalization of the in-plane moisture profile.

4.13 Effect of Initial Moisture Content: Constant through flow rate

Local nonuniformity in drying must become progressively worse as drying proceeds, as is demonstrated in Figure 4.3 by the growth of the nonuniformity in local air exhaust temperatures. It follows therefore that a lower value of initial moisture content, X_0 , which allows less time for local nonuniformity to develop.

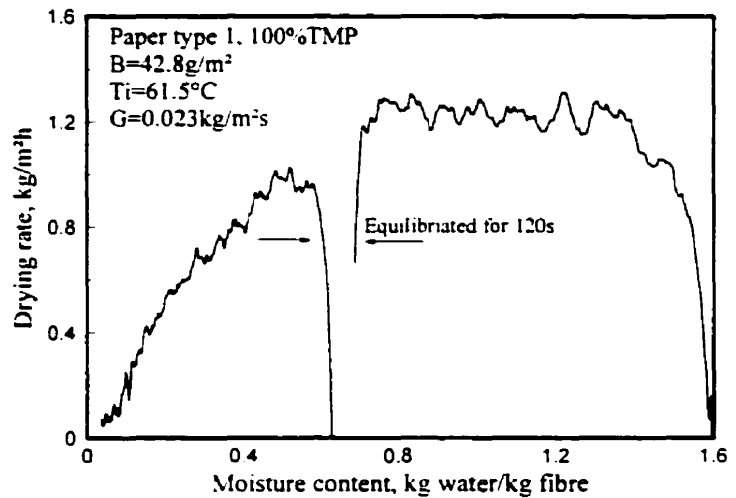


Fig. 4.15 Effect of moisture content equalization for 120 s

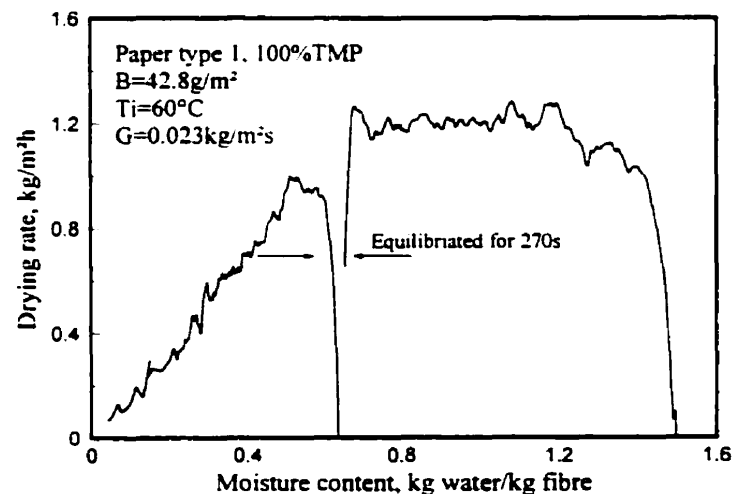


Fig. 4.16 Effect of moisture content equalization for 270 s

should result in less nonuniformity and hence in a lower sheet average value of X_c . This inference was tested by a series of experiments with papermachine sheets in which only X_0 was varied. The drying rate-pressure drop-moisture content relationships for two types of machine-formed paper. Figures 4.17 and 4.18, show that reducing the initial moisture content sharply reduces the critical moisture content. As a less important but not insignificant effect it is seen that, when starting the drying from 0.8 kg water/kg fibre instead of at moisture contents above 1.2 kg/kg, even the value of the constant drying rate R_c is higher, by about 15%. As the falling rate drying period has the predominant influence on drying time and hence on dryer size, the lower X_c is doubly advantageous because this effect reduces the amount of moisture to be removed in the falling rate period while necessarily also increasing the drying rate over this moisture content range.

Yet another benefit of decreased initial moisture content derives from the DP-X curves of Figures 4.17 and 4.18. The pressure drop to provide the through flow is a key economic factor restricting the use of through drying because of its effect on the capital and

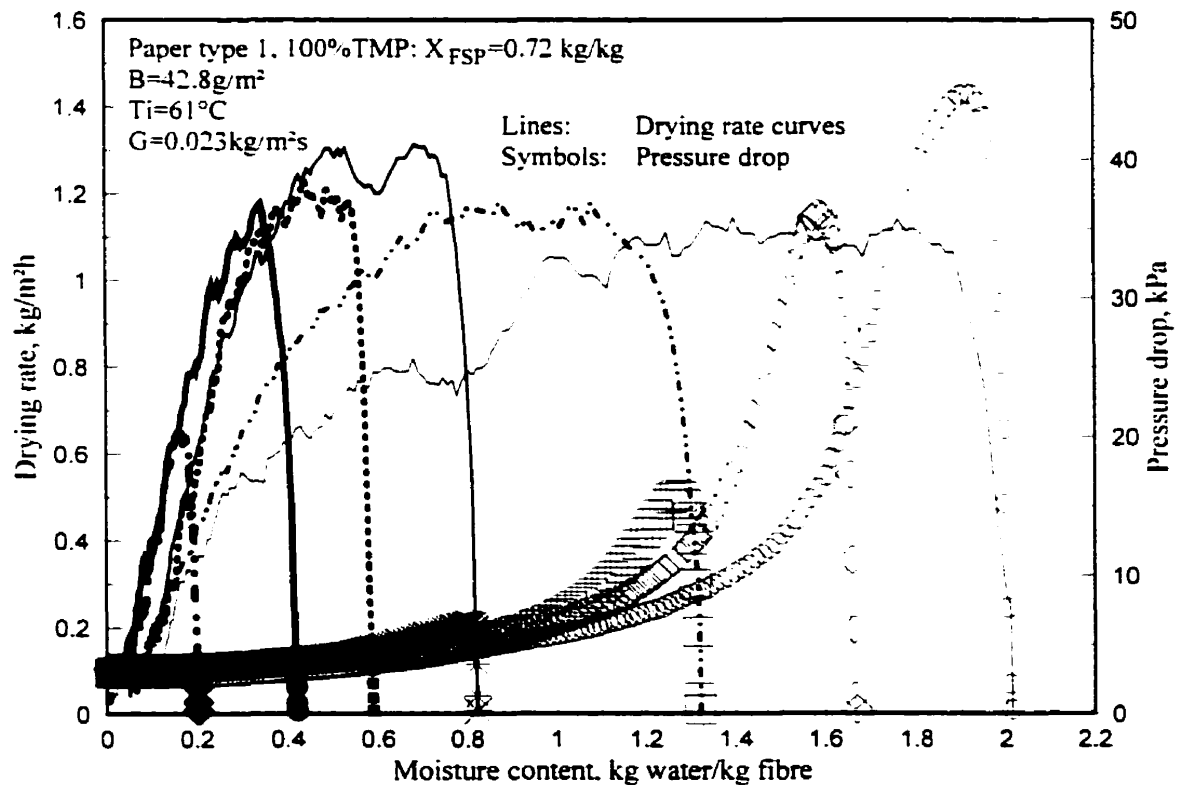


Fig. 4.17 Effect of initial moisture content at constant through flow rate: TMP paper

operating cost of the air fan. These results show that for the same through flow rate, $0.023 \text{ kg/m}^2\text{s}$, the pressure drop through the wet sheet decreases by about a factor of 10 with decreasing the initial sheet moisture content. Thus by through drying paper from a lower initial moisture content, not only the drying rate curves improve substantially, yielding a much shorter drying time and smaller dryer, but also one obtains a much higher sheet permeability. This higher sheet permeability enables either a reduction in through flow air fan cost or, for the same fan cost, operation at a much higher through flow rate and hence reducing further yet the drying time and dryer size.

For the drying rate curves for machine-formed TMP of Figure 4.17, the key parameters X_c and X_i , determined as noted in section 4.2, are presented on Figure 4.19 as a function of the initial moisture content X_0 . Thus the decrease in X_c as X_0 is reduced, as noted first in connection with Figure 4.19, is seen to be linear until X_0 has been decreased to the fibre saturation point X_{FSP} . The best fit line for X_c for just the three results in this region

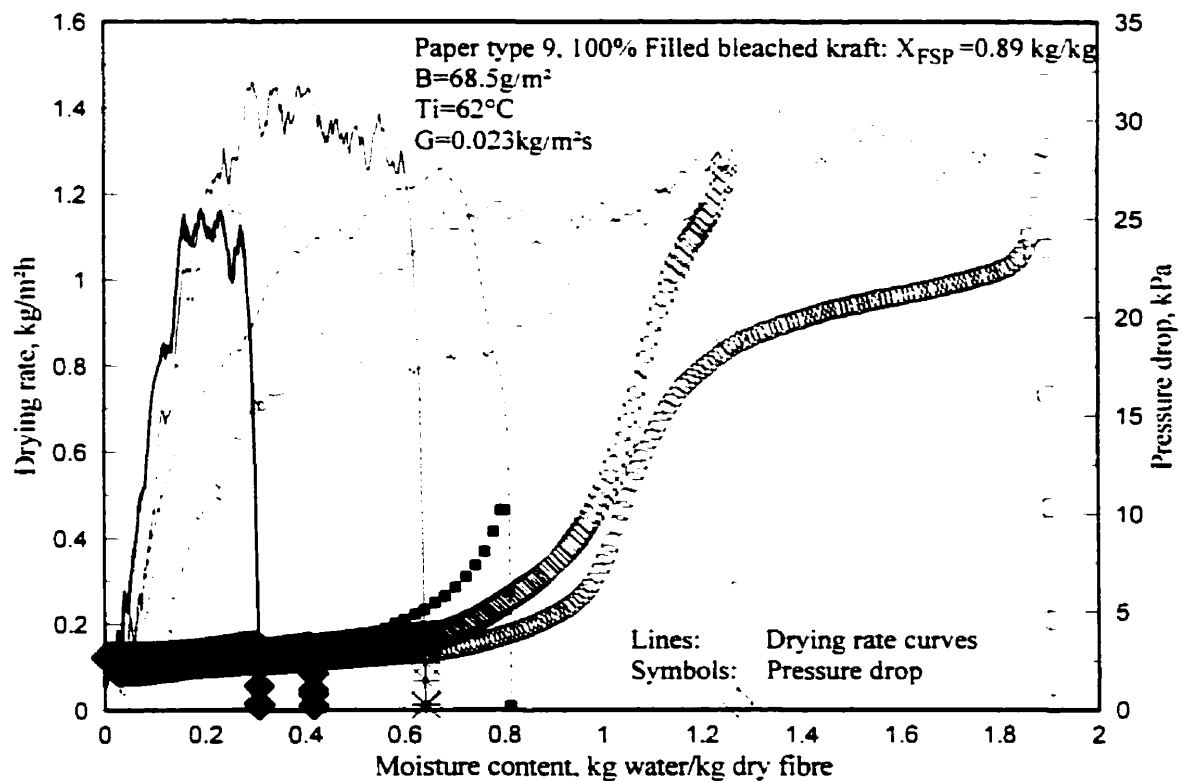


Fig. 4.18 Effect of initial moisture content at constant through flow rate: kraft paper

on Figure 4.19 gives $X_c/X_o = 0.56$, remarkably close to the value of $X_c/X_o = 0.45$ as determined by hundreds of through drying experiments by Polat [1989] and Chen [1994]. As their results were for kraft handsheets while the $X_c/X_o = 0.56$ value here is for machine-formed TMP paper, the somewhat higher value of X_c/X_o , 0.56 compared to 0.45, is consistent with the results in Table 4.1 showing that X_c increases as quality of formation decreases from the best possible formation of handsheets.

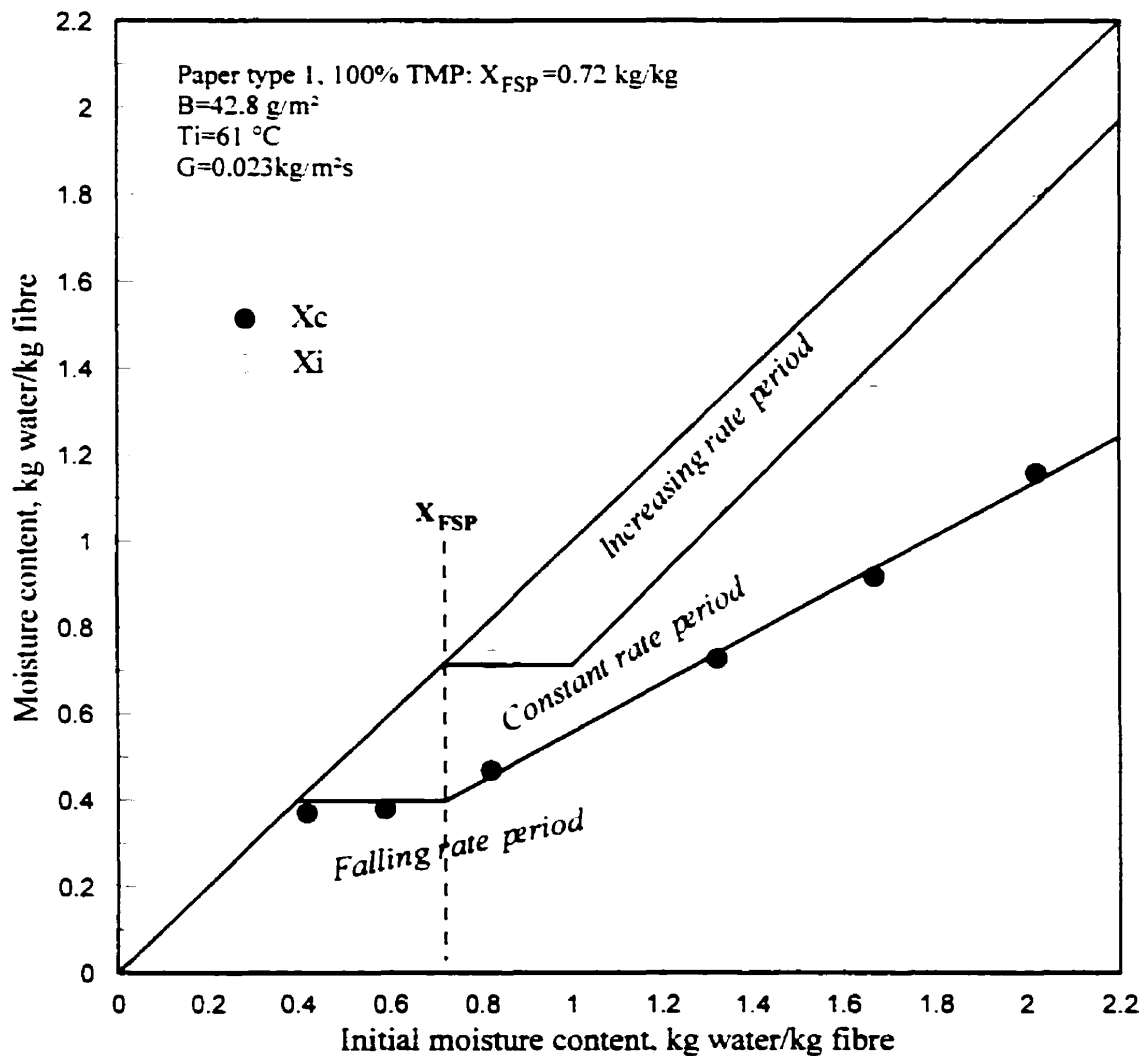


Fig. 4.19 Effect of initial moisture content on X_i and X_c : TMP paper

As X_0 is decreased below X_{FSP} , then X_c remains constant until, for $X_0 \leq 0.4$ kg/kg, there ceases to be any constant rate period. With no constant rate period the concept of X_c as the end of that period therefore disappears. This behavior, seen on Figure 4.17, is reflected on Figure 4.19 by the line of constant X_c for X_0 in the range from X_{FSP} down to about $X_0 = 0.4$, at which point the X_c line ends with disappearance of the constant rate period.

The line on Figure 4.19 for X_i , marking the end of the increasing rate period, likewise decreases with X_0 in the upper range of X_0 . The extent of the increasing rate period, $X_0 - X_i$, is essentially independent of X_0 . The mechanism creating the increasing rate period, i.e. the development of effective transfer area within the sheet as water is evaporated from the pores, is no longer present for $X_0 \leq X_{FSP}$. Therefore the increasing rate period ends at $X_0 = X_{FSP}$, with $X_i = X_{FSP}$. Interestingly, the experimental result for X_i obtained when $X_0 = 0.8$ kg water/kg fibre provides a data point in the region where the increasing rate period is disappearing as $X_i \rightarrow X_{FSP}$.

Thus for $X_0 > X_{FSP}$, a vertical line on Figure 4.19 shows the drying proceeding through three periods, those of increasing, constant and falling rate drying. When the initial moisture content falls in the region $X_{FSP} > X_0 > 0.4$ kg water/kg fibre, such a vertical line shows the drying starting with an abbreviated constant rate period. For $X_0 < 0.4$ kg/kg, drying is seen on Figure 4.19 to consist of falling rate drying only. For the range of $X_0 < 0.4$ kg/kg, the falling rate is seen on Figure 4.17 to start at a progressively lower point on a single R-X curve which no longer changes with initial moisture content.

In showing the extent of the increasing, constant and falling rate periods as a function of the initial moisture content Figure 4.19 is termed, as noted first by Polat et al. [1991a], the "drying period diagram". For the low intensity conditions of these tests Figure 4.19 shows that when through drying of this TMP paper is started at its value of X_{FSP} , about 40% of the drying occurs at the R_c constant rate while 60% occurs in the falling rate period. With higher drying intensity the $X_0 - X_c$ line on the drying period diagram moves up while the $X_0 - X_i$ line moves down, reflecting the growing extent ($X_0 - X_i$) of the increasing rate period and the progression towards disappearance of the constant rate period at higher intensity drying conditions.

4.14 Effect of Initial Moisture Content: Constant wet sheet pressure drop

While the comparisons of Figures 4.17 and 4.18 for the effect of initial moisture content were carried out at the same air through flow rate, hence with greatly varying pressure drop, Figure 4.20 compares the results for the complimentary case of changing the initial moisture content at the same level of the pressure drop for the wet sheet at the start of drying, hence with greatly different through flow rate. Over the entire region of common sheet moisture content on Figure 4.20, from about 0.6 kg water/kg fibre to dryness, the drying rate is seen to be about 10 times higher when starting drying at a moisture content of the fibre saturation point.

Through drying is currently used industrially with a drying air temperature of 300 - 400°C. Chen [1994] documented that the maximum drying rate in through air drying, R_c , varies with the temperature driving force, $T_i - T_{as}$, to the power 0.91. On this basis the

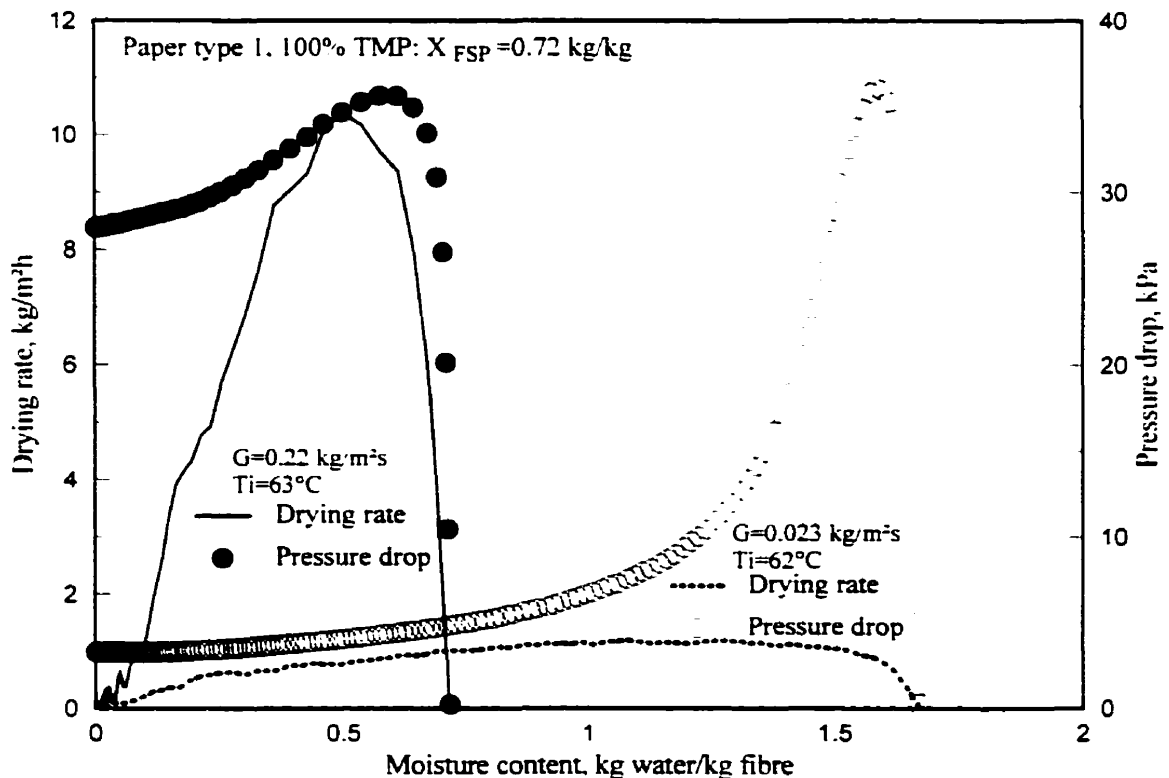


Fig. 4.20 Effect of initial moisture content at constant wet sheet pressure drop

drying rate in industrial application of through air drying of TMP paper, projected from that of Figure 4.20, could be about $90 \text{ kg/m}^2\text{h}$ at a moisture content of about $0.5 \text{ kg water/kg fibre}$. Under typical industrial operating conditions, steam heated cylinder dryers may give a value of constant drying rate R_c of about $25 \text{ kg/m}^2 \text{ h}$. As the critical moisture content for such cylinder dryer sections may be in the range $0.8 - 1.1 \text{ kg water/kg fibre}$, the drying rate when the moisture content has decreased to 0.5 kg/kg would generally be considerably below the R_c value, perhaps about $15 \text{ kg/m}^2\text{h}$. Thus from a moisture content of $0.5 \text{ kg water/kg fibre}$ to dryness, these approximate values of 90 and $15 \text{ kg/m}^2\text{h}$ indicate the possible extent of the drying rate advantage of through drying over cylinder drying. Although the economic optimization of the drying of paper involves many considerations beyond those investigated here, the above results at least indicate the substantial potential of a multiple technique dryer section in which the sheet moisture content is brought down to the level of the fibre saturation point by other drying techniques, such as conventional cylinder drying, then completion to dryness by through air drying.

4.15 Summary and Conclusions

- (1) In order to provide direct evidence concerning local nonuniformity of through air drying the local exhaust air temperature from the sheet was monitored at four locations. These measurements confirmed the hypothesis that different parts of the sheet enter the falling rate period locally at distinctly different times.
- (2) The in-plane moisture diffusivity was determined to decrease very strongly with decreasing sheet moisture content. The great difference found between in-plane diffusivity compared to that in the thickness direction from previous studies was related to an analysis of the way in which the nonisotropic structure of paper affects the diffusion of moisture differently in these two directions. In-plane moisture diffusion is too slow to affect significantly the nonuniformity of moisture content in through drying.

- (3) As drying nonuniformity is an effect which develops during drying, its negative consequences should be reduced by starting through drying at a lower initial moisture content. This inference was confirmed by tests with machine - formed TMP and kraft printing papers. It was demonstrated that by reducing the moisture content at which through drying is started, the critical moisture content decreases linearly, which is highly advantageous for effective drying. When the initial moisture content is decreased to the fibre saturation point the increasing rate period disappears, and as the initial moisture content is decreased below the fibre saturation point the constant rate period likewise starts to disappear. The relationships between initial moisture content and the increasing, constant and falling drying rate periods are seen best on "drying period diagrams".
- (4) The momentum transfer aspects of through drying were also shown to be greatly improved by starting through drying from lower levels of initial moisture content. For machine-formed TMP paper, starting through drying at an initial moisture content of about the fibre saturation point rather than from the typical moisture content of paper exiting the press section of a papermachine results in either an order of magnitude reduction in pressure drop for the same through flow rate, or an order of magnitude increase in through flow rate and drying rate for the same pressure drop.
- (5) The findings of the present study address both of the constraints noted at the outset against the use of through air drying for grades of paper heavier than tissue and toweling, i.e. high cost of providing the air flow through heavier paper, and excessive local nonuniformity in drying. In fact the findings point to a strategy for dealing with the restraints. Both of these negative effects may be substantially moderated by considering through air drying not as a process for the complete drying of such paper, but only as the final step when drying is carried out by two or more drying techniques, where the through drying is not started until the moisture content has been reduced to or below the fibre saturation point.

CHAPTER 5:

Nonuniformity in Through Drying: Local Moisture Content

5.1 Introduction and Objectives

Since the first papermachine was started up there have been problems in obtaining the dry sheet with a uniform moisture profile across the width of the machine. Now with papermachines for printing grades producing 9m wide sheets at speeds of 1600 m/min, 100km/h, the drying nonuniformity problem remains a technical challenge. Local nonuniformity in the drying of paper may lead to both a reduction in quality of the dry sheet and to a drying cost higher than for operation without moisture nonuniformity. For printing and heavier grades of paper, the focus of the present study, the problem of drying nonuniformity can occur with the now dominant technique of cylinder drying. However local nonuniformity of drying may become even more of a problem with the various techniques of much higher drying rate which are competing to become elements of the dryer sections of the future. Kuhasalo [1995], Bond et al. [1996]. In spite of the concern regarding degradation of paper quality from local nonuniformity of drying, quantitative treatment of drying nonuniformity has remained a difficult challenge.

The present study was undertaken to develop a technique for local moisture content measurement during drying that would be applicable to any type of paper drying process, and to apply this technique to investigate for machine formed paper the effects on nonuniformity in through air drying that are caused by parameters of both the papermaking process and the drying process.

5.2 Literature Review

Studies of drying nonuniformity have been generally of two types - either examination of the origin of nonuniform profiles and parameters involved in its

development, or attempts to measure and control the uniformity of sheet final moisture content. Most studies have naturally focused on papermachines with standard steam heated cylinder dryers. As to where the problem comes from, most investigations have dealt with sources of the moisture nonuniformity ahead of the dryer section, an important focus certainly, with less effort on parameters of the drying process that cause nonuniform drying. Rhorer [1971] concluded that most moisture profile problems originate from ahead of the dryer. Marshall [1972] showed that for newsprint, papermaking parameters such as headbox temperature, type of fabric and functioning of the wet press may affect the uniformity of moisture profile. However even a sheet entering the dryer with a uniform moisture profile may develop moisture nonuniformity due to the interaction of sheet structure with drying conditions, yielding nonuniform evaporation rates and thereby a nonuniform moisture profile. Such effects would be specific to the type and intensity of the drying process. For this second type of study, Cutshall [1991] provided a comprehensive survey on CD moisture profile control. The traditional method of overdrying the sheet in order to obtain a uniform moisture profile is now outdated. The current objective is for production of a dry sheet of moisture profile both uniform and at the desired level.

For through air drying, one of the high intensity drying processes whose use may be extended in future, no study of moisture nonuniformity has been reported except for the simulation by Gomes et al. [1992] which demonstrated quantitatively the effect of paper formation on drying nonuniformity.

5.3 Paper Structure and the Physics of Through Drying Nonuniformity

In drying by passing hot unsaturated air directly through the wet sheet, the resulting exceptionally good air-fibre contacting can give order of magnitude higher drying rates than the cylinder drying process universally used now for printing and heavier grades of paper. Relative to other drying techniques however, the passage of drying air through the sheet makes this process much more sensitive to the inherent nonuniformity in paper structure.

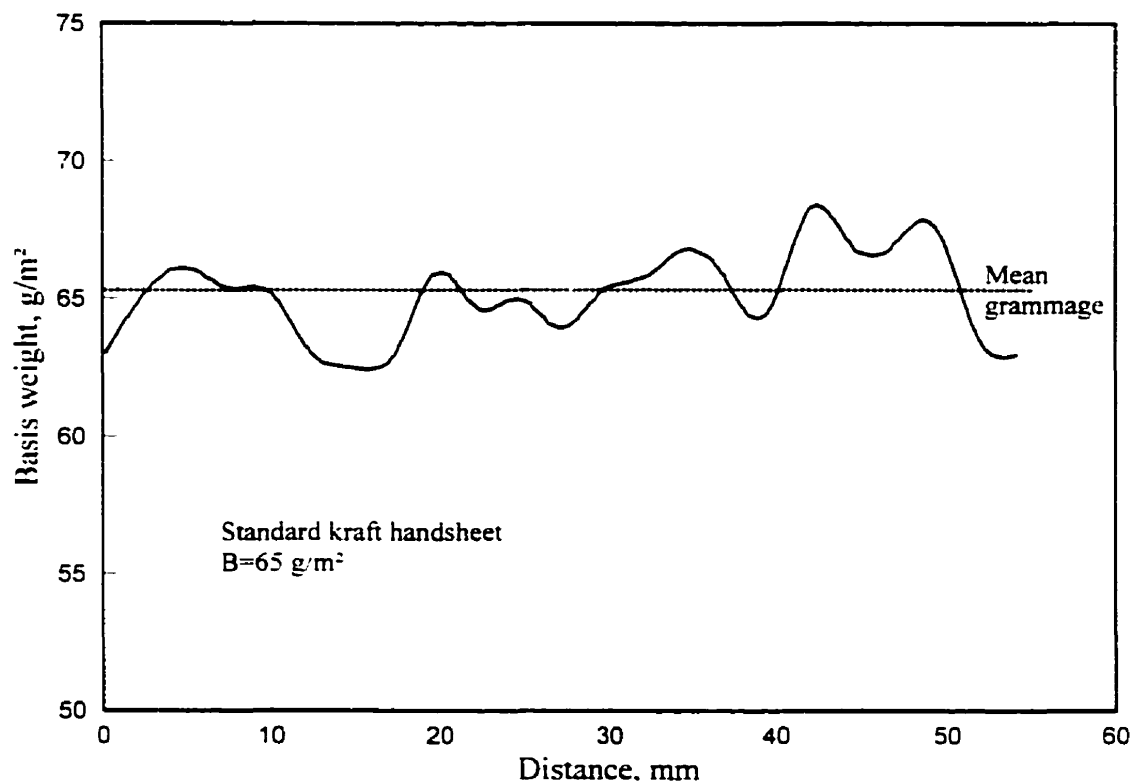


Fig. 5.1 Local grammage distribution

Unevenness is a basic characteristic of paper. The way in which fibres are distributed over the sheet is referred to as its "formation". The basis weight of paper, measured over a relatively large area, provides the sheet average value. However the local grammage varies considerably, with this distribution dependent not only on the sheet itself but also on the fineness of resolution of measurement. In his recent work on characterizing the formation of paper Cresson and Luner [1991] provided the local grammage distribution of kraft handsheets of various quality. Figure 5.1 shows the local grammage distribution of a standard kraft handsheet produced by the image analysis facility of our laboratory, described by Bernié and Douglas [1996].

Robertson [1956] long ago pointed out that local uniformity of paper applies not only to grammage but also to thickness, porosity and density, and thereby to local permeability. Through drying nonuniformity derives from the characteristics of air flow across a thin packed bed of fibres of locally nonuniform permeability because of its local

nonuniformity in grammage, thickness, porosity and density. The scanning electron micrograph of a cross section of TMP newsprint, Figure 5.2, illustrates these local nonuniformities.

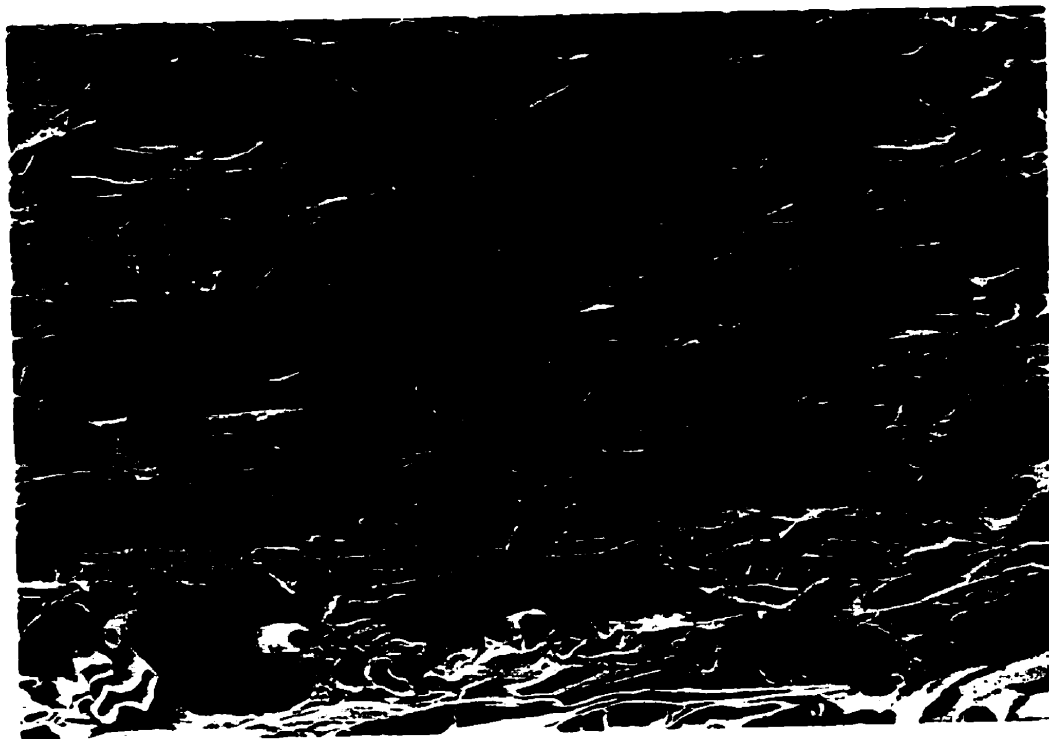


Fig. 5.2 SEM cross section of TMP paper

Local grammage of fibres is then only one component of the local nonuniformity of paper, but is more easily measured than the distribution of local porosity, density or permeability. As the local grammage variability is fortunately a dominant factor in paper unevenness, it can be used to indicate the degree of nonuniformity, and is the only factor discussed below. A primary determinant of grammage nonuniformity is that paper has regions of flocs and interflocs, originating at the moment of sheet formation from a suspension with regions of flocculated fibres. Thus regions of the sheet with flocs are of locally higher grammage, while regions between flocs have a grammage correspondingly lower than the sheet average value. Through drying rate is a function of through flow rate. As a through dryer operates with uniform pressure drop across the sheet, the local through

flow rate depends on local permeability, which in turn depends on local grammage. Because of this coupling between local values of grammage, permeability and through flow rate, the regions of flocs experience lower flow rates of air, thus have lower drying rates and slower decreases in moisture content. In the interfloc regions of relatively high permeability it is just the opposite, with a locally higher air through flow rate and locally faster drying. Figure 5.3. This is the mechanism by which local nonuniformity of moisture content is generated during through drying and, if there is any local nonuniformity present in the wet sheet at the start of drying, this mechanism amplifies such initial moisture nonuniformity. The present study investigates the extent to which this drying nonuniformity depends on the type of paper, formation and moisture content at the start of drying, as well as on the conditions of the drying process - the through flow rate and temperature of the drying air.

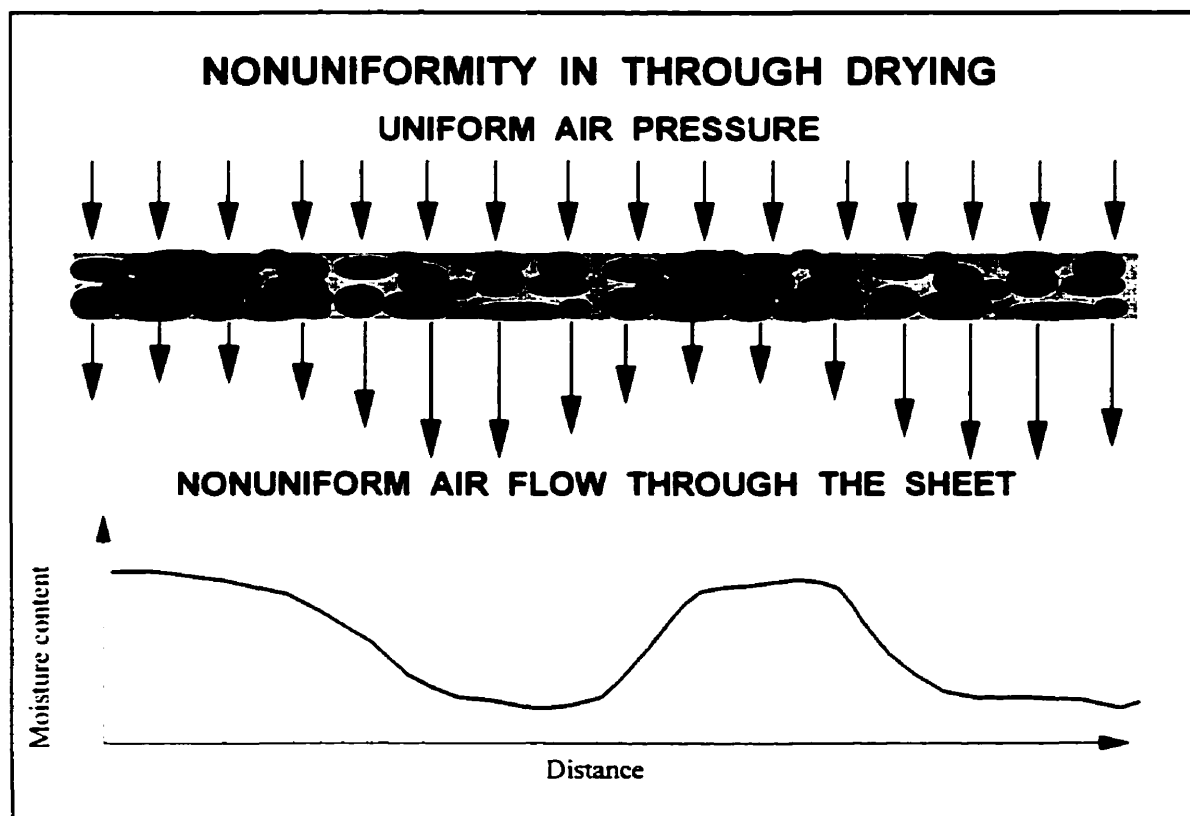


Fig. 5.3 Development of nonuniformity in moisture profile

Whatever the type of process used, the drying of paper ends with a period of falling drying rate, sometimes but not necessarily preceded by a period of drying at a constant rate. The critical moisture content which marks the onset of the falling drying rate period

constitutes an important parameter which is a function of the particular drying process, the specific conditions of that process as well as the specifications of the sheet. At higher than the critical moisture content X_c water is sufficiently freely available for evaporation that the drying rate is independent of sheet moisture content. The onset of the period of falling drying rate marks the conditions for which moisture is no longer that available for evaporation, with the drying rate now becoming dependent on sheet moisture content. For both cylinder drying as used now for all writing and heavier grades of paper, and impingement air drying as used for tissue and toweling, heat must be conducted from one surface of the sheet to its interior while moisture diffuses from the sheet interior to its evaporating surface. Thus for both hot surface and air impingement drying the critical moisture content represents the point at which these processes within the sheet start to proceed at a rate slower than the heat transfer rate to one surface of the sheet. For cylinder and impingement drying these processes of heat and moisture transport within the sheet thus occur on a dimension of the thickness of the sheet.

In through drying the critical moisture content similarly represents the point at which evaporation rate ceases to be controlled purely by the rate of heat transfer. Relative to cylinder and air impingement drying, the conditions giving the critical moisture content for through air drying differ fundamentally in that, within the sheet, heat and moisture are transported not just by conduction but by convection with the through flow. Moreover, in through drying the falling rate period starts when moisture transport to the surface of individual fibres for evaporation proceeds at a rate slower than the heat transfer rate to the fibre surface. Thus the transport processes controlling the critical moisture content occur on the dimension of sheet thickness for hot surface or impingement air drying, but on the dimension of individual fibres for through air drying. As fibre dimensions are an order of magnitude smaller than sheet thickness, critical moisture contents for through air drying could be expected to be lower by a corresponding proportion. At the same drying intensity, i.e. at similar values of constant drying rate, R_c , the values of critical moisture content, X_c , are lower for through air drying than for hot surface or impingement air drying, but not greatly lower. Glifberg and Parker [1990] provided some comparative data at industrial drying conditions. These observations concerning the relative values of X_c for these various

techniques of drying paper suggest that the reason why values of X_c for through air drying are not lower yet, relative to those for hot surface and impingement air drying, is because of the local nonuniformity effect in through drying. From this perspective the observed sheet average value of X_c for through drying corresponds not to the entire sheet entering the falling rate period but rather, to the falling rate period starting locally over just a fraction of the sheet, which would be in the lowest grammage, interfloc regions. Thus for through air drying the local nonuniformity of formation can be a factor which dominates the drying characteristics, especially the value of the critical moisture content marking the onset of the falling rate period.

5.4 Measurement Methods

Small and large scale variations in local grammage have been related to fibre flocculation and instabilities in the sheet formation process, Sara [1978]. Small scale variation deals with the uniformity of the product, large scale variation concerns the uniformity of the production. The limit between these scales is rather arbitrary and dependent also on the size of the measurement area. The present study deals only with the small-scale structure of formation.

The most direct technique to study drying nonuniformity would be to measure local sheet moisture content continuously during drying. Such monitoring is very difficult. An easier alternative would be to use an indirect method such as monitoring local exhaust air temperature out of the sheet, or local paper temperature. Following either of these temperatures can however show nonuniformity in sheet local moisture content only during the latter part of the drying process because prior to the falling rate drying period both local paper and exhaust air temperatures are independent of local sheet moisture content. This may not be a major limitation in studying local nonuniformity for through drying under high intensity conditions because Polat [1989] and Chen [1994] have shown that there would then be no constant rate drying period. In this chapter a modified version of the direct method was used, i.e. measuring local sheet moisture content. As continuous measurement

of paper local moisture content during drying is very difficult, the alternative adopted here was to make discontinuous measurements, that is, to interrupt the drying by removing the sheet for scanning with a moisture sensor sufficiently quickly that the local moisture content does not change significantly during the measuring process.

Two key factors in the measurement of local values of grammage and moisture content are the spot size for these measurements, and the extent of the sheet over which such local spot determinations are made. The spot size for measuring local grammage should not be smaller than about 0.1 mm in order to remain an order of magnitude above fibre dimensions, and should be not larger than about half the floc size in order to remain sensitive to the variation in local grammage on the scale of the floc size. For characterizing paper formation Sara [1978] used a spot size of 0.1 to 1 mm while Bergh and Luner [1981] used spots of 0.04 to 0.38 mm. Floc size depends on the furnish and the type of sheet formation process. For standard kraft handsheets floc size has been reported to be about 10 mm, and has been measured in our lab at about 8 - 9 mm. Therefore the acceptable spot size for local grammage and moisture content measurement is in the range up to about 4 mm. The measurement of local moisture content and grammage should extend over a length several times that of the floc size in order to obtain representative information. Sara found that for a measurement dimension larger than 20 to 30 mm the standard deviation of spot measurement values levels off. Bergh and Luner [1981], Demeyer and Luner [1982] and Jordan and Nguyen [1986] have recommended the 30 to 100 mm range for the measurement dimension.

As standard IR moisture sensors for paper are accurate only over the range 0 - 20% moisture content, our laboratory obtained a custom - designed IR moisture sensor, described in detail in previous chapter, with a number of special features including the use of two reference wavelengths rather than the customary single reference beam, thereby enabling its use over the full moisture content range relevant for paper drying research. This sensor has a very fast response time, less than 85 ms, and is accurate to within 0.02 kg water/kg fiber. Interchangeable probe tips provide two spot sizes, 2.5 and 8 mm, of which the 2.5 mm diameter spot was used in the present work. In this instrument the IR beam passes between

the sensor heads and control box through fibre optic cables which provide flexibility for rapid scanning of the paper.

Change in local moisture content after the interruption of drying could occur by moisture diffusion in the plane of the sheet or by ambient drying. The drying air temperature was selected so that the sheet remained close to ambient temperature during drying, thereby minimizing ambient drying during the subsequent measurement. For the drying air temperature used, $62 \pm 2^\circ\text{C}$, the sheet assumes during much of the drying the corresponding adiabatic saturation temperature of $21 \pm 1^\circ\text{C}$. With essentially no heat transfer to the sheet during scanning, ambient drying was effectively eliminated. A small ambient drying correction was none the less made in each case, but for the scanning time of 20s this correction was always less than 3% of the measured moisture content. With respect to the other potential problem, reduction in the moisture content nonuniformity by in-plane moisture diffusion, repeated determination of a nonuniform moisture profile established that only negligible changes occurred during the normal 20s scanning time. This finding is consistent to the values of moisture diffusivity reported in previous chapter.

With use of the IR sensor in reflection, not transmission mode, another concern was whether moisture gradients in the thickness dimension of the sheet from through drying could lead to incorrect determination of moisture content. However Edgar and Hindle [1980] and Waechter [1980] have confirmed that a back scattering IR gauge is satisfactory for studies of the drying of paper of basis weight of below 100 g/m^2 . In the present study the highest basis weight used was 70 g/m^2 , giving sheets about 150 mm thick. Kelmz [1993] reported that short IR wavelengths, 0.76 - 2 microns, penetrate paper up to 200 microns. As the absorbing IR wavelength of this sensor is 1.94 micron its use in reflectance mode should introduce no error of this kind.

5.5 Experimental Procedures

The interrupted drying experiments were carried out in the through drying facility described in chapter 2. The IR humidity sensor on the exhaust air enables continuous determination of sheet average moisture content during drying, and thereby the sheet

average drying rate as illustrated in that chapter. The partially dried paper in the sheet holder was moved quickly from the dryer and mounted on a specially designed scanning table, described in previous chapter, for measuring local moisture content. As this transfer could be completed in less than 20s, the effect during scanning from lateral moisture diffusion was negligible and that from ambient drying could be compensated by a very small correction.

The resolution of position on the precision moving stage was 67 microns at each step of the stepper motor, giving very high accuracy in measurement of distance. Integration of the moving stage with the IR moisture sensor provided local moisture content as a precise function of time and position, $X=f(t, u)$. The local moisture content of spots of 2.5 mm diameter was measured quickly with the IR sensor at from 16 to 32 locations, spaced 2.5 mm apart, constituting a total scanning distance of 40 - 80 mm, a length 4 to 10 times the floc size for the paper used.

5.5.1 Development of moisture nonuniformity

The gravimetric check obtained by weighing the sheet before and after scanning was to within 1% relative to IR moisture sensor measurements. The reproducibility of measurement is demonstrated in Figure 5.4 for a sheet not dried but simply equilibrated at an average moisture content of 0.6 kg/kg. The local moisture content measured at 32 points was repeated for three complete scans. As the three data sets essentially superimpose, the reproducibility of measurement is seen to be very good. Moreover these results show that even for a sheet well equilibrated at a moisture content significantly below that of the fibre saturation point (FSP), local moisture content is not completely uniform. As the profile of local moisture content with position is reproduced, these results do not reflect simply measurement variability. The coefficient of variation for the equilibrium distribution of local moisture content shown in Figure 5.4 is 3%. As the coefficient of variation for local fibre grammage, i.e. the formation number, for standard kraft handsheets is about 3%, the coefficient of variation for local grammage of water would be greater than 3%. This moisture nonuniformity under equilibrium conditions is believed to derive from sheet local nonuniformity in density as well as in grammage.

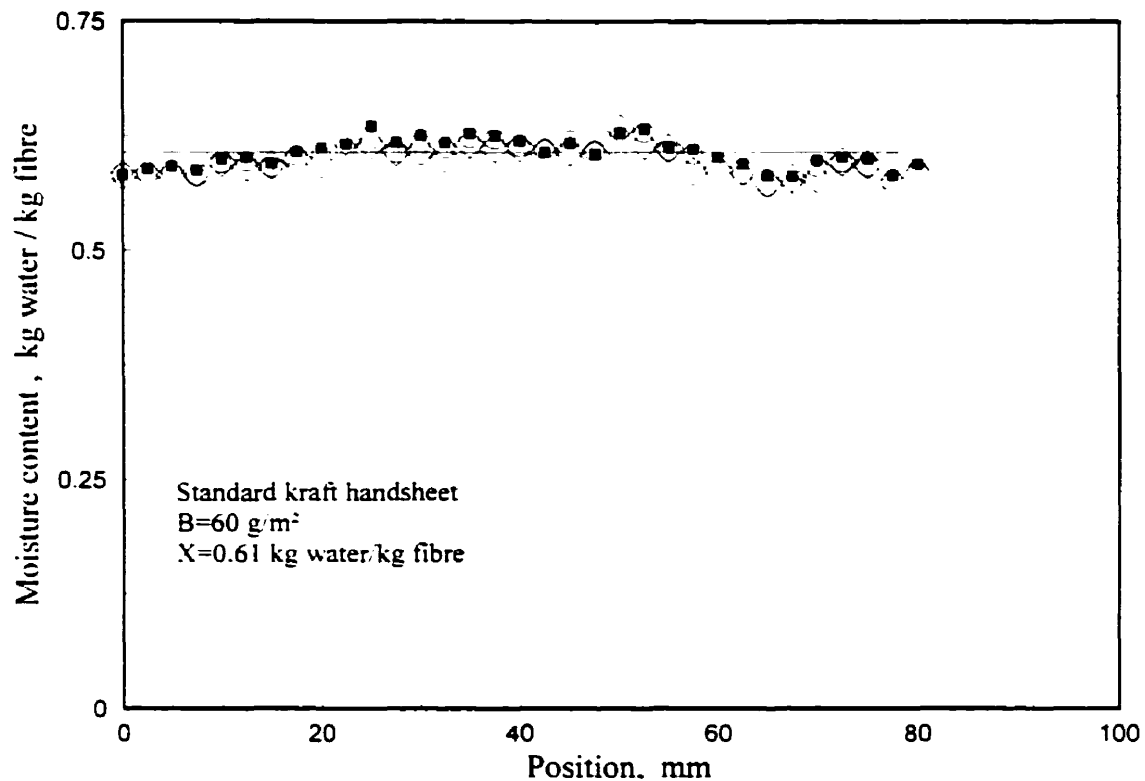


Fig. 5.4 Local moisture content at equilibrium

Figure 5.5 shows the distribution of local moisture content values at 32 spots each 2.5 mm diameter and spaced at 2.5 mm. for a sheet of average moisture content of 0.29 kg/kg. With 16 to 32 values, the nonuniformity in local moisture content can be characterized as its standard deviation or, divided by the average moisture content, as the "coefficient of variation":

$$I_{DNU} = \frac{\text{Standard deviation of sheet local moisture content}}{\text{sheet average moisture content}}$$

This nondimensional measure, termed here the "Drying Nonuniformity Index", I_{DNU} , corresponds to the formation number - the coefficient of variation of local grammage of fibres.

Definition of the drying nonuniformity index requires selecting the moisture content at which I_{DNU} is determined. The local nonuniformity of moisture expressed dimensionally as σ , kg water/ kg fibre, starts at the value for equilibrium distribution of moisture content

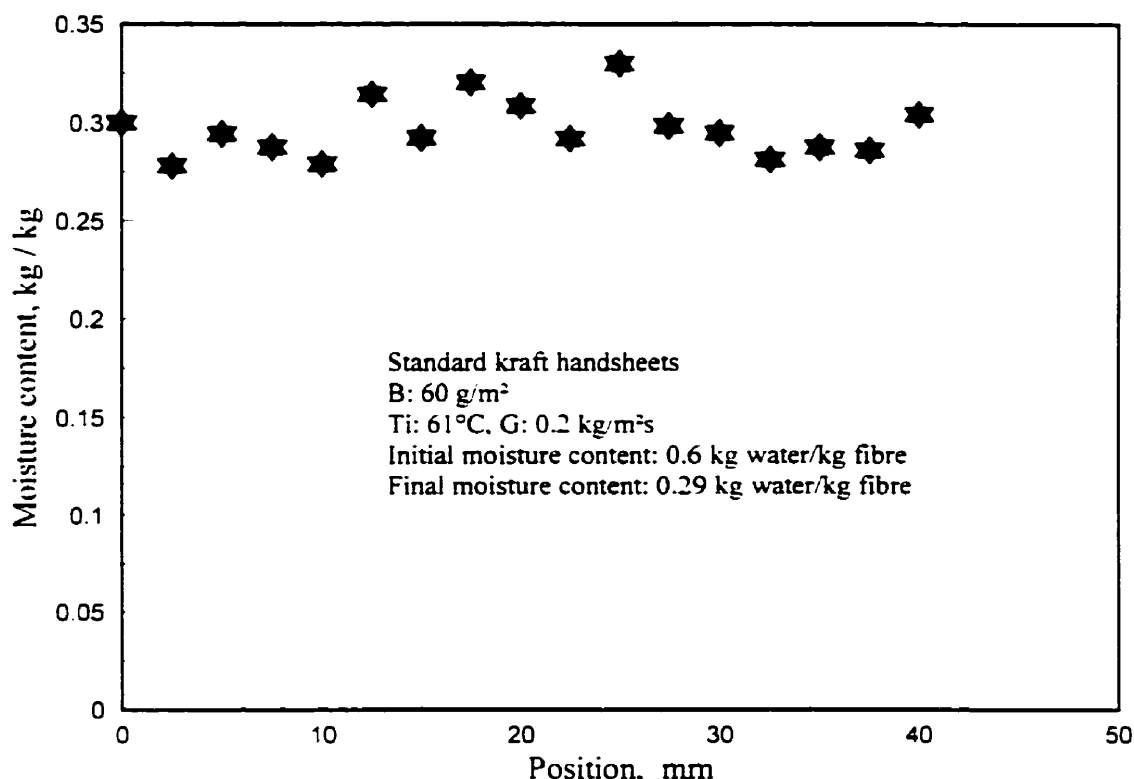


Fig. 5.5 Moisture nonuniformity after interruption of drying

for the sheet entering the dryer, increases as drying progresses and passes through a maximum before decreasing to approach zero as the sheet approaches dryness. For a handsheet dried at conditions of drying intensity corresponding to $R_c=11$ kg water/m²h. Figure 5.6 shows the evolution of σ for the distribution of local moisture, determined at intervals of 0.1 kg water/kg fibre in sheet average moisture content. For $X_0=1.6$ kg/kg the maximum in σ_X occurs at a moisture content of about 0.65 kg/kg, after which σ_X decreases linearly. Over the moisture content range where this relation is linear through $X=0$, $\sigma_X=0$, it necessarily follows that I_{DNU} remains constant at its maximum value.

The moisture content for determining I_{DNU} was then chosen as 0.3 kg water/kg fibre, a value high enough to be in the sensitive region and low enough from the perspective that the ultimate interest is the moisture nonuniformity for paper approaching the dryer section exit.

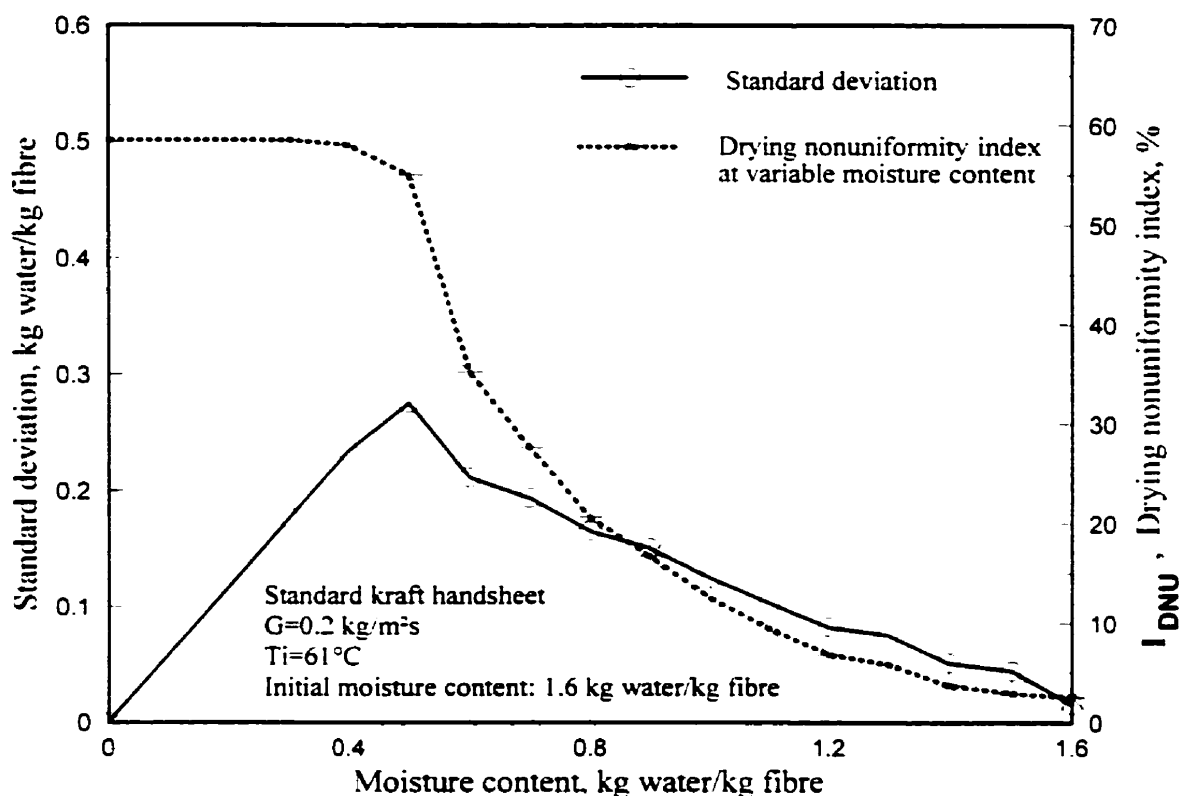


Fig. 5.6 Development of local moisture nonuniformity

5.5.2 Experimental plan

The effects on drying nonuniformity caused by both the conditions of drying and the parameters affecting sheet structure were examined. Normally a drying air temperature of 60°C was chosen in order to keep the sheet temperature near ambient temperature, as noted earlier.

The effect of drying intensity was investigated by varying the through flow rate by a factor of two, $0.2 - 0.4 \text{ kg/m}^2\text{s}$, and in some cases by using air at 80°C . Initial moisture content of the wet sheet was varied from 4 down to 0.4 kg/kg , a range which covers the high values used industrially for tissue and toweling, through the moisture content range of $1.2 - 1.6 \text{ kg/kg}$ out of the press sections for printing and heavier papers, down to moisture contents well below the fibre saturation point (FSP). Both handsheets and machine formed papers were used. Sheet formation, basis weight and furnish were changed. For some commercial sheets the nonuniformity was also examined separately in the machine direction (MD) and cross-machine direction (CD).

5.6 Drying Nonuniformity for Handsheets

5.6.1 Drying intensity

Drying intensity, varied by changing either through flow rate or temperature of the drying air, is represented as the drying rate during the constant rate period, R_c . Drying nonuniformity was expected to increase with drying intensity, and Figure 5.7 indicates the magnitude of this increase for the case of 60 g/m^2 kraft handsheets dried from $1.56 \pm 0.05 \text{ kg}$ water/kg fibre to a moisture content of $0.35 \pm 0.03 \text{ kg/kg}$. Results for three replicate tests for each drying intensity are shown.

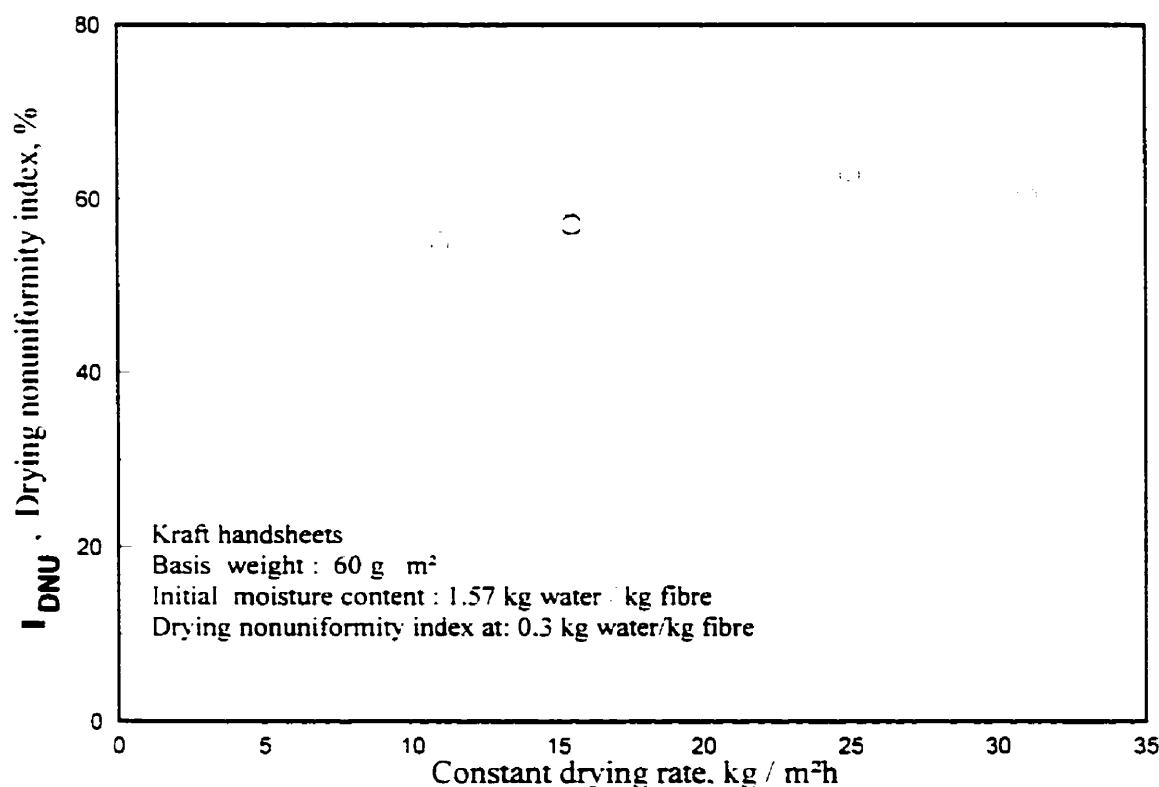


Fig. 5.7 Effect of drying intensity

Although drying air temperatures of $60\text{--}80^\circ\text{C}$ were used here for the practical reasons noted, current industrial practice with through drying of tissue is with air of $200\text{--}350^\circ\text{C}$, giving drying rates over $300 \text{ kg water/m}^2\text{h}$. However such drying conditions, satisfactory for tissue, may be of too high intensity for the through drying of printing and heavier grades of paper, the focus of the present study. With the current practice of cylinder

drying for such grades it is more pertinent to note the 25–45 kg water/m²h range of drying rates for the constant rate period of cylinder drying. From Figure 5.7 one notes that even with use of drying air temperature far below what could safely be used in industrial practice, values of R_c up to 32 kg water/m²h were obtained. Thus Figure 5.7 shows that for drying rates in the order of those for cylinder drying, drying nonuniformity with through air drying is sensitive to drying intensity but not excessively so.

As drying intensity is reduced to approach zero, the coefficient of variation of drying nonuniformity, I_{DNU} , should approach the coefficient of variation of the equilibrium distribution local moisture content. The results on Figure 5.4 show that for kraft handsheets at a sheet average moisture content of 0.6 kg/kg, this value is about 3%. This is the only moisture content level at which the equilibrium moisture distribution is available, but as the coefficient of variation probably does not vary much with moisture content in the range from 0.6 down to 0.3 kg/kg, the same 3% value may be assumed at the moisture content of about 0.3 kg/kg where the I_{DNU} values are calculated. Thus on Figure 5.7 there must be a nonlinear region for the I_{DNU} - R_c relation over the low range of R_c , ending at about $I_{DNU} = 3\%$ at zero drying rate. This range was not investigated because it would have no industrial relevance. Although drying nonuniformity is represented on Figure 5.7 relative to constant drying rate, when I_{DNU} was correlated not with R_c but separately with G and ΔT which control R_c , the resulting correlation, $I_{DNU} = 57 G^{0.13} (\Delta T)^{0.054}$, indicates a greater sensitivity to G . This behavior is consistent with the fact that local nonuniformity of drying derives from local nonuniformity of flow, hence the greater sensitivity to G than to ΔT .

5.6.2 Initial moisture content

Figure 5.8 shows that the drying nonuniformity behavior is basically different for initial moisture content above and below 0.8 kg/kg, the fibre saturation point (FSP) for this type of paper. For the range above the FSP, drying nonuniformity is high and increases very sensitively with initial moisture content but when drying is started below the FSP, drying nonuniformity is low and quite insensitive to X_0 . Over the range measured for $X_0 < \text{FSP}$, I_{DNU} averages 9.5%, which should be viewed in the perspective of two related coefficients

of variation, the typical formation number for such paper and for the equilibrium distribution of local moisture content, both about 3%. It is the coupling of grammage nonuniformity with local permeability nonuniformity to produce the local drying rate nonuniformity that results in the amplification of I_{DNU} above the level of the coefficient of variation for local moisture distribution at equilibrium. Thus in the range of X_0 from the lowest value measured, 0.47 kg/kg, to the limit of 0.3 kg/kg, the $I_{\text{DNU}} - X_0$ line of Figure 5.8 must decrease to approach the coefficient of variation for equilibrium moisture content at 0.3 kg/kg, about 3%.

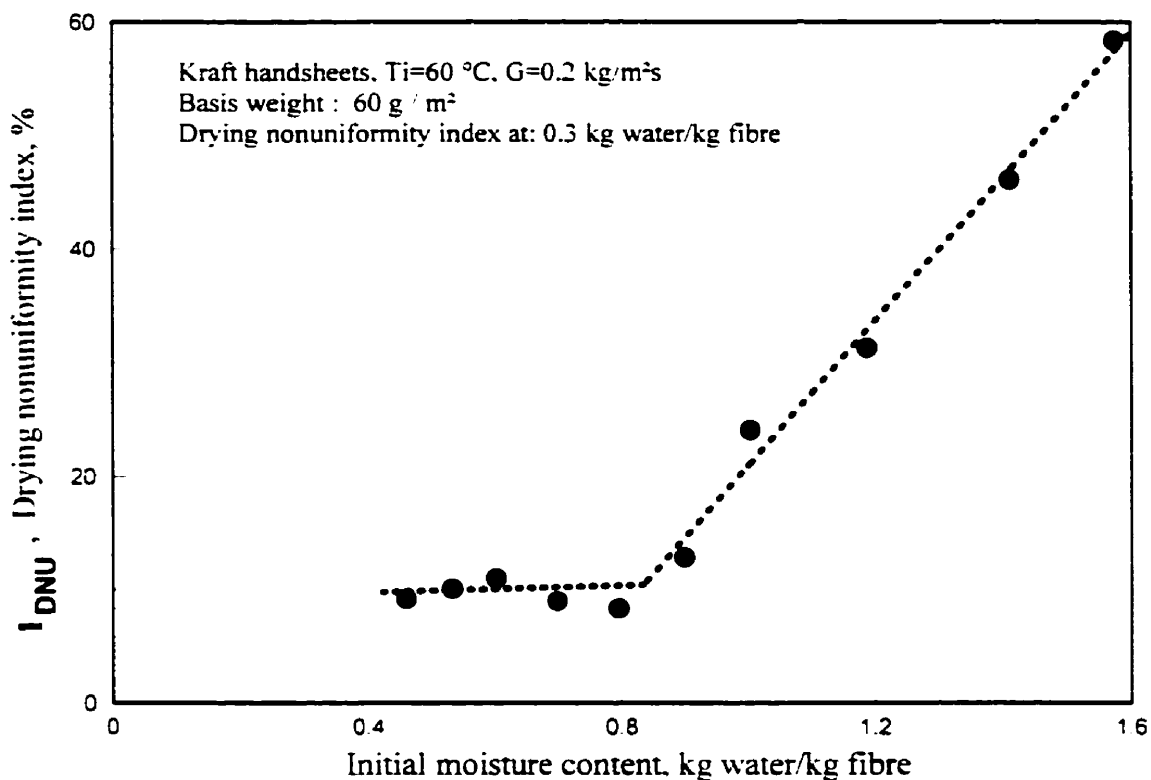


Fig. 5.8 Effect of initial moisture content

These sharp differences in the characteristics of drying nonuniformity with respect to initial moisture content derive from the presence and role of water in the pores at moisture contents above the FSP, while below that value the sheet consists of unsaturated fibres with no water in the pores. When drying starts above the FSP for sheets thicker than tissue the through flow local nonuniformity is much worse because there can be zero through flow in local regions where the pores are filled with water. By contrast, the

development of drying nonuniformity for paper of initial moisture content below the FSP no longer has this extreme sensitivity to X_0 but would be expected to depend on the quality of formation of the paper. Thus the effect of sheet formation is tested next.

5.6.3 Sheet formation

To illustrate the effect of sheet formation on drying nonuniformity experiments were carried out with 60 g/m² kraft handsheets of variable formation. Quality of formation is known to deteriorate as the fibre suspension is allowed more time to flocculate prior to forming the sheet. Thus 10 handsheets were prepared with a quality of formation decreasing from the best possible, at about 1s retention time, to the poorest quality formation after 100s retention. The quality of sheet formation for retention times from 1s to 100s ranges from considerably better than, to appreciably worse than that for machine-formed sheets. As the FSP for this pulp was 0.8 kg/kg, the initial moisture content for these sheets was fixed slightly lower, at 0.74±0.03 kg/kg, so that the effect from variable sheet formation would not be obscured by the high sensitivity of drying nonuniformity to water in the pores that was demonstrated above.

For the possible use of through drying for paper in the higher basis weight range it is encouraging that the Figure 5.9 shows the index of drying nonuniformity only doubling as the formation of the sheet is varied so greatly, from better than to much worse than a machine-formed sheet from the same furnish.

5.6.4 Paper basis weight

The dependence of drying nonuniformity on basis weight was investigated in a series of experiments with kraft handsheets of basis weight 19, 30, 60 and 120 g/m² dried using the conditions noted on Figure 5.10. Paper of 120 g/m² is the upper limit for accurate moisture content determination by the IR sensor used and moreover represents very high grammage for through drying, roughly six times that of the grades currently dried industrially by this technique. Scanning at 24 points was used for determining the I_{DNU} value.

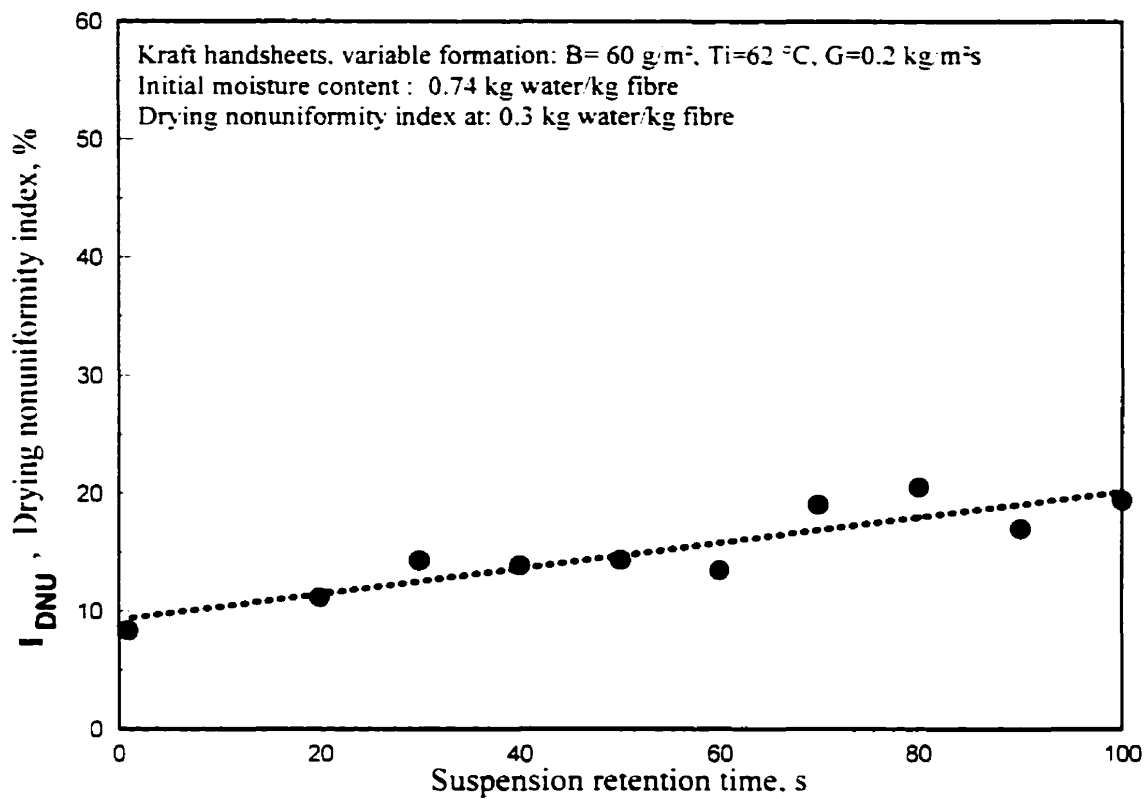


Fig. 5.9 Effect of formation

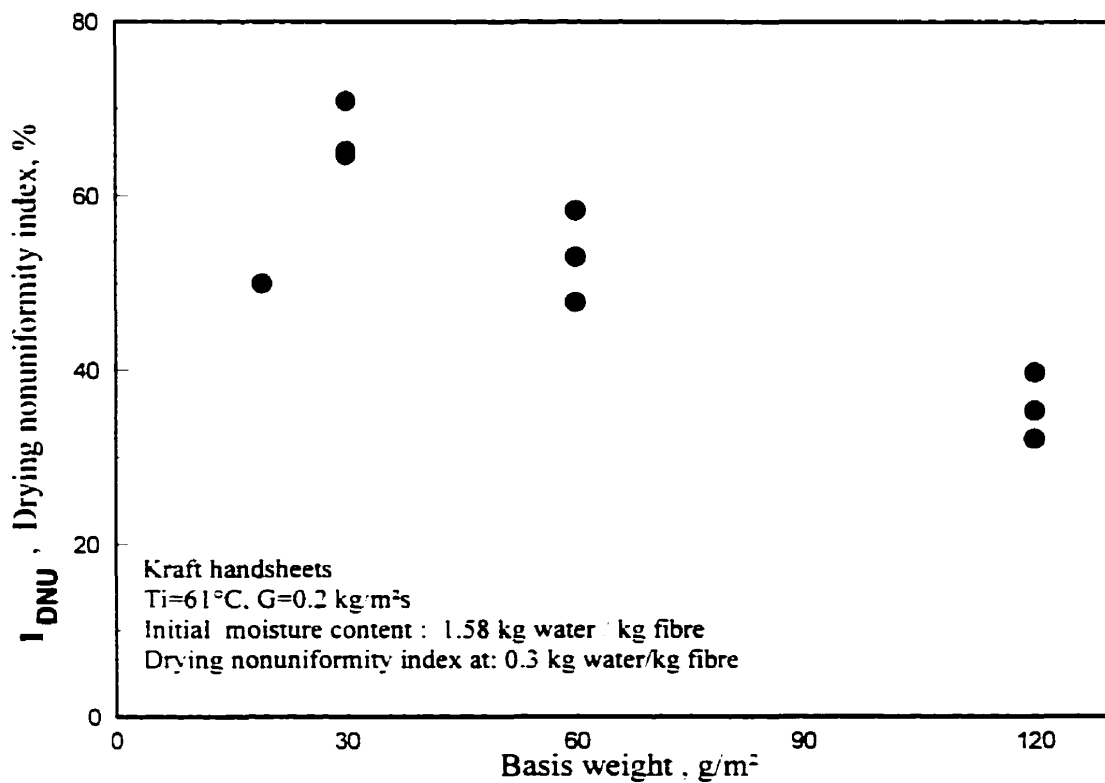


Fig. 5.10 Effect of paper basis weight

For the four-fold increase in basis weight over the 30 to 120 g/m² range, Figure 5.10 shows that the index of drying nonuniformity is decreased by about a factor of 2, while reducing the basis weight from 30 to 19 g/m² also decreases the I_{DNU} , in this case by almost one-third. Thus these experiments lead to the interesting finding of a maximum in this relation. Over the region above 30 g/m² the drying nonuniformity is reduced because, as has long been recognized, thicker paper is also more uniform paper. Corte and Kallmes [1962]. Formation number likewise decreases with increasing basis weight over this range. Decreasing grammage below 30 g/m² reduces drying nonuniformity because now the sheet is becoming less of a packed bed, more like a screen having low resistance to through flow and hence less potential for local nonuniformity of flow under a uniform pressure drop.

5.7 Drying Nonuniformity for Machine-Formed Paper

Having of necessity used handsheets to determine the effect of the individual parameters described above, the measurement technique was then applied to machine-formed paper.

5.7.1 Towel paper

As the use of through air drying is standard industrial practice with tissue and toweling the effect of initial moisture content on drying nonuniformity was checked for such light weight paper. In the drying of this grade the typical initial moisture content is around 3–4 kg water/kg fibre. For the same drying conditions with these sheets as used above, $G=0.2$ kg/m²s and $T_i=62\pm 2^\circ\text{C}$, the effect on drying nonuniformity with initial moisture content varied over the range 4 to 1.1 kg/kg was determined by interrupting the drying at 0.26 ± 0.02 kg/kg. Figure 5.11 shows that drying nonuniformity of this light weight paper is very much less sensitive to initial moisture content than the 60 g/m² paper shown on Figure 5.8. This finding is consistent with the demonstration on Figure 5.10 that drying nonuniformity decreases as basis weight is decreased to this low level. Thus these trends on

Figures 5.10 and 5.11 both reflect the shift in sheet structure from that of a packed bed for printing and heavier papers, to approaching a screen for tissue and toweling.

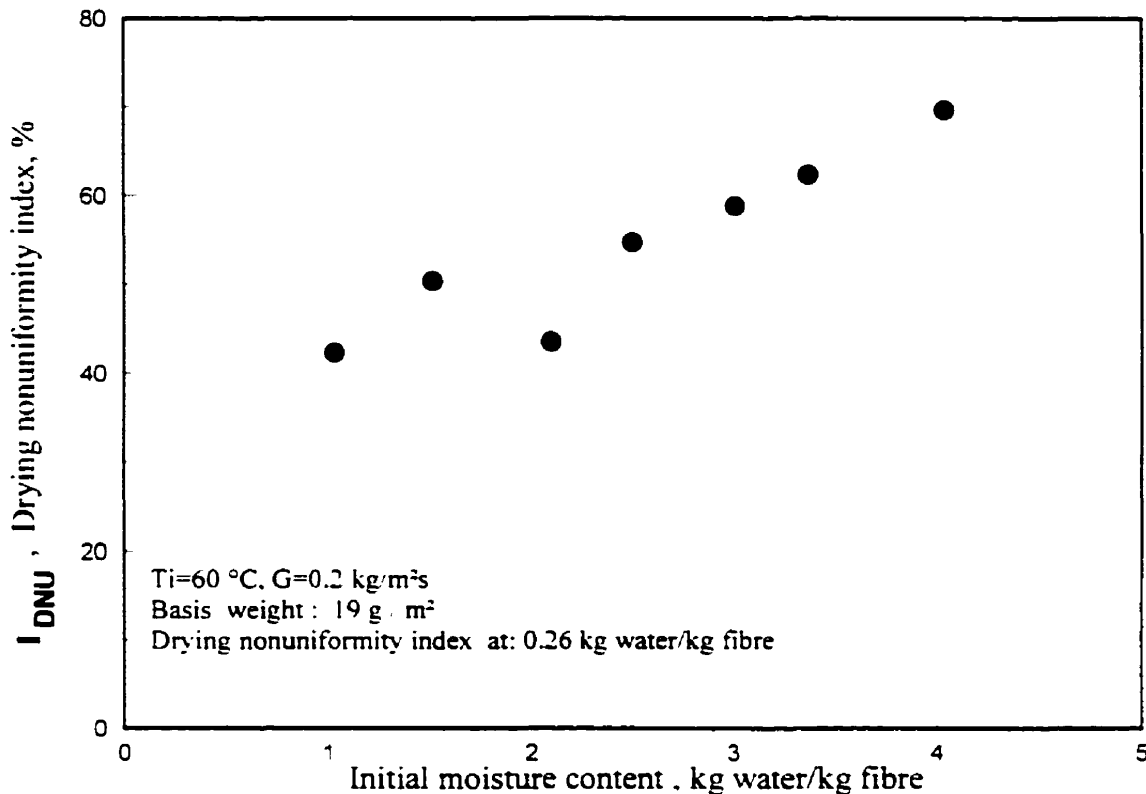


Fig. 5.11 Drying nonuniformity for towel paper

5.7.2 Medium weight machine-formed paper

For the two types of heavier machine-formed paper of different furnishes and formation that were chosen, 44 g/m^2 newsprint and 46 g/m^2 sack paper, the same experimental conditions were again used but with the important addition that the drying nonuniformity was determined in both the MD and CD dimensions. In view of the results on Figures 5.8 and 5.11, the drying nonuniformity was determined for two levels of initial moisture content, the upper level around the value currently used industrially for paper entering dryer sections, the lower level around the FSP. The FSP moisture content for the sack paper and newsprint used was 0.88 and 0.65 kg/kg , respectively. Figure 5.12 shows that for both types of paper and both levels of initial moisture content, the drying

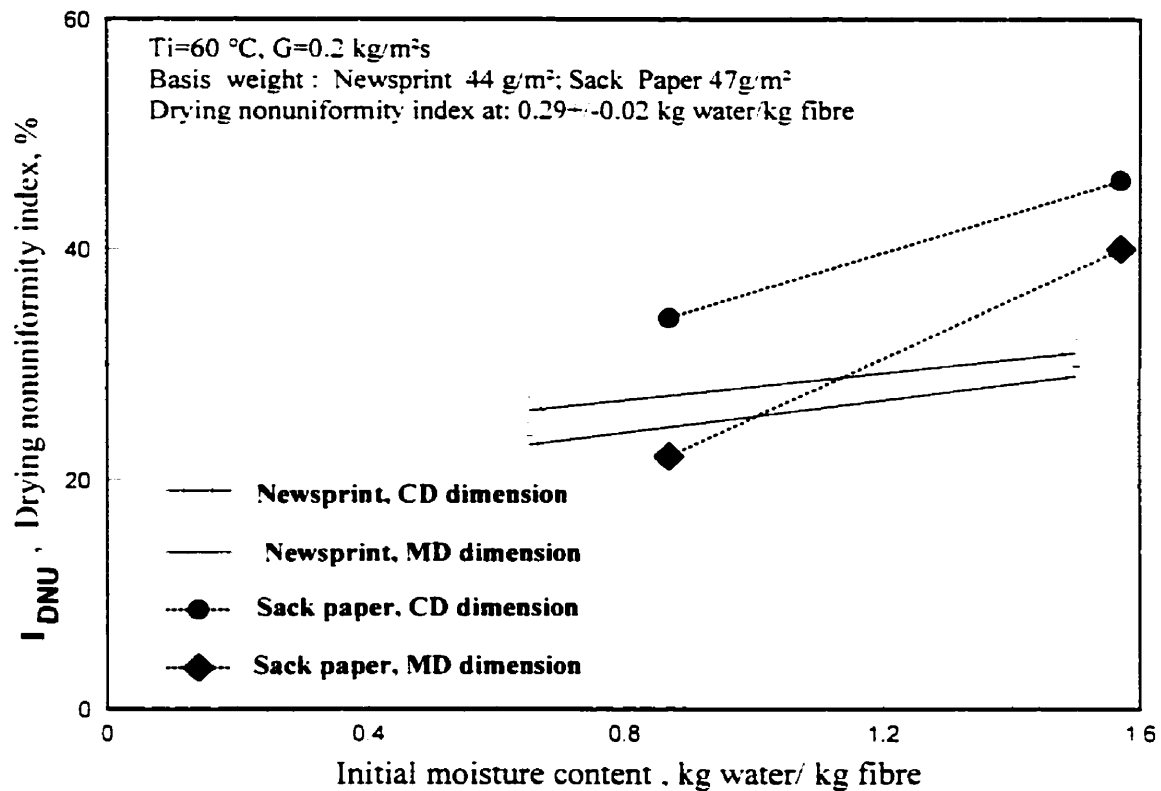


Fig. 5.12 Drying nonuniformity for newsprint and sack paper

nonuniformity index is always higher in the CD than in the MD dimension. As there is greater variation in sheet formation in the CD than the MD dimension, this trend in drying nonuniformity along the sheet in the two directions is consistent with the finding from Figure 5.9 that the greater the formation nonuniformity, the greater the drying nonuniformity. Likewise for all conditions tested the drying nonuniformity is decreased by starting drying at a lower initial moisture content, as was observed also on Figures 5.8 and 5.11 for paper both heavier and lighter than those shown on Figure 5.12. It is probable that considerations of paper properties, an aspect beyond the scope of the present study, would show that I_{DNU} values of 25-30% would be unacceptably high. The through drying step in the drying could be started at a moisture content sufficiently low to maintain the drying nonuniformity below the level acceptable for reasons of paper quality.

5.8 Local Basis Weight - Local Moisture Content

As a final step we tested for a relation between local grammage and local moisture content during drying, given that local nonuniformity in thickness, porosity and density may also affect drying nonuniformity. For that purpose the local grammage and moisture content of exactly the same spot on the sheet must be determined. Therefore after a sheet from an interrupted drying experiment had been scanned to determine the local moisture content at 24 spots, each 2.5 mm diameter, the paper was allowed to dry completely and the local grammage then determined for exactly those 24, 2.5 mm spots. For this last step the sheet was transferred to the light transmission image analysis facility of this laboratory, described by Bernié and Douglas [1996].

The fact that paper tends to shrink during drying might make a problem for obtaining an exact match of the spots for the successive determinations. Smook [1992] states that for kraft pulp the shrinkage occurs as paper moisture content drops from about 1 to 0.3 kg water/kg fibre during drying. Here the moisture content for drying interruption was about 0.3 kg/kg, i.e. after the shrinkage would be essentially complete. Moreover, with our conditions of the paper being dried under restraint in circular sheet holders, drying stresses are developed but the strain is zero, so this potential source of error was not present.

When those two sets of data are combined in Figure 5.13, the dependence of local moisture content on local grammage is apparent. These results provide the first quantitative documentation of the direct relationship between local grammage and local moisture content during drying. The good correlation apparent on this graph provides the important conclusion that although paper is also locally nonuniform with respect to thickness, porosity and density, for the purpose of drying nonuniformity most of the variability is accounted for by the local nonuniformity of fibre grammage.

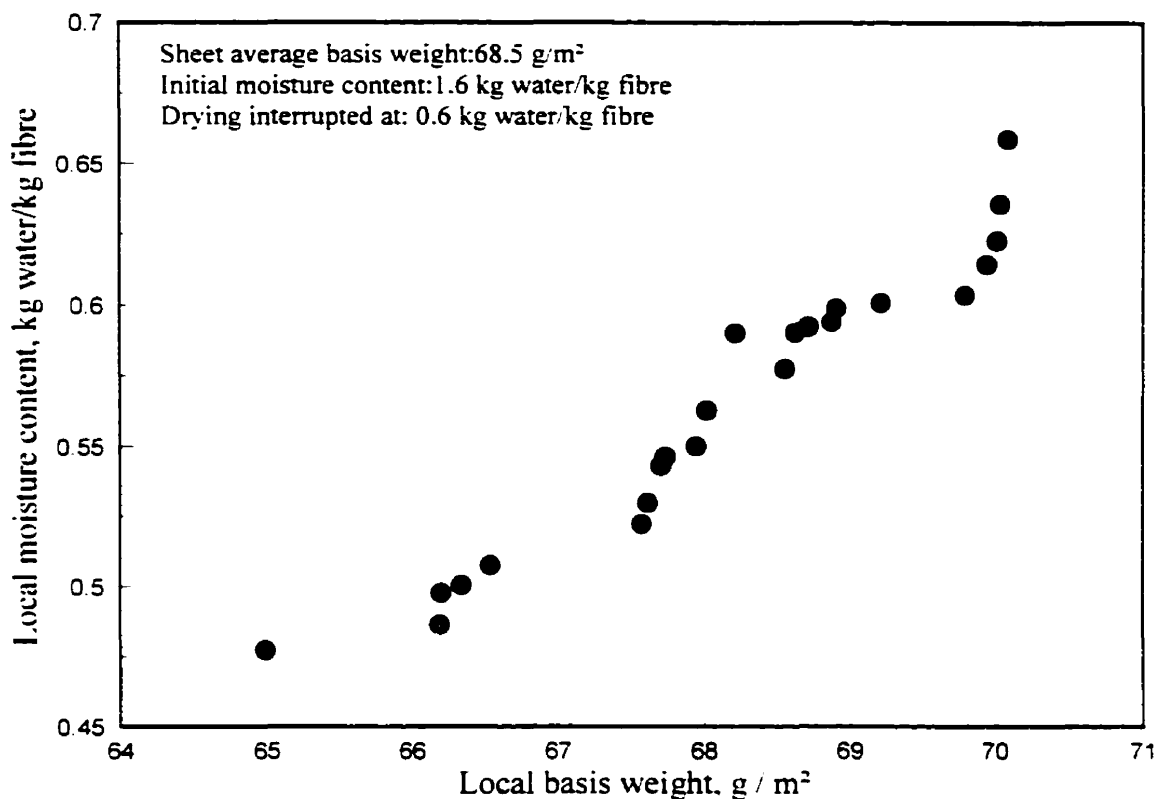


Fig. 5.13 Local moisture content-local grammage relation

5.9 Summary and Conclusions

- (1) Although the method developed here for determination of local nonuniformity of drying was demonstrated for one particular kind of drying, this technique is perfectly general. This procedure could be used to determine the distribution of local moisture content whenever incompletely dried paper is available from a laboratory, a pilot plant or from a paper machine dryer.
- (2) The standard deviation of the distribution of local moisture content provides the dimensional measure of drying nonuniformity, while the drying nonuniformity index, I_{DNU} , introduced here provides a useful nondimensional measure:

$$I_{DNU} = \frac{\text{Standard deviation of local moisture content distribution}}{\text{Sheet average moisture content}}$$

This index corresponds exactly to that of the formation number, the nondimensional index of local nonuniformity of fibre grammage, in that both represent the coefficient of variation of the distributed variable. In contrast to formation number, determined for dry paper, the definition of I_{DNU} is completed by specification of the sheet average moisture content at which it is determined, chosen as about 0.3 kg water/kg fibre for the present investigation.

- (3) The effects on drying nonuniformity come from two sources: paper specifications and drying conditions. The paper specifications checked were formation, basis weight and initial moisture content. Formation was changed through the use of handsheets, various machine-formed papers and by evaluation in both the CD and MD dimensions. Variation in the drying intensity was obtained by changes in temperature and flow rate of the drying air.
- (4) Drying nonuniformity becomes worse as the quality of formation decreases and as drying intensity increases. At the drying air temperatures currently used for tissue and toweling, much higher than those of the present study, this nonuniformity would be correspondingly higher. The effect of basis weight revealed an interesting effect, that the drying nonuniformity is worst for paper of about 30 g/m^2 . For higher basis weight, drying nonuniformity decreases as the thin packed bed of fibres becomes thicker and hence more uniform, while for paper lighter than 30 g/m^2 the drying nonuniformity also lessens because now the thin packed bed has been changed towards becoming a screen.
- (5) The biggest effect on drying nonuniformity comes from the choice of initial moisture content. The more the initial moisture content is above FSP, the worse the drying nonuniformity is. This effect is not large for tissue and toweling because these sheets are almost screens. For newsprint and sack paper, however, the present study establishes that through drying should not be started until the sheet moisture content is below the FSP, thereby avoiding the amplification of drying nonuniformity that comes from the coupling of local drying rate with both the nonuniformity of distribution of local pore water and local grammage of fibres.

- (6) The drying nonuniformity for machine produced paper is greater in the CD than MD dimensions, which parallels the corresponding greater variability in local grammage for the CD than the MD dimension.
- (7) Overall, this study addressed the questions of how and why moisture local nonuniformity develops in through air drying. All such nonuniformity in through drying derives from local nonuniformity in permeability to air flow through the sheet. Even for dry paper no measurements exist for the distribution of local permeability, and here it is the effect of variability of local permeability of moist paper which causes drying nonuniformity. When a sheet is through dried from an initial moisture content below the FSP the nonuniformity of local permeability may have several sources, including local nonuniformity in sheet thickness and porosity. However the evidence obtained here is that in this moisture content range most of the measured drying nonuniformity derives from the local nonuniformity in grammage, i.e. from the quality of formation. When a sheet is through dried from a moisture content above the FSP value, the effect of grammage nonuniformity is magnified greatly by the nonuniformity in distribution of moisture in the pores. Nonuniform distribution of pore water derives from the wide range of pore size distribution and the associated importance of surface tension on the structure of pores available for air flow through the sheet.
- (8) Concerning the possible future application of through drying for paper of grammage heavier than tissue or toweling, the present study provides some conclusions. For such paper of a given furnish and formation, there are two practical ways to keep drying nonuniformity within acceptable limits: to limit the drying intensity, and to start the through drying at a sufficiently low initial moisture content, and certainly at a moisture content not greater than the FSP. Appropriate combinations of these two strategies may permit the extension of the use of through drying to grades additional to the light weight products to which it is currently restricted.

CHAPTER 6:

Nonuniformity in Through Drying: Local Exhaust Air Temperature

6.1 Introduction and Objectives

Characterizing drying nonuniformity directly by the determination of the local moisture content profile of partially dried paper, discussed in previous chapter, is a general technique which can be used for any drying process from which an incompletely dried sheet could be obtained. A shortcoming of this technique is that it does not document the development of nonuniformity continuously during the drying. Such detailed information on how nonuniformity evolves during drying could provide insight into the mechanisms of this phenomenon and thus how it could be minimized. Among the methods reviewed in the previous chapter for characterizing drying nonuniformity, one applicable uniquely to through drying is to monitor continuously the local exhaust air temperature immediately below the sheet.

Local temperature measurement could be very precise with the appropriate choice of size and type of sensor. A limitation of this technique is its inability to provide any nonuniformity information until the specific local region being monitored enters the falling rate drying period. Until then the sheet remains at the adiabatic saturation temperature and the exit air remains at a constant temperature somewhat above or, in the limit, approaching the adiabatic saturation temperature of the drying air. This limitation may not be of consequence under industrial conditions of high intensity through drying where there is typically no constant rate drying period.

Thus documentation of the moment at which specific local regions of the sheet enter falling rate drying and the subsequent development of this indication of local nonuniformity would provide quantitative evidence concerning the role of nonuniformity in through air drying.

6.2 Experimental

The through air dryer facility described in chapter 2 could provide a continuous measurement of the sheet average drying rate-moisture content relation. Hence that setup was modified by the addition of a network of very small thermocouples located in the exhaust air flow immediately below the sheet.

6.2.1 General description

Local exit air temperatures on the through flow exit side of the sheet were monitored by placing immediately beneath the sheet an assembly of 16 E-type thermocouples, 0.125mm diameter, each supported inside the 150-300 mm long stainless steel sheath of 0.25 mm diameter, Figure 6.1. This number of thermocouples is more than adequate to provide statistically significant information on the variability of local exhaust temperature. As this thermocouple assembly must be very close to the sheet to ensure that

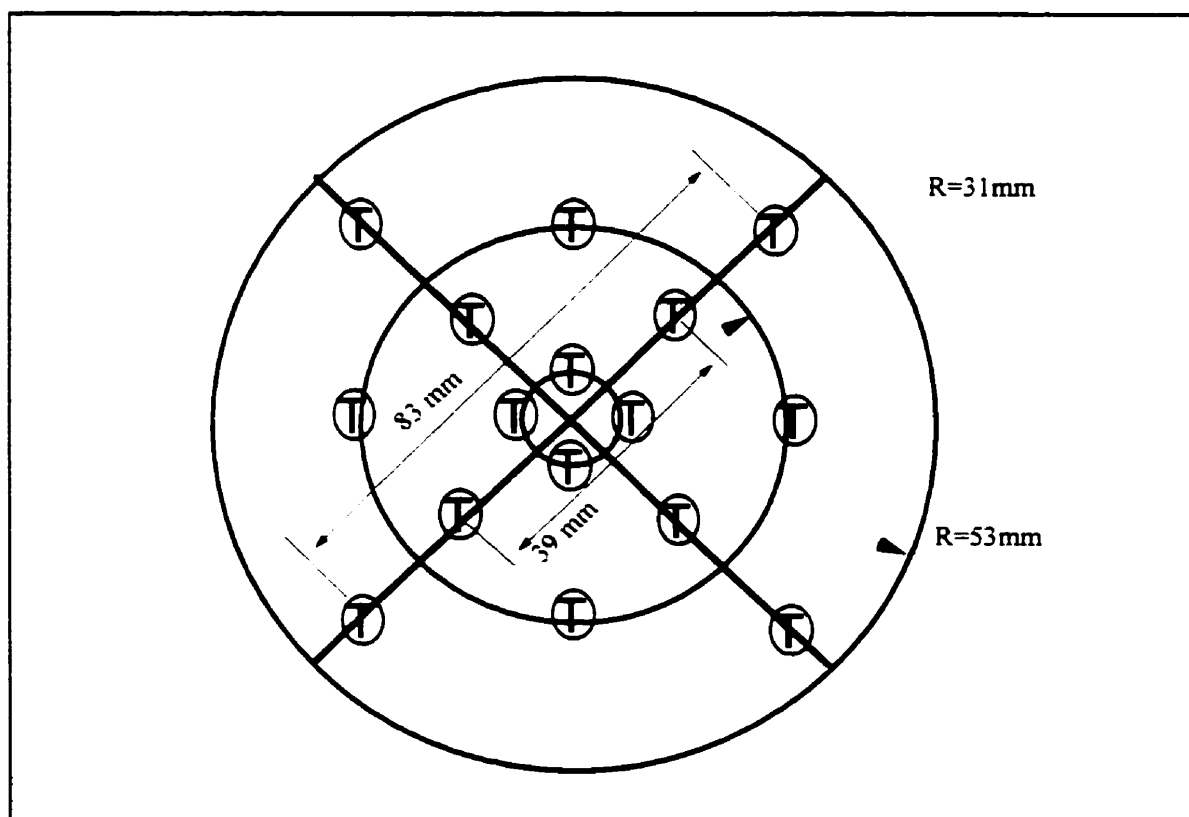


Fig. 6.1 Thermocouple assembly

the exhaust air temperature measured is that exiting the sheet prior to lateral mixing, and as these delicate thermocouples must remain at precisely fixed locations, a new sheet holder and insertion-retraction plate were needed. The sheet holder, of the same general layout described in section 2.3.3 and Figure 2.2, sits in the insertion-retraction plate and the thermocouples pass through its base and middle ring layers. In this way each thermocouple is positioned to remain at the center of a cell in the honeycomb support of the sheet. The 16 thermocouples are fixed on a light weight aluminum thermocouple holder ring which in turn is attached inside the insertion-retraction plate. The sheet holder occupies precisely the same radial position each time due to pins that fix its position on supporting plate. Installation of all thermocouples at 1 ± 0.1 mm below the sheet is a very precise and tedious exercise.

Removing the sheet holder assembly from the dryer between each drying test as practiced in the experimental work preceding the present chapter would damage the fragile thermocouples, hence it was essential to keep the base and middle ring layers of the sheet holder, including the honeycomb sheet support, in position permanently. In this way for each experiment only the top ring layer, which has no connection with the thermocouples, need be removed to replace a dried sheet with a wet one. However the previous insertion-retraction plate was designed to accommodate only one sheet holder which, if it must remain in the dryer between experiments, would become hot and thus increase the drying rate through being a heat source additional to the drying air. To prevent this effect a new insertion-retraction plate was constructed with two holes the outside diameter of the sheet holder, only one which ever carries the sheet holder. During the heat-up period and between experiments the insertion-retraction plate was positioned with the sheet holder out of the dryer and the matching opening inside the dryer. The dryer with the new sheet holder and insertion-retraction plate was tested against any leakage according to the procedure of section 2.3.4.

The original data acquisition board accepts only eight sensors while this measurement needs at least 24 channels. A PAP-611 data acquisition board developed at the Pulp and Paper Research Institute of Canada was used along with very accurate thermocouple amplifiers and a precision adjustable cold junction compensator, quite

sensitive to any change in data acquisition terminal panel temperature. The raw data acquired by the data acquisition software were later processed with a spreadsheet processing file written using macro commands in Quatro Pro and Fortran.

6.2.2 Thermocouple assembly specifications

Accuracy and time constant are important in the choice of thermocouples. According to NIST Monograph 175, Bruns and Strouse [1993], the E-type thermocouple (Nickel-Chromium alloy versus Copper-Nickel alloy) has the highest Seebeck coefficient of types of thermocouples in our temperature range. Thermocouple response time is a direct function of its bead size. According to the manufacturer, for a 0.25mm bead unsheathed E-type thermocouple the response time to a step function of 800 °C for reaching to 95% of the true value is 0.05s in still air and 0.004s in air flowing at 20 m/s.

The appropriate size of thermocouple for this purpose must be larger than the biggest pores for air flow through the sheet. Corte [1968] gave the range of pore size distribution of dry paper as 1-100 μm . As discussed in chapter 2, Polat et al. [1989] established that in through drying the bigger pores are opened to the flow of drying air at the beginning of drying while smaller pores start to contribute progressively as the sheet moisture content decreases. For handsheets of unbeaten, unfilled kraft pulp they showed that at the start of through drying the effective pore size for air flow was about 15 μm . Thus a thermocouple inside a 0.25 mm O.D. sheath is about 15 times the size of the biggest pores from which the air flow exits while also being very much smaller than the size of flocs in paper. As the through flow exits at a linear velocity in the range 0.18-0.35 m/s for the present experiments, a 0.125mm bead inside a 0.25mm sheath is estimated to have a very fast response time, 5-8 ms. This response time is fully adequate for the shortest drying time from the onset of the falling rate period to dryness, a few seconds.

In treating a through flow exhaust temperature as a local value a basic question is: how local is local? Figure 6.2 shows the precise dimensions of a thermocouple positioned within a honeycomb cell. The temperature measured could correspond to that between the extent of the sheet being the size of thermocouple sheath, 0.25 mm diameter, up to that of a honeycomb cell, about 4 mm across. For the range of flow rates and temperatures used

in this study, the linear velocity of through flow air exiting at the adiabatic saturation temperature is about 0.18 to 0.35 m/s. For the equivalent diameter of a honeycomb cell, the corresponding Reynolds numbers are in the range 48 to 93. As the flow exits the sheet as a plug flow and starts transition to a very low Reynolds number laminar flow it is evident that the amount of radial mixing will be negligible while advancing only 1mm (the paper-to-thermocouple spacing) in a honeycomb cell of hydraulic diameter about 4mm. This analysis indicates that the exhaust air temperatures obtained here correspond to those from a region of the sheet of diameter only slightly greater than 0.25 mm, and are therefore quite local.

6.2.3 Performance tests

A performance check of the thermocouples at various inlet air temperatures and flow rates was performed in order to assure the desired accuracy of $\pm 0.5^\circ\text{C}$. One of the

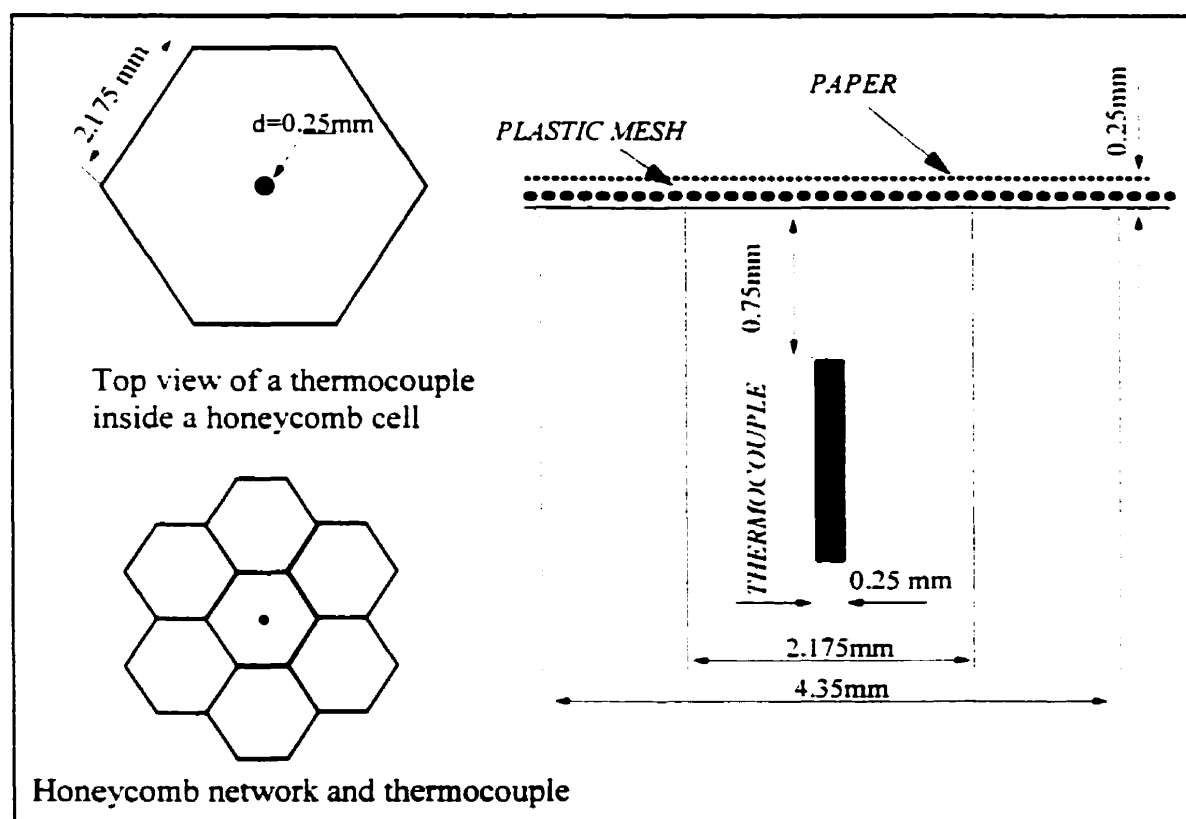


Fig. 6.2 Thermocouple layout

thermocouples was rendered inoperative during the small adjustments in positioning and was not replaced due to the long procedure required. Thus this assembly monitored the exit air temperature immediately below the sheet at 15 lateral positions.

A different type of test of the technique was made by through drying a sheet of highly uniform structure. For this test fiberglass filter paper was through dried and the local exit air temperature monitored. For better clarity Figure 6.3 shows the output of only 5 of the 15 thermocouples. For a sheet with such uniform structure the local exit air temperatures are seen to diverge very little during the falling rate drying period, the variation between thermocouple readings being only about $\pm 0.5^\circ\text{C}$. This graph establishes that the differences in local exit air temperature subsequently measured are directly related to nonuniformity in drying and sheet structure, not to the accuracy of temperature measurement.

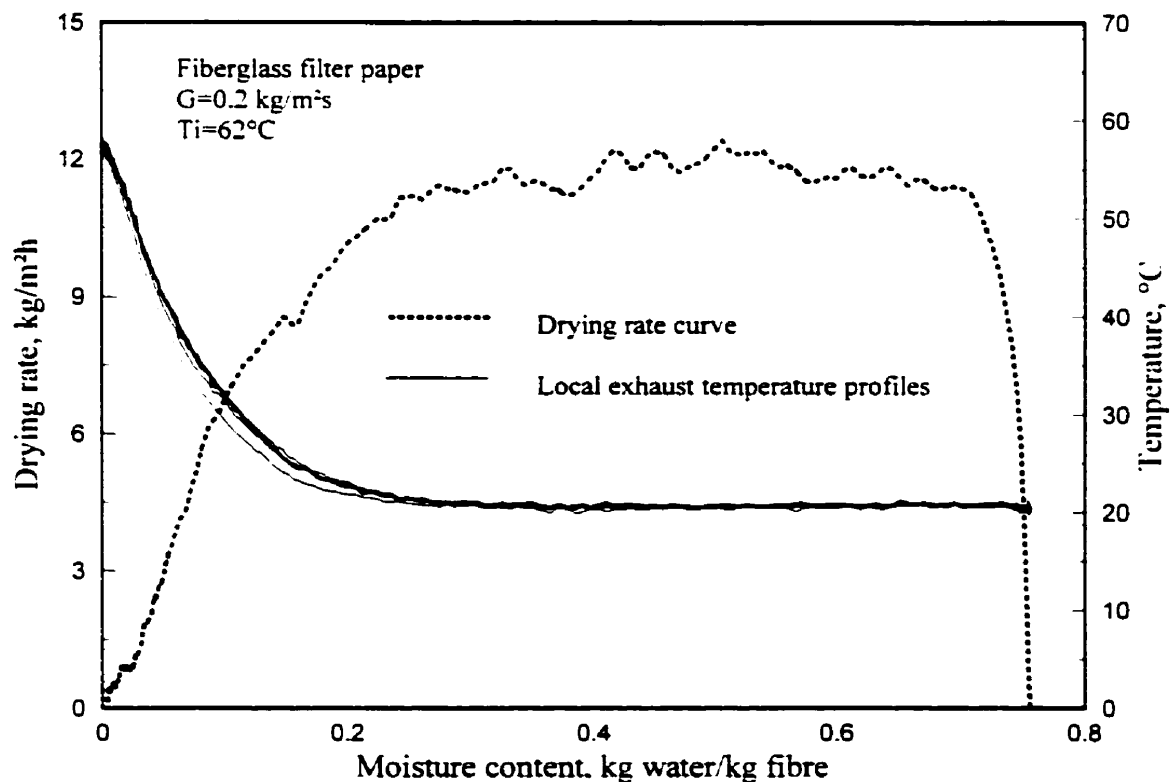


Fig. 6.3 Local exhaust air temperature for a uniform sheet

6.2.4 Demonstration results

A typical result for a kraft handsheet. Figure 6.4. shows the profiles of local exhaust air temperature at 15 lateral positions as well as the overall drying rate curve, both as a function of sheet average moisture content. Within the accuracy of the thermocouples there is negligible divergence of local exit air temperatures during the increasing rate and constant rate drying periods. During both of these drying periods the paper assumes the adiabatic saturation temperature, 23°C in this case, and the drying air changes to approach that temperature as it flows through this packed bed of wet fibres. All subsequent measurements showed this behavior. Exhaust air temperatures begin to increase at the moment the small element of paper just above the particular thermocouple enters its falling rate period. Thus the dispersion of local exhaust air temperature is seen on Figure 6.4 to increase to a maximum, then towards the end of the falling rate period it decreases to a very low level as the sheet approaches dryness.

In the previous chapter the standard deviation and coefficient of variation of local moisture content were introduced as the dimensional and nondimensional indices of

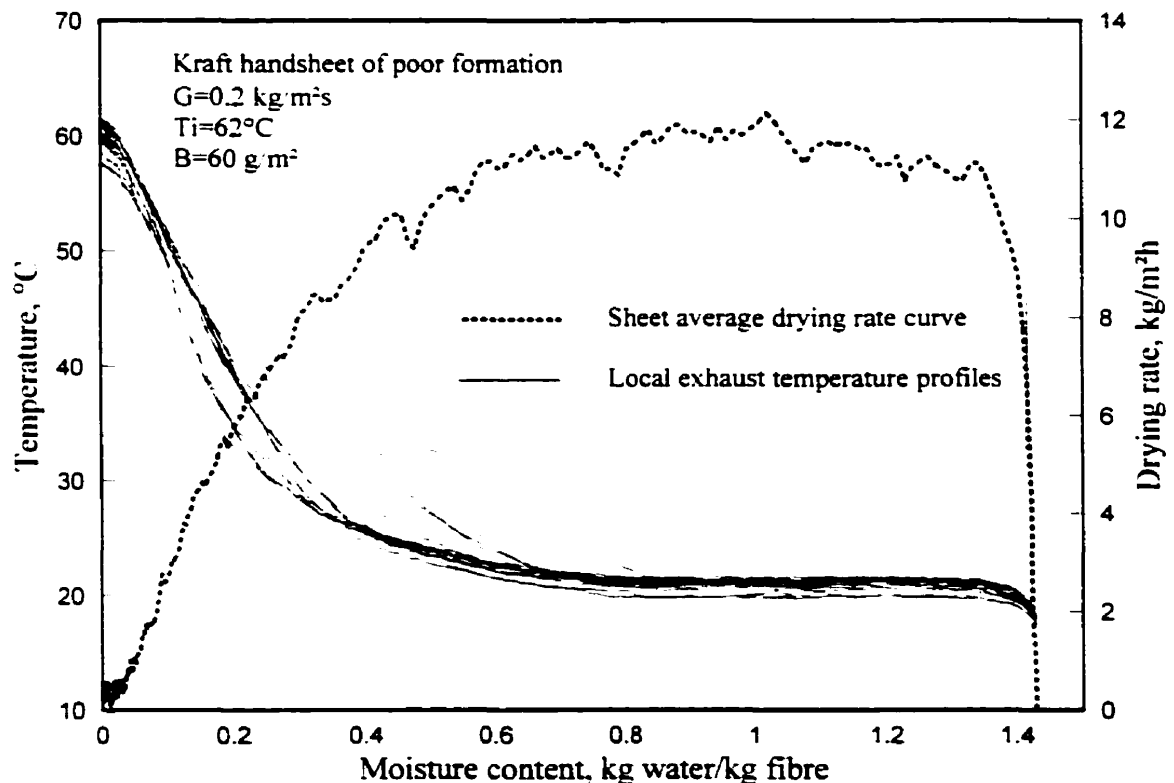


Fig. 6.4 Local exit air temperature profiles and drying rate curve

drying nonuniformity. The same bases are again used to characterize quantitatively the drying nonuniformity, but now applied to the distribution of local exhaust air temperature. An important difference is that exhaust air temperature T_e provides a continuous record of drying nonuniformity as a function of sheet average moisture content X rather than the single values at a particular moisture content for the technique using interrupted drying. The development and decay of drying nonuniformity is indicated here by reference to plots showing the dispersion of T_e as a function of X , such as Figure 6.4. For examining the effects of drying parameters however it is useful to have a single index of drying nonuniformity, for which the coefficient of variation of T_e at a particular value of X is used. Examination of the development and decay of the standard deviation of T_e , σ_{T_e} , indicated 0.4 kg water/kg fibre to be an appropriate value of sheet average X at which to calculate the coefficient of variation for T_e , in that by this point drying nonuniformity is developed substantially but has not yet started to decay.

The distribution of local exhaust air temperatures is generally shown as the 4σ value of this dispersion, thus indicating the range of T_e . This style of representation of drying nonuniformity is for convenience referred to here as the “ 4σ curve”. Paralleling the chapter 5 definition, the coefficient of variation of T_e at the chosen value of X is denoted the “index of drying nonuniformity”, I_{DNU} . An index reflecting the dispersion of T_e during the entire period of drying is $\int (4\sigma_T) dX$, denoted the “average drying nonuniformity index”, $\bar{I}_{DNU}$. For simplicity a satisfactory approximation of the $\bar{I}_{DNU}$ index is provided by the product of the maximum value of the 4σ dispersion of local exhaust temperature, $4\sigma_{max}$, and the width of 4σ - X curve at its half height, ΔX_{mid} . These methods of expressing drying nonuniformity are used in the presentation of results.

6.2.5 Experimental plan

Figure 6.5 and Tables 6.1 and 6.2 show the experimental plan, drying conditions and paper specifications. The initial moisture content was chosen to cover the range from that used for tissue and towel paper down to well below the fibre saturation point moisture content where all water is in the fibres with no free water in the pores. Sack

paper was chosen as a commercial grade of relatively high permeability and thus appropriate for through drying. Handsheets were used to study the effect of individual parameters on drying nonuniformity as these variables occur in only limited combinations in machine-formed paper, making it impossible to extract individual effects using papermachine sheets.

Table 6.1 Drying conditions

Inlet Air Temperature °C	Air Flow Rate std. m ³ /m ² s	Air Mass Flow Rate kg/m ² s	Initial Moisture Content kg water/kg fibres
60-80	0.20-0.40	0.18-0.35	0.4-4.0

Table 6.2 Specifications of paper tested

Paper Type	Basis Weight g/m ²	Pulp Furnish	Fibre Saturation Point, kg/kg
Towel paper	22.0	Bleached kraft pulp	0.68
Sack paper 7	46.7	Kraft pulp	0.88
Sack paper 11	100.3	Kraft pulp+20% Recycled fibres	0.99
Sack paper 13	54.7	Kraft pulp	0.87
Handsheets	20-100	Unbeaten kraft pulp	0.80

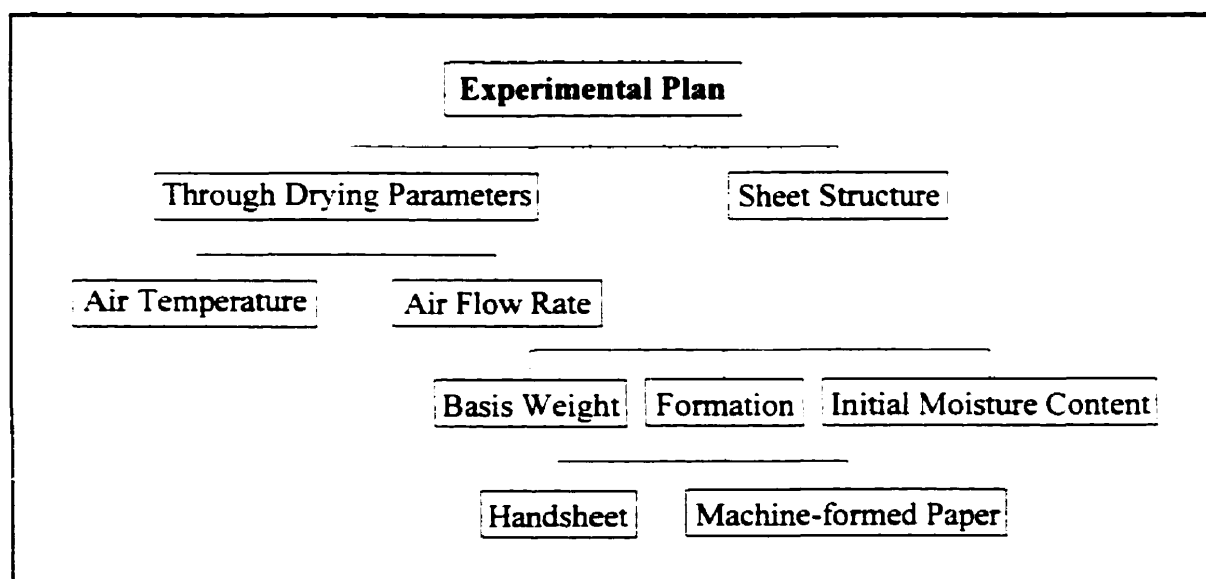


Fig. 6.5 Experimental plan for drying nonuniformity study

6.3 Effect of Sheet Structure

For one set of drying conditions the basis weight, initial moisture content and paper formation were in turn varied.

6.3.1. Paper basis weight

While the formation of all paper webs is nonuniform this degree of nonuniformity becomes progressively less for thicker paper because of the greater opportunity for compensation between nonuniform regions. During sheet formation, regions which are initially thinner have a lower resistance to flow, leading to an increased flow of the fibre suspension into these areas, thereby decreasing the nonuniformity of local grammage. Reduced nonuniformity of local grammage and permeability for heavier sheets would lead to lower nonuniformity in through drying. However at the other extreme when paper grammage is so low that the sheet structure is no longer a thin packed bed but approaches that of a screen, the nonuniformity in local through flow should also decrease.

Figure 6.6 provides quantitative verification of these expectations. The index of drying nonuniformity, I_{DNU} , decreases around a maximum value which is near a basis weight of 40 g/m^2 . The decrease in I_{DNU} for higher paper basis weight results from the lower nonuniformity of thicker sheets, while the decrease for lower grammage derives from the sheet structure changing from a thin packed bed towards that of a screen. On both sides of the maximum value of I_{DNU} the decreases are large, indicating a high sensitivity of drying nonuniformity with sheet grammage. The lower drying nonuniformity for the lightest weight handsheets is found also for the case of machine-formed towel paper of 19 g/m^2 basis weight. The higher drying nonuniformity for papermachine towel paper than the equivalent handsheets reflects greater nonuniformity of structure for papermachine formation. This expectation was confirmed using image analysis technique of Bernie and Douglas [1996] to characterize the formation of these sheets. This method reveals that the average value for the "floc formation index" (FFI) of five sheets is 2.13 for towel paper and 1.94 for the kraft handsheet, where the lower the FFI value, the better the sheet formation. This effect of sheet formation on drying nonuniformity for one case here is examined further in section 6.3.3.

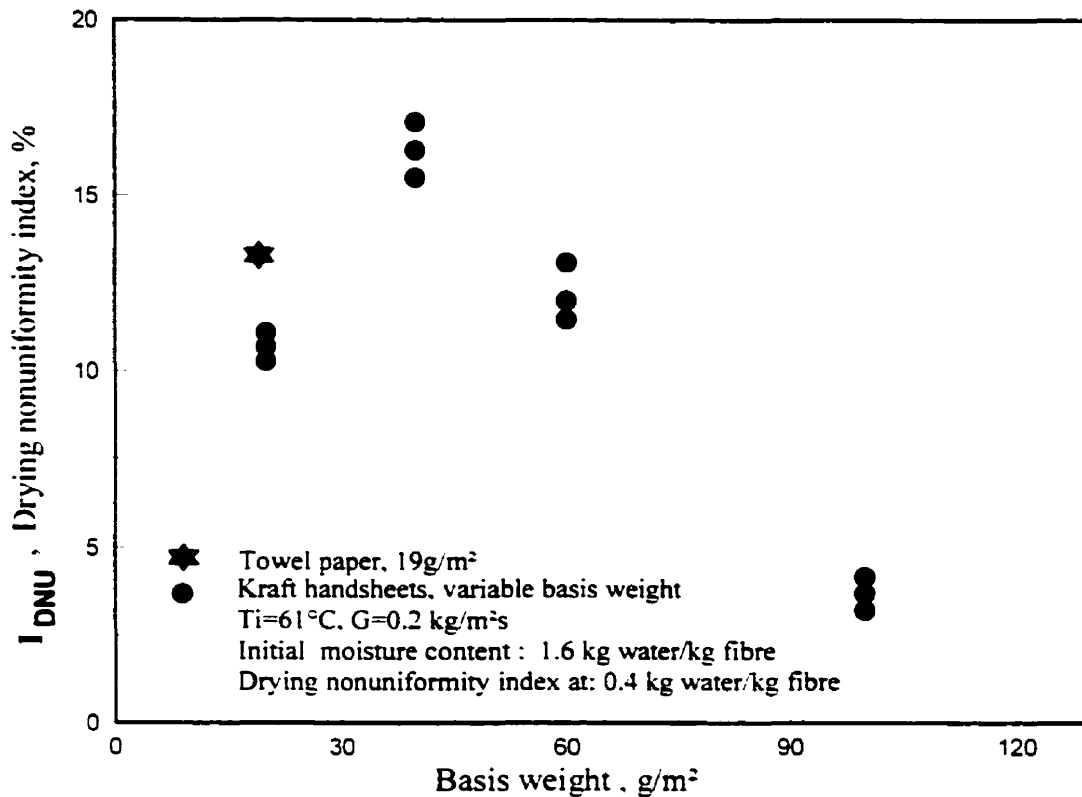


Fig. 6.6 Effect of paper basis weight

These results for the effect of basis weight the I_{DNU} for local exhaust air temperature are consistent with those in the previous chapter for the I_{DNU} for local moisture content. The sets of results by the two methods are consistent and suggest that the maximum in drying nonuniformity for this type of sheet occurs for basis weight in the range 30–40 g/m².

6.3.2. Initial moisture content

The structure of the wet sheet that is effective for the drying nonuniformity is the structure of the pores available for the through flow. As the air pore structure at moisture contents above that of the fibre saturation point, FSP, depends on the distribution of both the fibres and the pore water while that below this moisture content depends only on the dispersion of fibre local grammage, it should be expected that the effect on drying nonuniformity of sheet initial moisture content would be fundamentally different above and below the FSP value. This hypothesis was checked by drying sheets from industrially relevant values, 1.6 kg/kg, to low moisture contents of 0.4 kg/kg. The standard handsheets were made from unbleached kraft pulp having a fibre saturation point of about 0.8 kg/kg.

Figure 6.7 reveals that for sheets of initial moisture content X_0 above the fibre saturation point, the I_{DNU} value increases sharply with increasing initial moisture content, while below that point the nonuniformity index remains essentially independent of X_0 . At initial moisture contents giving no water in the pores, the FSP, the nonuniformity in drying is due only to the nonuniformity in fibre grammage. In the range of initial moisture content above the FSP the sensitivity of I_{DNU} to X_0 is so high that I_{DNU} is over 5 times as high at an initial moisture content of 1.6 kg/kg. The extent of free water in the pores clearly exerts a multiplying effect on the effect of local nonuniformity of fibre grammage.

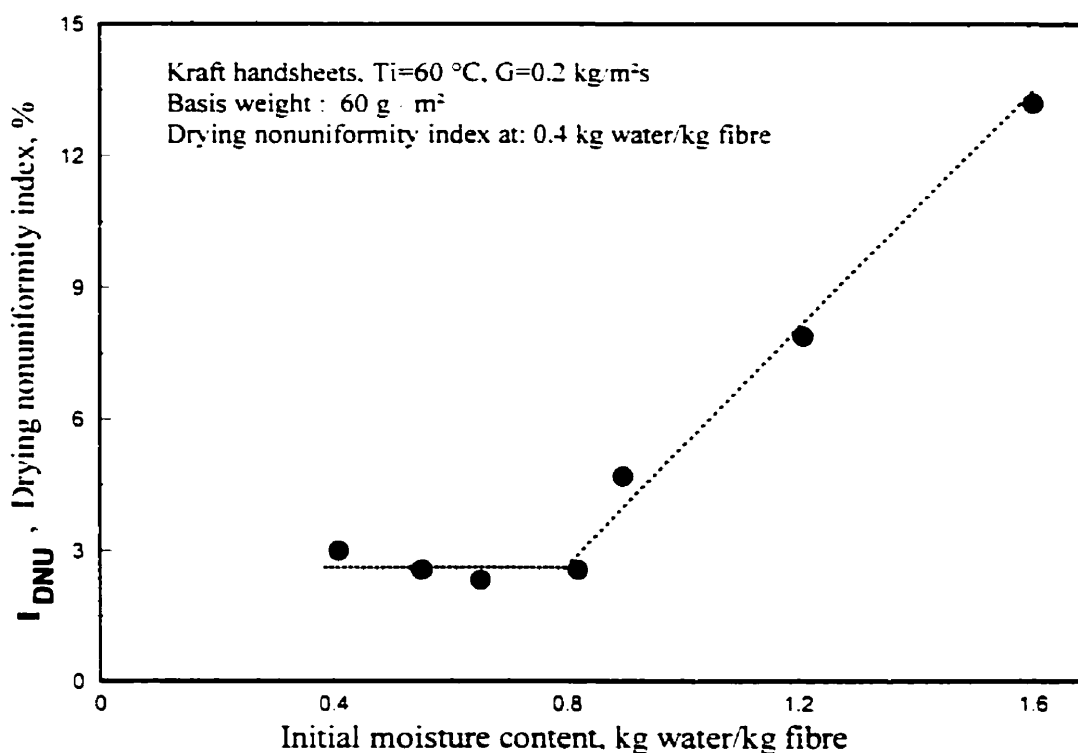


Fig.6.7 Effect of initial moisture content on I_{DNU} index

While Figure 6.7 shows the coefficient of variation of T_c at $X=0.4$ kg/kg, the complete development and decay of drying nonuniformity after the end of constant rate drying is shown by the 4σ range in dispersion of local exhaust air temperature on Figure 6.8. For clarity these complete curves are shown for just four of the initial moisture contents shown on Figure 6.7, the maximum and minimum values and at two values just around the FSP, 0.8 kg/kg for this kraft pulp. The results expressed as “average drying

nonuniformity index" defined in section 6.2.4 are shown in Figure 6.9. with the assumption that drying nonuniformity approaches 0 as $X \rightarrow 0$. This representation suggests that even below the FSP the initial moisture content has some limited effect on the drying nonuniformity. The product $(4\sigma_{\max})(\Delta X_{\text{mid}})$ is seen to be a satisfactory approximation of $\bar{I}_{\text{DNU}} = \int 4\sigma dX$ for use when the I_{DNU} index evaluated at $X=0.4$ kg water/kg fibre does not provide an adequate representation of the complete T_e dispersion curves as shown on Figure 6.8.

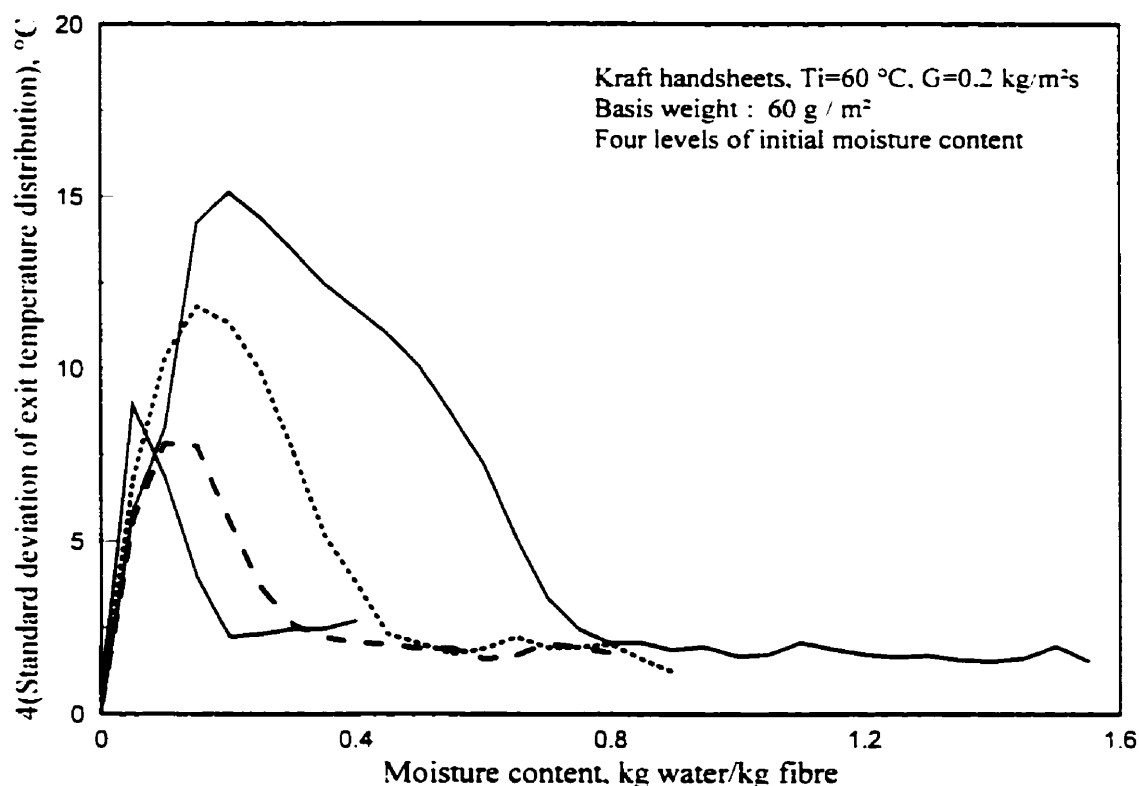


Fig. 6.8 Dispersion in local exit air temperature

The previous chapter showed the dispersion of sheet local moisture content increasing through a maximum value before converging to zero as the drying approaches completion. When now the dispersion of local T_e rather than local X is used, the nonuniformity of drying only becomes measurable as elements of the sheet being monitored enter individually their falling rate period. Thus for the same paper dried from about the same initial moisture content of 1.5-1.6 kg water/kg fibre, where the maximum in σ_X was reached on Figure 5.6 at about $X=0.5$ kg/kg, the maximum σ_{T_e} is as expected

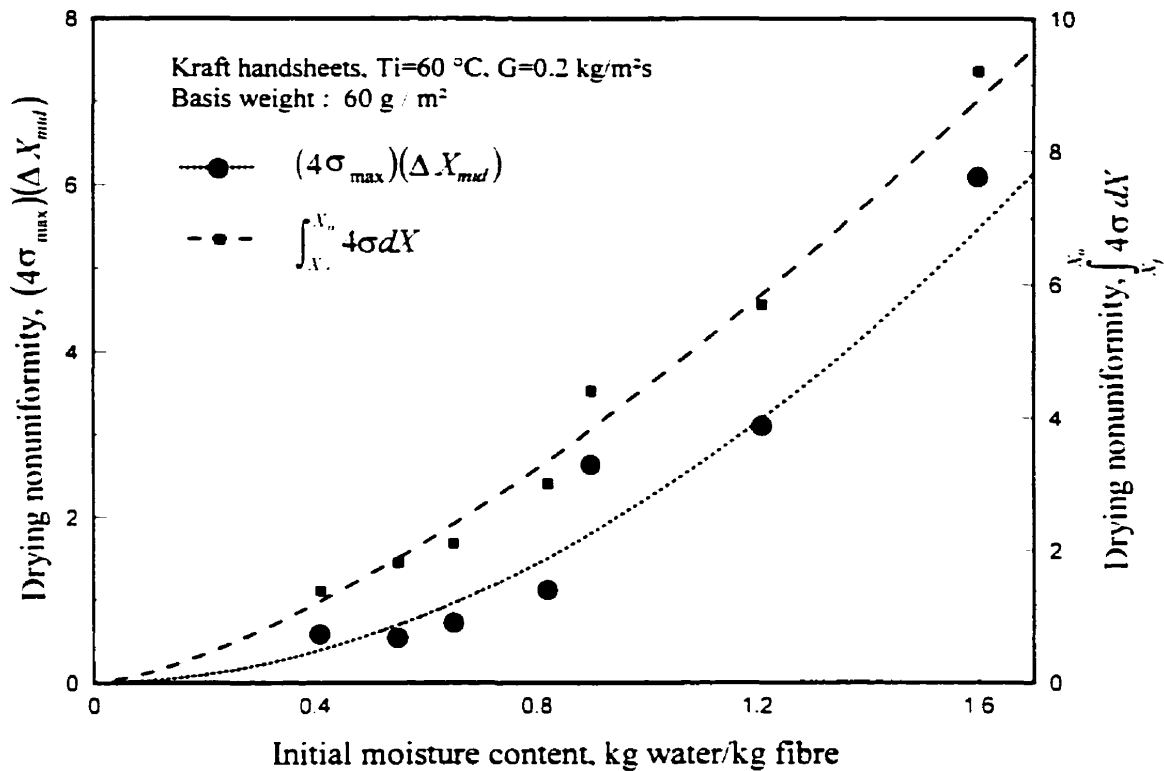


Fig. 6.9 Effect of initial moisture content on indices of drying nonuniformity

reached later, at about $X=0.2\text{ kg/kg}$ on Figure 6.8. Thus the dispersion of sheet local moisture content and of local exhaust temperature display the effects of nonuniformity of through air drying in different but related ways.

6.3.3. Formation

If the distribution of fibre in a sheet of paper were random the local grammage would be described by a Poisson distribution, but the process of forming the sheet leads to deviation from such a distribution. During through drying, regions of locally higher grammage have a locally lower permeability to flow, hence experience locally lower through flow rates and dry more slowly than the sheet average. Although the nonuniformity of local grammage has traditionally been quantified as the coefficient of variation of this distribution, Bernie and Douglas [1996] have shown that sheet formation may be described more sensitively by the floc formation index (FFI).

The effect of formation on nonuniformity in through air drying was studied using handsheets of different quality of formation obtained with the well known technique of varying the retention time of the fibre suspension in the making of handsheets. A retention time, R_t of 1s produces a sheet of better formation than that from a papermachine, the quality of formation decreasing as the time for fibre flocculation is increased. For these sheets Table 6.3 documents the retention times, FFI values and the I_{DNU} values calculated at $X=0.4$ kg/kg., while Figure 6.10 shows the 4σ -X curves of the dispersion of local exhaust air temperature for handsheets of various quality of formation dried similarly from initial moisture contents of about 1.6 kg water/kg fibre. The extent of drying nonuniformity as evidenced by the complete 4σ -X curves and the I_{DNU} value at $X=0.4$ kg/kg parallels the FFI measure of quality of sheet formation. Thus there is a large reduction in drying nonuniformity for the decrease in FFI from 12.8 to 4.5, but negligible further nonuniformity reduction when the formation is improved to better than machine-formed quality at an FFI value of 3.2.

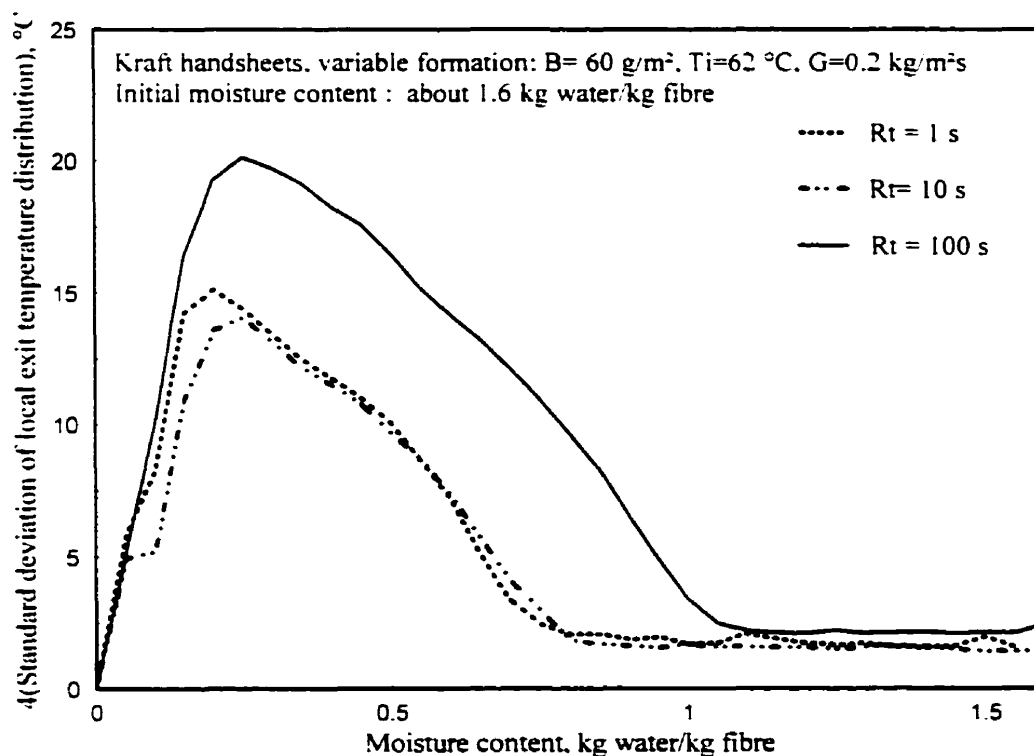


Fig. 6.10 Effect of formation on extent of drying nonuniformity

Table 6.3 Effect of formation on drying nonuniformity index

$T_{inlet}=62^{\circ}\text{C}$, $G=0.2\text{ kg/m}^2\text{s}$, $R_c=11.2\text{ kg/m}^2\text{h}$			
Retention time, s	X_o , kg water/kg fibre	Floc Formation Index, FFI	I_{DNU} , %
1	1.6	3.2	13.1
10	1.66	4.5	13.0
100	1.58	12.	18.2

As quality of sheet formation drops, drying time increases due both to the earlier start of falling rate drying period and to the lower drying rates during that period, as discussed in Chapter 3. Figure 6.11 shows that local elements of the poor formation quality sheet begin entering the falling rate period after only 13s of drying while the good quality sheet is seen to remain at the constant drying rate until about 26 s of drying time. To reach a moisture content of 0.05 kg water/kg fibre the poor quality sheet requires 21% longer drying time (52s vs. 41s).

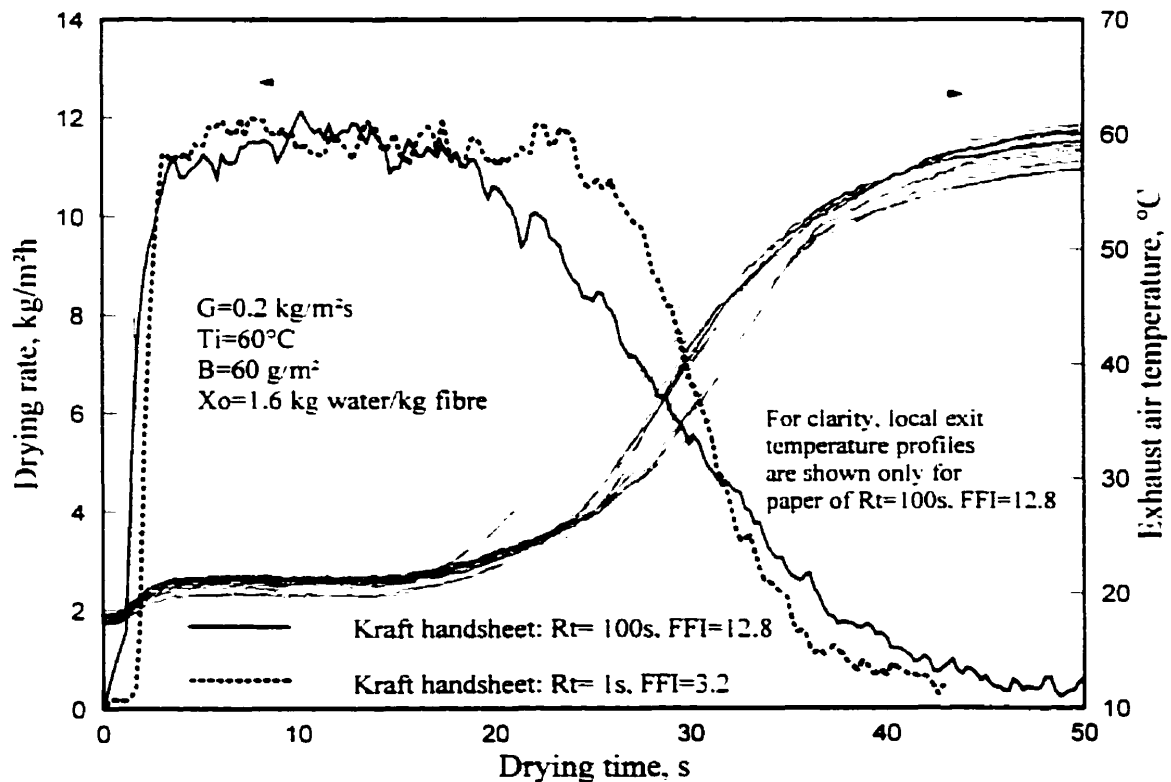


Fig. 6.11 Effect of formation on drying rate and drying time

6.4 Effect of Through Drying Parameters

It is expected that the nonuniformity of through drying would increase with drying intensity as controlled either by the temperature or through flow rate of the drying air. The effect of air flow rate was investigated with experiments for standard kraft handsheets dried at 0.2 and 0.4 kg/m²s. Table 6.4 shows that although the index of nonuniformity, I_{DNU} , was unchanged within the accuracy of measurement, the more sensitive average index of drying nonuniformity, $\bar{I}_{\text{DNU}}$, increased by about 10% for this increase in drying intensity.

Table 6.4 Effect of inlet air flow rate

X_0 , kg water/kg fibre	T_{inlet} , °C	G , kg/m ² s	R_c , kg/m ² h	I_{DNU} , %	$\int 4\sigma dX$
1.6	60	0.2	11.2	13.1	9.2
1.6	60	0.4	25.2	12.7	10.2

The driving force for heat transfer from the beginning of through drying is the difference between the inlet air temperature and its corresponding adiabatic saturation temperature, i.e. $T_i - T_{\text{as}}$. Constrained by the plexiglas material of construction of the dryer, the inlet air temperature was varied only between 60 and 80°C. As the maximum driving force corresponding to these two drying air temperatures is not greatly different, the corresponding values of the index of drying nonuniformity, I_{DNU} , listed in Table 6.5 are within the experimental variability of this determination. The results of Table 6.4 show that when drying intensity is doubled, the $\bar{I}_{\text{DNU}}$ value increases by about 10%. Thus in industrial practice with temperatures of the through drying air in the range of 200-300 °C and the drying intensity an order of magnitude higher, the drying nonuniformity would be expected to be significantly higher.

Table 6.5 Effect of Inlet Air Temperature

X_0 , kg water/kg fibre	T_{inlet} , °C	$T_i - T_{\text{as}}$, °C	G , kg/m ² s	R_c , kg/m ² h	I_{DNU} , %
1.60	60	38	0.2	11.2	13.1
1.73	80	53	0.2	14.0	12.4

6.5 Drying Nonuniformity for Machine-Formed Paper

6.5.1 Towel paper

With these indications of the sensitivity of local drying nonuniformity to quality of sheet formation this study was extended to machine-formed paper with its quite different structure. Because through drying is widely used for drying light grades such as tissue and toweling, the drying nonuniformity of such paper was determined. Figure 6.12 is very informative in showing that there is no sheet average constant drying rate period and, consistent with this finding, not one of the local exit air temperature profiles shows even a short period of locally constant rate drying. All such temperatures increasing from the onset of drying. From the Table 6.6 listing of test conditions and specifications of towel paper and the equivalent handsheet, there is negligible difference in either quality of formation or drying nonuniformity index within the experimental variability.

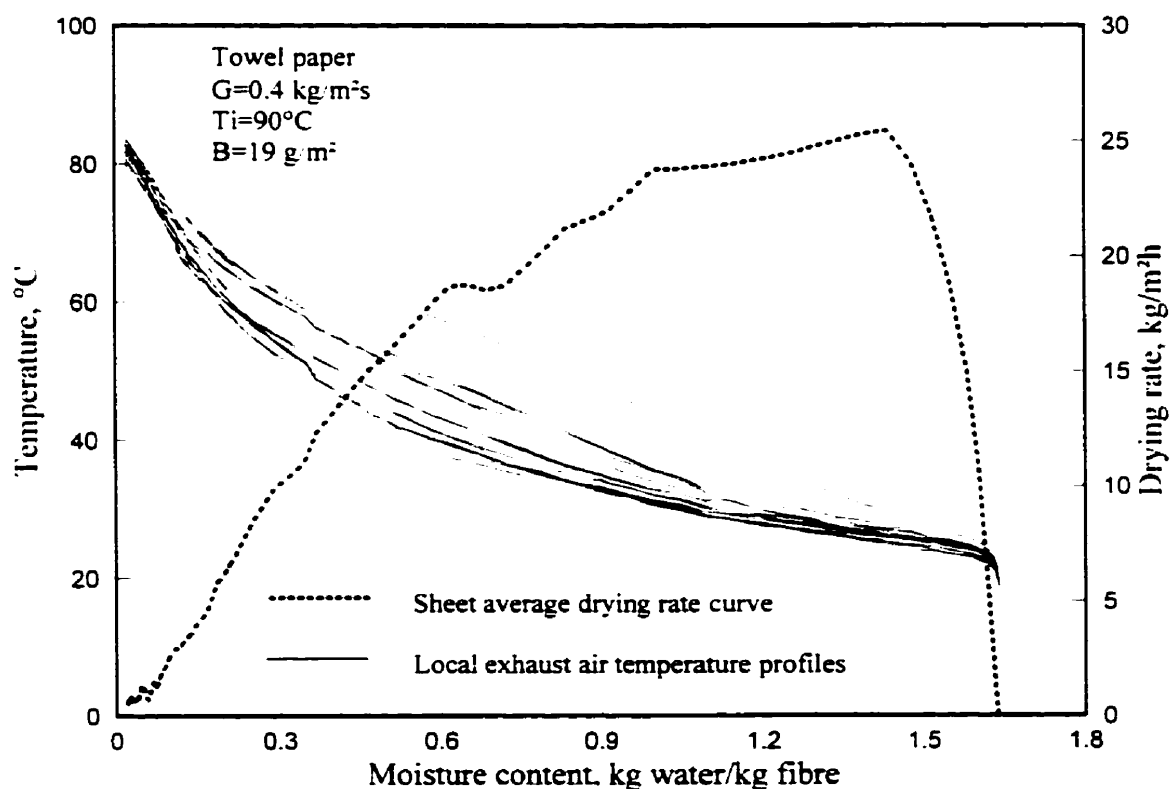
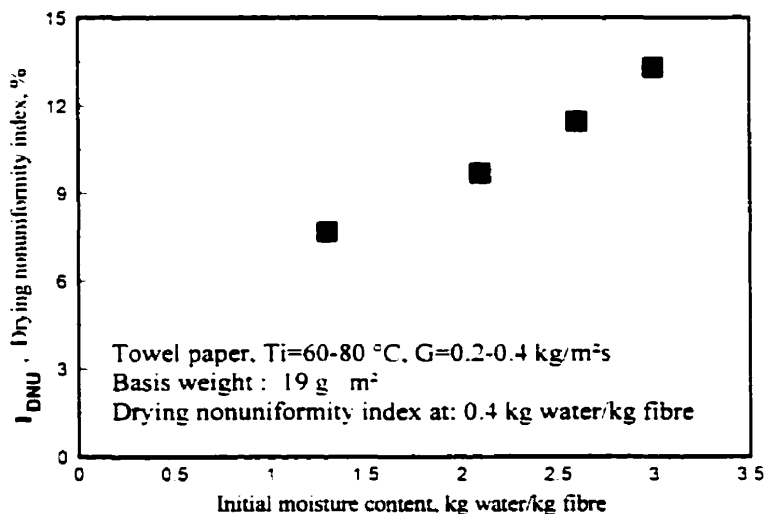


Fig 6.12 Drying nonuniformity and drying rate for towel paper

Table 6.6: Comparison of nonuniformity of a towel paper with a handsheet

$T_{\text{inlet}}=62^{\circ}\text{C}$, $G=0.2 \text{ kg/m}^2\text{s}$				
Paper Type	Grammage, g/m^2	X_0 , kg water/kg fibre	FFI	I_{DNU} , %
Towel paper	19	3.07	1.8	13.3
Handsheet	20	2.70	1.9	13.7

As such permeable sheets are often through dried industrially in two stages. Figure 6.13 shows the effect of initial moisture content on drying nonuniformity. Although there is a consistent decrease in I_{DNU} with decrease in X_0 this effect for towel paper is very much smaller than that observed on Figure 6.7 for 60 g/m^2 kraft handsheets, paralleling what was reported in Chapter 5 when local moisture content was used as the criterion. As was pointed out in section 6.3.1, sheets of 20 g/m^2 are effectively screens, for which the sheet thickness during drying is in the order of only 1 to 2 d_p . However the 60 g/m^2 sheets of Figures 6.7 - 6.11 are thin packed beds, about 3 to 7 d_p thick during drying according to the Polat et al. [1989] determination of the characteristic dimension d_p as a function of moisture content.

**Fig. 6.13 Effect of initial moisture content for towel**

6.5.2 Sack paper

For the potential future use of through drying of heavier grades of paper the sheet permeability is a key criterion because of the high capital and operating cost to provide air flow through the wet paper. Sack paper could be a potential candidate for through air drying because, in contrast to printing grades, finely divided inorganic filler is not added and it is not made from furnishes of significant content of mechanical pulp with the associated high content of pulp fines. Due to the high strength required for sack paper it is made of kraft

pulp or, more recently, of blends with small amounts of mechanical pulp. Thus sack paper is of relatively high permeability compared to printing papers.

Table 6.7 shows the specifications of the three commercial sack papers used and the drying nonuniformity index determined under the same conditions and from similar initial moisture contents. Again the variation in the I_{DNU} parallels the floc formation index.

Table 6.7: Index of drying nonuniformity for sack papers

$T_{\text{inlet}}=62^{\circ}\text{C}$, $G=0.2 \text{ kg/m}^2\text{s}$, $R_c=11.5 \text{ kg/m}^2\text{h}$					
Paper Type	Grammage, g/m^2	Permeability, m^2	X_0 , kg/kg	FFI	I_{DNU} , %
Sack paper 7	46.7	3.6×10^{-14}	1.59	8.1	10.3
Sack paper 11	100.3	12.1×10^{-14}	1.60	9.0	12.2
Sack paper 13	54.7	2.4×10^{-14}	1.65	9.5	12.8

Figure 6.14 shows a typical result which documents the development and decay of drying nonuniformity for sack paper 11. After a short constant drying rate period during which there is negligible dispersion in local exhaust air temperature, the sheet average falling rate drying period starts, at X_c of 1.14 kg/kg , simultaneously with first small area of the sheet entering falling rate drying as indicated by the first exit air temperature to diverge from the constant rate condition.

It is of interest to compare the drying nonuniformity of machine-formed sack paper with a kraft handsheet of the same basis weight and same formation. By changing retention time, a handsheet of 108 g/m^2 basis weight was made with a floc formation index of 7, very close to that of the target sack paper. Table 6.8 indicates that these closely matched sheets have a quite similar drying nonuniformity behavior, with the sheet of slightly better formation (FFI of 7.0) having predictably a slightly lower drying nonuniformity (I_{DNU} of 10.9%).

The effects of some parameters studied previously for kraft handsheets were examined again for machine-formed paper. Thus Figure 6.15 shows for one sack paper the effect of drying intensity, indicated by the value of the constant drying rate R_c . This effect is shown for two levels of initial moisture content, for X_0 of 1.6 kg/kg , typical of operation in some paper mills, and a lower level, about that of the fiber saturation point,

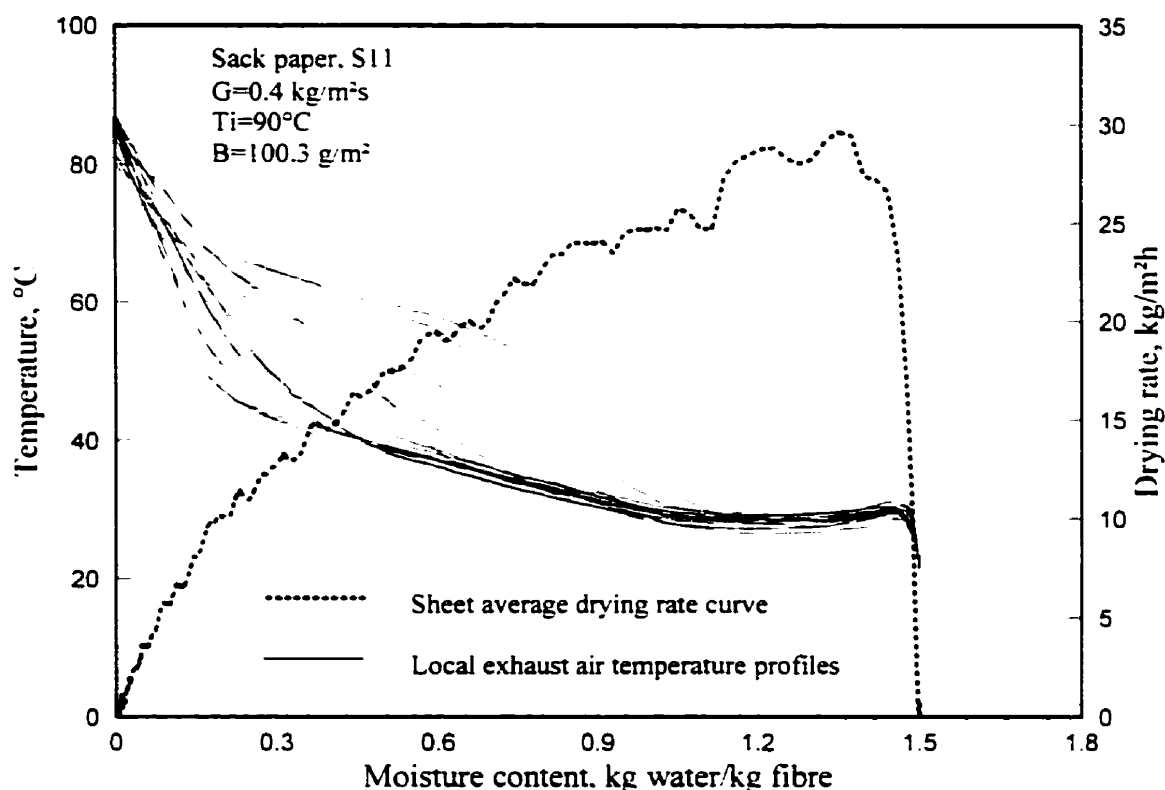


Fig 6.14 Drying nonuniformity and drying rate for sack paper

FSP. The sensitivity of the index of drying nonuniformity to initial moisture content of the 47 g/m² sack paper shown on Figure 6.16 is greater than that for 19 g/m² towel paper (Figure 6.13) but less than that of 60 g/m² kraft handsheets (Figure 6.7). For the case of sack paper it seen that the drying nonuniformity can be reduced by almost one-half if drying were started at the fibre saturation point of about 0.8 kg water/kg fibre instead of at 1.6 kg/kg.

Table 6.8: Drying nonuniformity comparison of sack paper with a matching handsheet

$T_{inlet}=62^{\circ}\text{C}$, $G=0.2 \text{ kg/m}^2\text{s}$, $R_c=11.5 \text{ kg/m}^2\text{h}$				
Paper Type	Grammage, g/m ²	X_o , kg water/kg fibre	FFI	I_{DNU} , %
Sack paper 11	100	1.6	9.0	12.2
Handsheet	108	1.6	7.0	10.9

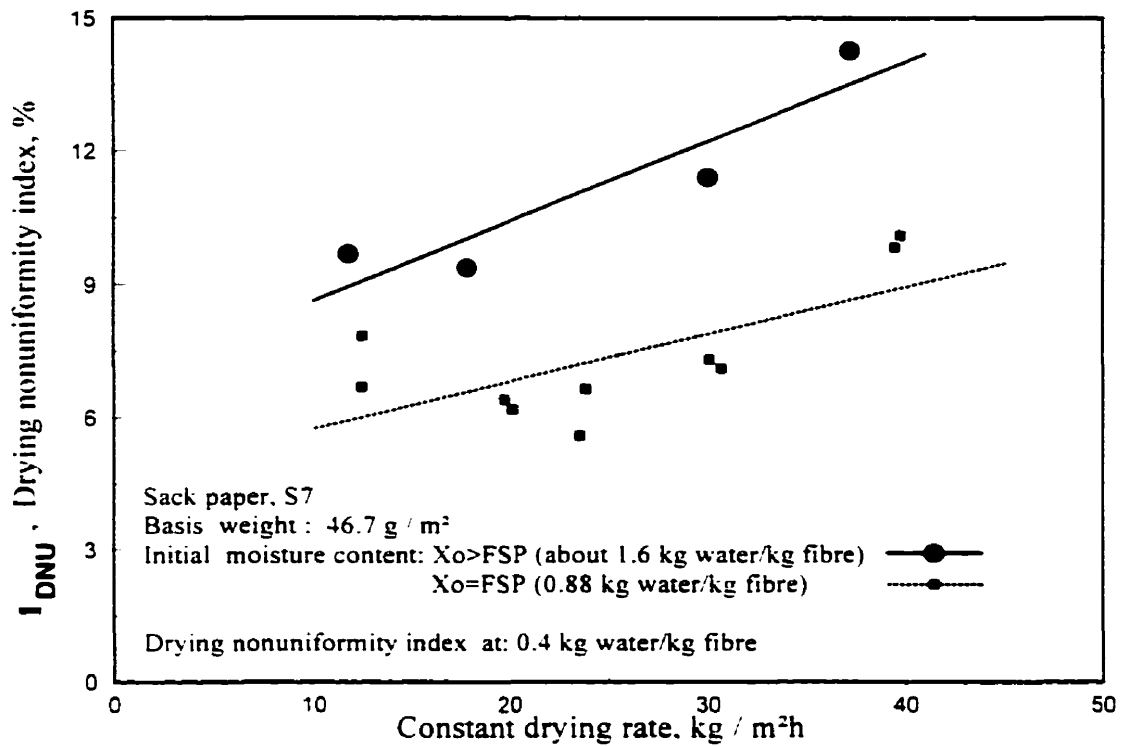


Fig. 6.15 Effect of drying intensity on drying nonuniformity of sack paper

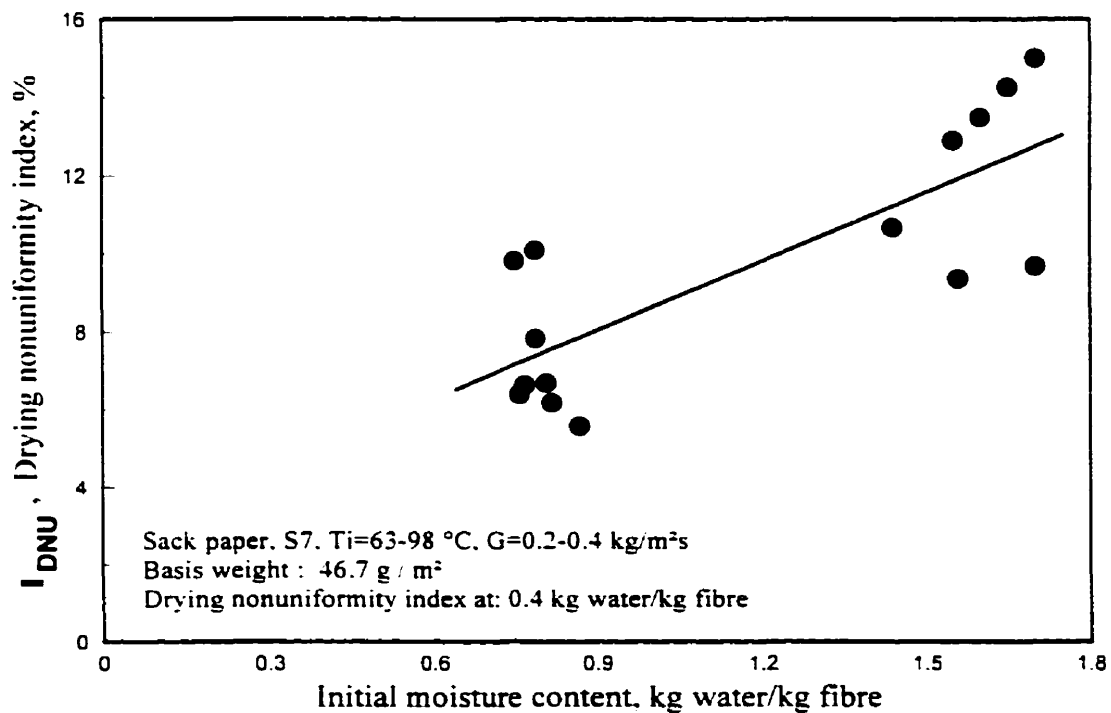


Fig. 6.16 Effect of initial moisture content on drying nonuniformity of sack paper

6.6 Local Grammage - Local Exhaust Air Temperature

An unsuccessful attempt was made to relate local exit air temperatures with local grammage at the same position, as had been successfully done for local sheet moisture content, reported in the previous chapter. Positions of the thermocouples were determined to an accuracy of 0.5 mm by using a magnifier with light transmitted through the sheet. When local grammage of the sheet was determined for regions 1.1 mm square around the thermocouple positions no correlation was found between these local grammage values and the corresponding local exit air temperatures. The evident explanation is that the thermocouples were effected by a much smaller area of the sheet than the 1.1 mm square. With determination of local grammage by image analysis using a 0.25mm pixel size, a 1.1 mm square contains about 25 pixels, over which local grammage varied from 50 to 68 g/m² for a sheet average value of basis weight of 60 g/m². As a 0.25 mm diameter thermocouple could be affected by as little sheet area as the size of one pixel, while the position of the thermocouple could be determined to about 0.5 mm, it was therefore impossible to determine the local grammage at the position of a local exit air temperature measurement.

6.7 Effect of Drying Nonuniformity on Critical Moisture Content, X_c

In addition to the thermodynamic and transport phenomena factors which can contribute to the onset of the falling rate drying period, discussed in chapters 2 and 3, it was hypothesized that the local nonuniformity in through drying could be an additional factor. As the present technique of measurement of local exhaust air temperature is so sensitive to any drop in local drying rate, this hypothesis may now be tested. Figure 6.17 shows local exit temperature profiles for a kraft handsheet of poor formation with $R_t=100s$. Where standard handsheets made with $R_t=1s$ and dried under the same conditions show critical moisture contents of about 0.7 kg/kg, this sheet has a much higher X_c , about 1.0 kg/kg. The reason for the unusually high value of X_c is clear from the exhaust air temperature traces on Figure 6.17, i.e. some low grammage local regions

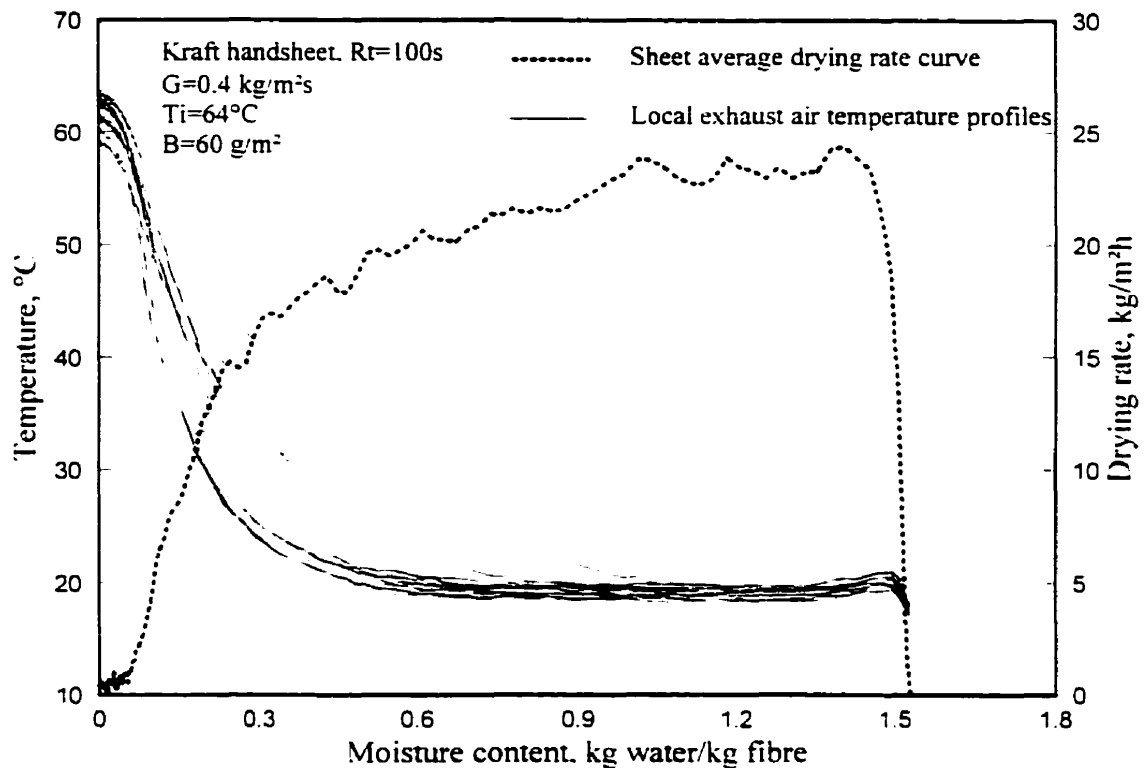


Fig. 6.17 Effect of nonuniformity in drying on onset of falling rate drying period

of this sheet entered the falling rate unusually early in the drying, at 1.0 kg/kg, thereby raising the sheet average value X_c to this value.

While the above example illustrates the effect of local nonuniformity on critical moisture content and the falling rate curve for a single handsheet, Figure 6.18 demonstrates this relationship for a number of sheets of commercial sack paper. Here the drying nonuniformity index I_{DNU} has been changed by varying the air through flow rate and temperature. Figure 6.18 shows the consistent and highly sensitive I_{DNU} - X_c relationship, i.e. the higher the drying nonuniformity, the more disadvantageous the sheet average critical moisture content. The value of $X_c/X_0=0.45$ as $I_{DNU} \rightarrow 0$ derives from the drying rate curves for the many hundreds of sheets of paper that have been through air dried by Polat [1989], Chen [1994] and in the work reported in chapters 2 and 3 of the present study. Polat and Chen worked with the best formation quality of kraft handsheets, so the value of $X_c/X_0=0.45$ from their work corresponds to the limit for little drying nonuniformity. The work reported here in chapter 2 is for machine-formed paper and in

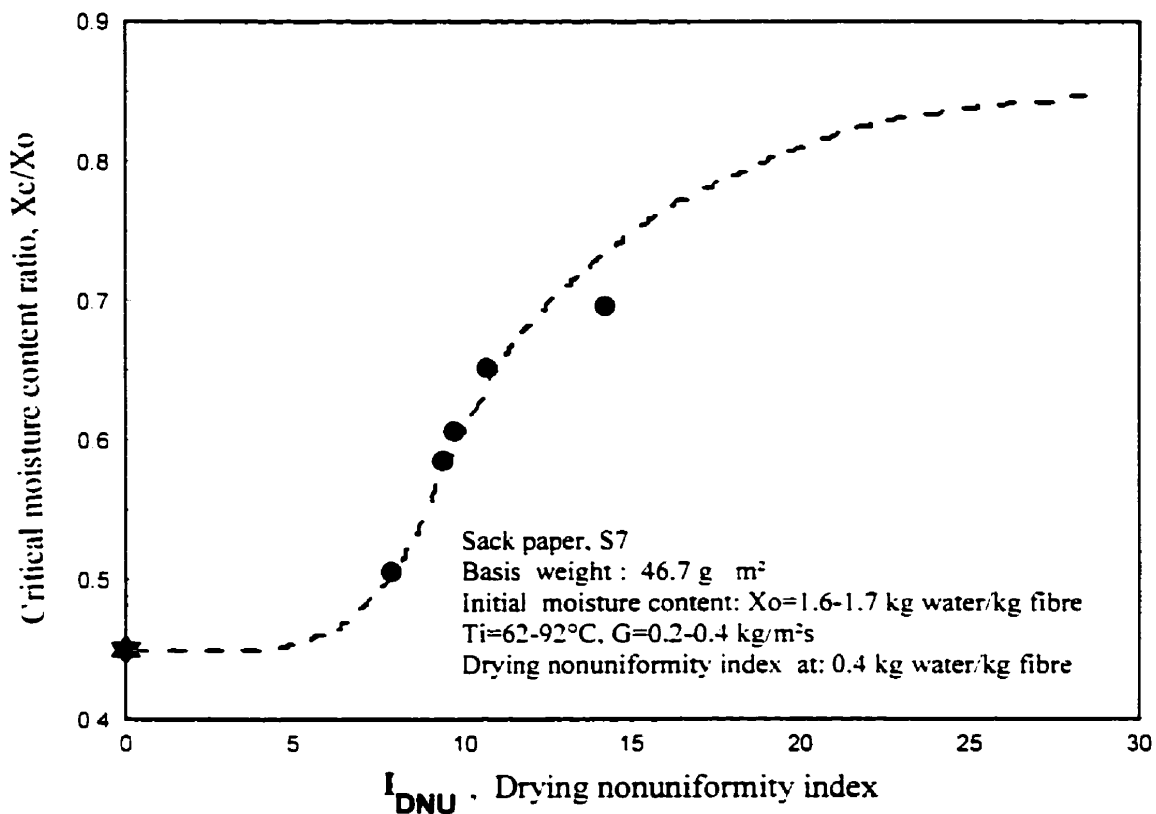


Fig. 6.18 Effect of drying nonuniformity on X_c for sack paper

chapter 3 is with special handsheets for the simulation of commercial papermaking parameters. Although the formation of papermachine sheets is not as uniform as handsheets, the experiments of chapter 2 and 3 were carried out at low intensity drying conditions for which there is negligible drying nonuniformity, and hence the average value of $X_c/X_0=0.45$ provides an overall representation for these types of paper dried at low intensity conditions. Thus on Figure 6.18 the $X_c/X_0 - I_{DNU}$ relation is shown asymptotic to the $X_c/X_0=0.45$ value as $I_{DNU} \rightarrow 0$.

For the upper limit of X_c/X_0 on Figure 6.18 as I_{DNU} becomes large, the effect of conditions such as high drying intensity and poor sheet formation on increasing the value of X_c/X_0 is to reduce and then eliminate the constant drying rate period so that the drying proceeds directly from the increasing to the falling rate period. For the Figure 6.18 specification for X_0 of 1.6-1.7 kg water/kg fibre, the drying period diagram, Figure 4.19, shows that the condition of $X_c=X_i$ as the constant rate period vanishes corresponds to about $X_i/X_0 = X_c/X_0=0.85$. Thus on Figure 6.18 the upper limit is for the line to approach

asymptotic to about $X_i/X_o=0.85$ at some high value of the index of drying nonuniformity. As reasons of dryer size and paper quality center the practical interest on the lower range of I_{DNU} , there is no need to determine the line precisely in the high I_{DNU} range. The X_c/X_o - I_{DNU} line will be specific to the furnish, formation and grammage of the paper, with the line on Figure 6.18 being specific to the commercial 47 g/m² sack paper tested.

Thus the representation of Figure 6.18 provides a comprehensive perspective for the effect of drying nonuniformity on critical moisture content, and does so in a form that relates the work of present study with the results of the theses of Polat [1989] and Chen [1994] on through air drying.

6.8 Comparison of Drying Nonuniformity Techniques

The work of these two chapters may now be over-viewed. Characterizing of drying nonuniformity with scanning the local sheet moisture content of incompletely dried paper is a general technique but requires considerable effort to develop the history of local nonuniformity throughout the drying. The indirect technique based on measurement of local exhaust air temperatures at a number of positions is unique to through air drying, and it can provide a continuous record over the entire drying from wet to dry. However this technique is unable to show any difference in sheet local conditions until the sheet enters the falling drying rate period and exit air temperatures start to rise. The two coefficients of variation, I_{DNU} , being for different variables, naturally do not have the same value but, as detailed below, show the same trends.

Table 6.9 compares the conclusions as to drying nonuniformity resulting from each drying process parameter and sheet structure parameter as determined by these two methods. Although these two complementary techniques are basically different, both lead to the same conclusions as to the importance of the effects for each parameter. The consistency in results obtained with two quite different techniques confirms both the accuracy and relevance of each technique and the significance of the effects of these various parameters on local nonuniformity in through air drying.

Table 6.9 Comparison of methods of characterizing drying nonuniformity

Parameter	Direct Technique Local sheet moisture content	Indirect Technique Local exhaust air temperature
Initial moisture content	Above FSP: Very significant Below FSP: Low significance	Above FSP: Very significant Below FSP: Low significance
Formation	Significant	Significant
Grammage	Significant	Significant
MD-CD dimension	Always nonuniformity is higher in CD than MD dimension	Not tested
Drying intensity	Significant	Significant

6.9 Summary and Conclusion

- (1) An accurate technique uniquely related to through air drying, continuous monitoring of the local exit air temperature at multiple locations under the sheet, was developed and successfully applied to characterize local nonuniformity of through drying for handsheets and machine-formed paper.
- (2) A limitation of the technique is that it provides no indication of drying nonuniformity occurring prior to the onset of falling rate drying at the monitored region because until then the exit air temperature is independent of any local moisture nonuniformity.
- (3) The most complete record is provided by the development and then the decay of the dispersion in local exhaust air temperature as a function of sheet average moisture content. The coefficient of variation of this distribution evaluated at an appropriate value of sheet average moisture content, taken here as 0.4 kg/kg, was defined as the index of drying nonuniformity, I_{DNU} . As the I_{DNU} has the disadvantage of representing drying nonuniformity at one point during drying, a more representative average index of drying nonuniformity is provided by $\int 4\sigma dX$ over the full extent of drying, which may be approximated by the product $(\sigma_{\max})(\Delta X_{\text{mid}})$.
- (4) As the effects on drying local nonuniformity of through drying process parameters and paper structure parameters obtained by measuring sheet local moisture

content, as reported in the previous chapter, were confirmed by this independent technique, a description of those effects is not repeated.

- (5) It was demonstrated that by producing a handsheet from the same furnish as for a machine-formed sheet, of the same basis weight, and with the quality of formation matched by varying the handsheet making conditions, the extent of drying nonuniformity of papermachine paper could be reproduced and documented using such a handsheet. This technique was demonstrated for two cases, commercial towel and sack paper.
- (6) Experiments with machine-formed paper and handsheets established the effect of local nonuniformity on advancing the start of the falling rate period, which reduces the sheet average drying rate and increases drying time or dryer size. The strong and sensitive relation shown between critical moisture content and drying nonuniformity index provides an integrated view in a form which also integrates the work of present study with the results of the theses of Polat [1989] and Chen [1994] on through air drying.
- (7) As a general conclusion to the studies of local nonuniformity effects on through air drying characteristics, both momentum and heat and mass transfer, if through drying is to be used effectively for drying grades of paper heavier than its present use for tissue and toweling, local nonuniformity considerations indicate the use of lower drying intensity conditions and starting through drying at a low moisture content. Through drying should not be started at initial moisture contents higher than the FSP to avoid both the low permeability caused by free water in the pores and excessive local drying nonuniformity which reduces the drying rate by increasing the critical moisture. For a sheet of specific grammage and quality of formation, there is an interrelationship between initial moisture content, drying intensity and drying nonuniformity. The latter is likely to be constrained by product quality considerations, an aspect beyond the scope of present study. In this case there remains an interplay between initial moisture content and drying intensity, i.e. the higher one of these variables is, the lower must be the other variable in compensation.

CHAPTER 7

Conclusions

7.1 Contributions to Knowledge

Through air drying characteristics of machine-formed paper

Both the momentum transport and drying rate characteristics of *semi-permeable* printing and heavier papers were determined. Momentum transport is very sensitive to any change that affects the wet sheet structure but the effects on drying rate are limited.

(1) Permeability

The permeability of dry and moist uncalendered machine-formed paper was determined using the proper momentum transport equation. This specialized equipment provides not only the permeability for dry paper, which could be determined nearly as accurately by test instruments now used in industry but, because of being designed for use with wet paper, enables determination of the permeability - moisture content relationship not obtainable with commercial instruments which are limited to dry paper testing. Determination of the increase of permeability of machine-formed paper after a wetting-drying cycle, important for all laboratory research involving the rewetting of dry paper, showed that for TMP paper this increase was much smaller than that previously reported for unfilled kraft paper.

Correlations of modified permeability, k/L , with paper moisture content were presented. Also a generalized permeability-moisture content relation was obtained for machine-formed papers and kraft handsheets for approximating the permeability of moist paper when its only dry permeability is obtainable with commercial test instruments.

(2) Specific surface

With various types of paper the comparative results obtained for specific surface determined from the Kozeny-Carman equation, the light scattering coefficient method and mercury porosimetry established that the Kozeny-Carman equation substantially over predicts the specific surface of paper containing fines. This is a major effect, with specific surface being over-predicted by over 100% with as little as 5% fines content.

(3) Characteristic dimension

The characteristic dimension d_p for flow through paper, required for the Reynolds, Sherwood, Nusselt and Peclet numbers used in transport phenomena treatment of through drying, was determined for the first time for papermachine paper. Having d_p enables use of the Reynolds number-friction factor alternative to permeability in characterizing momentum transport through paper.

(4) Through drying rates

Determination of more than 400 drying rate curves for 10 types of machine-formed paper established that of the five parameters required to model complete drying rate curve for the through drying of any paper, only the critical moisture content X_c was found to be dependent on the furnish. The greater than 40% variation in X_c with furnish would lead to a substantial difference in drying time and hence in size of an industrial through dryer.

Effect of papermaking parameters on through air drying characteristics

With controlled experiments using handsheets the effects on through air drying were determined for major papermaking parameters.

(5) The effects of papermaking parameters on through drying were:

<u>Papermaking parameter</u>	<u>Sensitivity of</u>	
	<u>Momentum transport</u>	<u>Drying rate</u>
Bleaching	very small	not measurable
Beating	very high	not measurable
Wet pressing	high	not measurable
Formation	small	high

(6) Effect of pulp blending

Experiments using handsheets made with a controlled variation in proportions of TMP and kraft pulp provided the first knowledge of the effects of the composition of such blended pulp furnishes on the characteristics of through air drying. The momentum

transport parameters are highly sensitive, nonlinear functions of composition of the pulp blend. Analysis of more than 100 drying rate curves showed that, of the five parameters required to characterize drying rate curves, only the extent of the increasing rate period depends on the composition of these blends. The extent of the increasing rate period for TMP paper is almost three times that for the kraft paper tested, with this difference attributed to the sensitivity of pore size distribution to fines from the TMP and to the low porosity and hence low pore water content of local regions of high fines content.

A consistent feature of this nonlinear dependence of properties on the composition of blends is that as kraft pulp is added to a TMP furnish, properties remain relatively little changed until the kraft pulp content reaches 25-50%. By contrast, when as little as 10% TMP is added to kraft pulp, sheet thickness, paper density and permeability change by between 1/4 and 1/3 of the total change between TMP and kraft paper, while for the characteristic dimension d_p the nonlinearity is greater yet, with the occurrence of a minimum. The disproportionate influence of the TMP content in TMP-kraft blends is attributed to the control of the macrostructure by the stiff TMP fibres and of the microstructure of pores by the high fines content of TMP.

In-plane moisture diffusivity and equalization

The role of moisture diffusivity in the plane of the sheet was addressed for paper with locally nonuniform moisture content during drying.

(7) Moisture diffusivity in the plane of the sheet

The in-plane moisture diffusivity was determined to decrease very strongly with decreasing sheet moisture content. The great difference found between in-plane diffusivity relative to that in the thickness direction from previous studies was related to the way in which the nonisotropic structure of paper affects the diffusion of moisture diffusivity in these two directions.

(8) Equalization of moisture content by diffusion

Experiments documented that in-plane moisture diffusion is too slow to affect significantly the nonuniformity of moisture content in through drying.

Drying nonuniformity

Along with the cost of providing the flow of air through the wet sheet, nonuniformity of through drying is considered an obstacle to the extension of this process from current use for tissue and toweling to possible future use with semi-permeable grades such as printing and heavier paper.

(9) Nonuniformity of drying: Local nonuniformity of sheet moisture content

The nonuniformity of moisture content for incompletely dried paper was documented by determining the moisture content of 2.5 mm diameter spots extending in a line for 40-80 mm.

(10) Nonuniformity of drying: Local nonuniformity of sheet exit air temperature

The exhaust air temperature 1mm below the sheet at 15 lateral positions within an 83 mm diameter circle were monitored continuously over the entire drying time, thereby characterizing drying nonuniformity.

(11) Nonuniformity of drying: Quantitative characterization

For both of the above methods the development and decay of local nonuniformity throughout drying was determined. Likewise for each method the coefficient of variation of the distributed variable, local sheet moisture content or local air exhaust temperature, was defined as the index of drying nonuniformity, I_{DNU} . For temperature of local exhaust air, more sensitive average indices of drying nonuniformity, $\bar{I}_{\text{DNU}}$, were only used.

(12) Nonuniformity of drying: Effect of parameters of papermaking and drying

Application of these two novel techniques with kraft handsheets of variable formation and basis weight and with machine-formed towel paper, sack paper, TMP newsprint and filled bleached kraft printing paper, along with analysis of drying rate curves, led to the conclusions summarized below:

<u>Parameter</u>	<u>Sensitivity of drying nonuniformity</u>
Initial moisture content	Above fibre saturation point: Very significant Below fibre saturation point: Low significance
Quality of formation	Significant
Basis weight	Significant (passes through maximum)
MD-CD dimension	Nonuniformity always higher in CD than MD dimension
Drying intensity	Significant

7.2 Recommendations for Future Study

- (1) While the present study provides a basic understanding of through air drying of machine-formed paper and of the effects of industrial papermaking parameters and composition of TMP-kraft pulp blends, it does so at low intensity drying conditions. Therefore it is recommended that the industrial relevance of these findings be further established by extending these investigations to higher intensity drying conditions.
- (2) As the in-plane moisture diffusivity obtained here was with handsheets, this determination should be extended through use of machine-formed papers of various furnishes and for which the diffusivity in the machine-direction (MD) and cross-machine (CD) direction should be individually determined and related to the micro-structure of the paper.
- (3) Although the form of the through drying models determined by Polat and Chen with unfilled kraft handsheets were applied successfully here for the prediction of drying rate and drying time for papermachine produced paper, these macro-scale models should be extended by development of a micro-scale model of through air drying based on local moisture content in the thickness direction. Such a model would facilitate analysis of multiple-technique drying in which through drying could be one component.
- (4) Further experimentation is needed to test the hypotheses proposed here concerning the possible extension of through air drying to grades of paper heavier than the tissue and toweling for which it is now used. The interplay between the pulp furnish and grammage of the paper, the initial moisture content, the intensity of through drying, the drying nonuniformity and the quality of the paper produced should be determined. The possibility of through drying being one technique used in a multiple - technique dryer section requires the study of through drying as a part of the drying process.

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Appendix A

Flow chart of data acquisition program

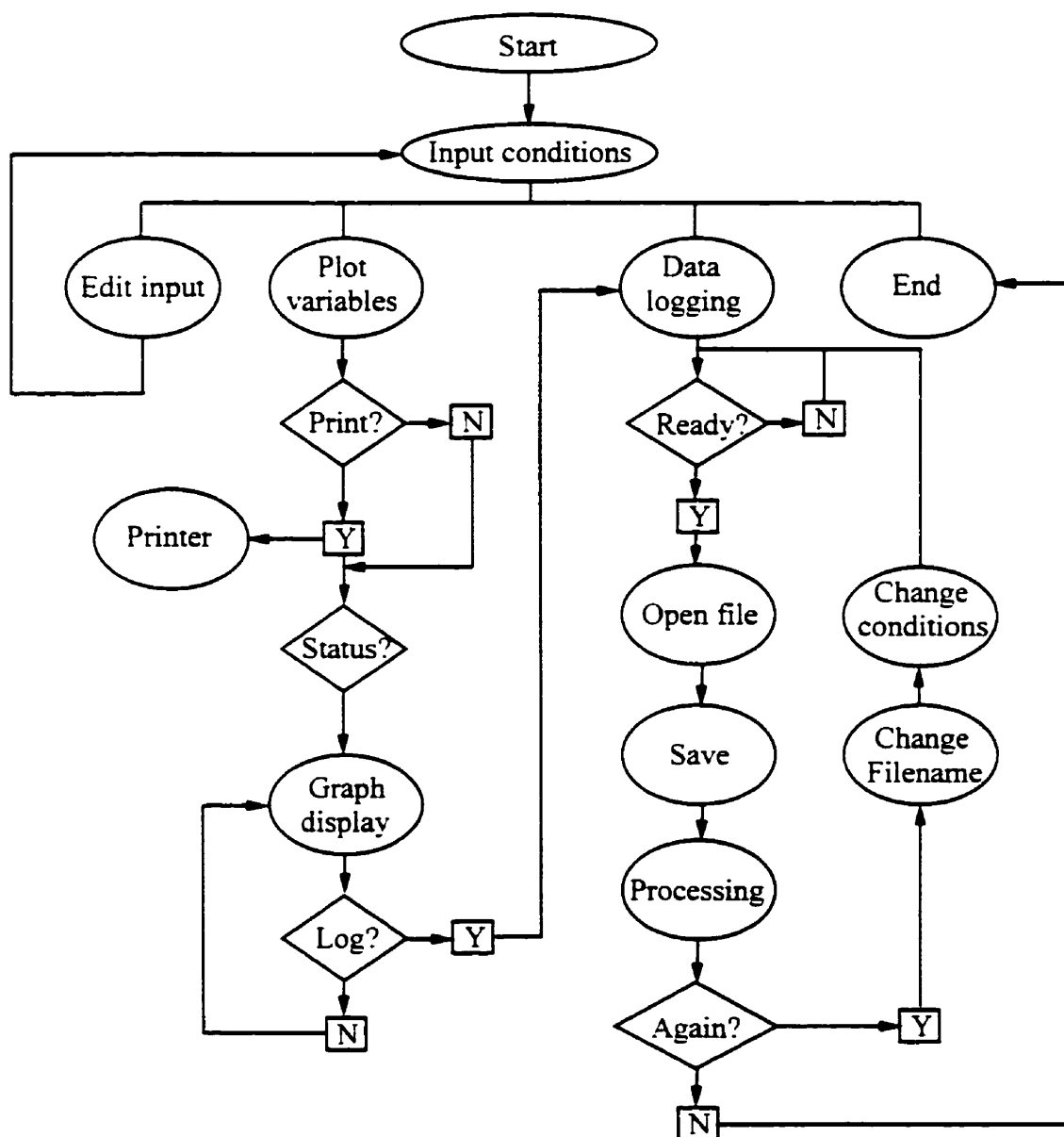


Figure A.1 Schematic diagram of data acquisition program for nonuniformity study from local exhaust air temperature measurement

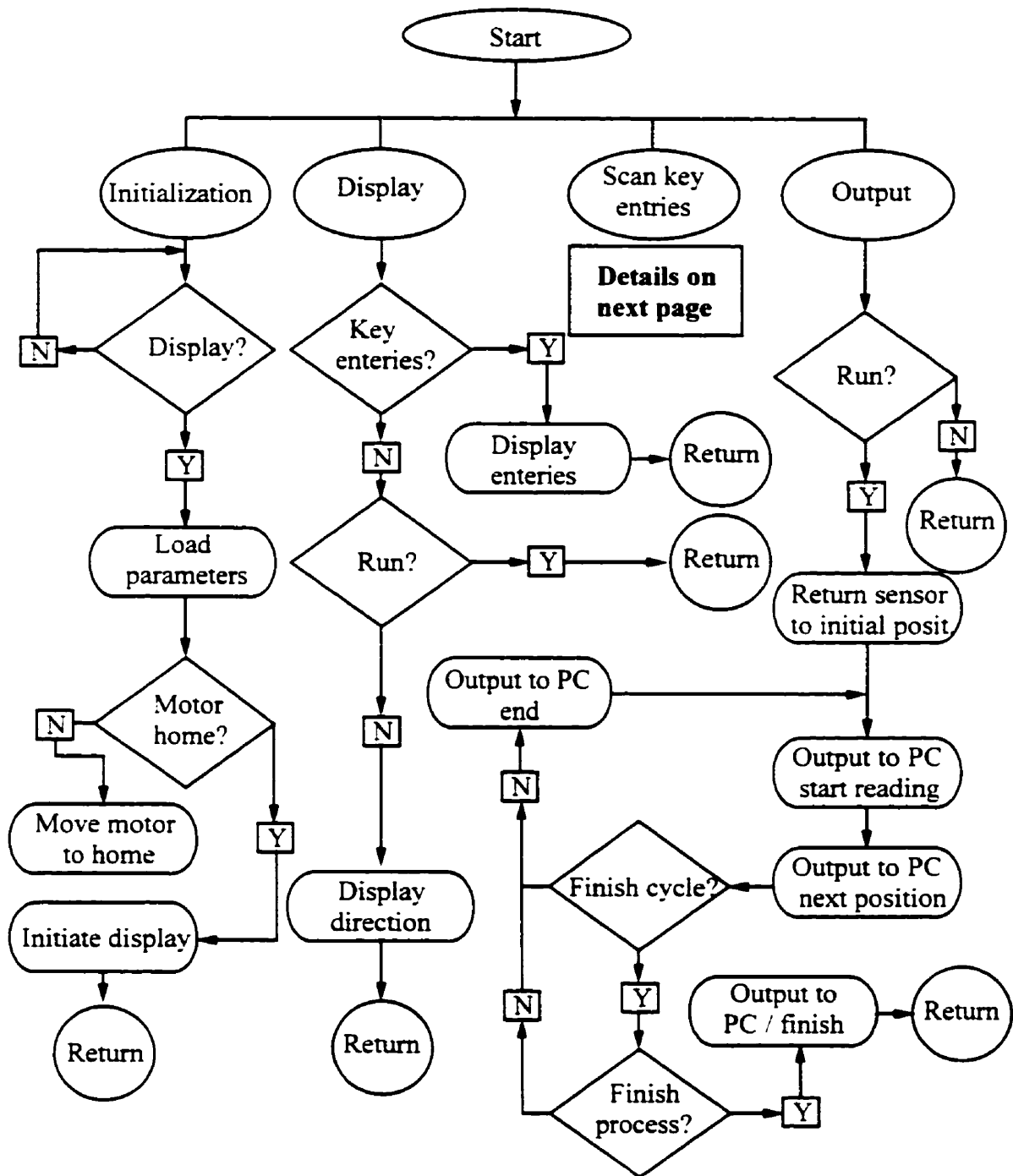


Figure A.2 Schematic diagram of data acquisition program for lateral moisture diffusivity measurement

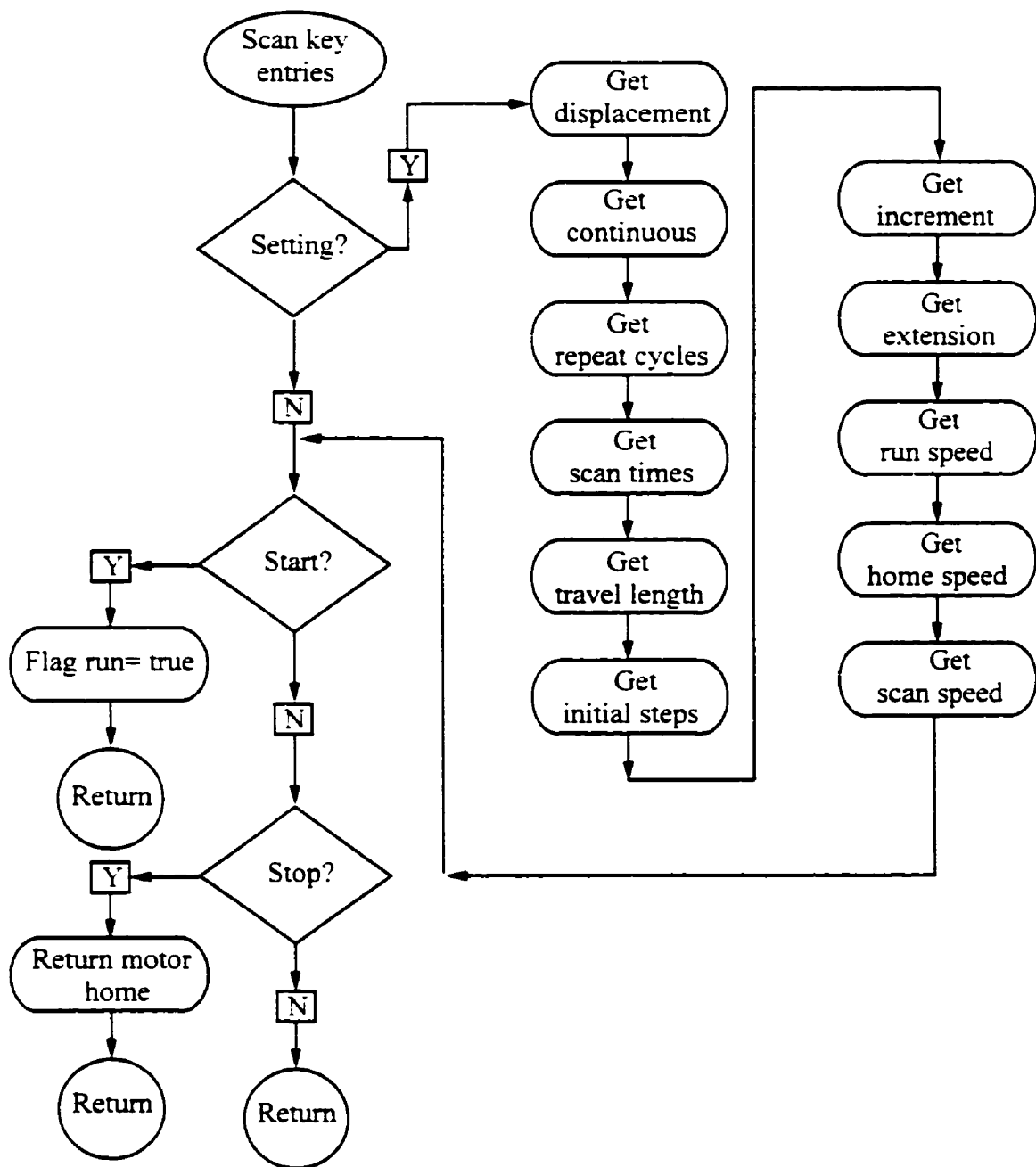


Figure A.2b Schematic diagram of data acquisition program for lateral moisture diffusivity measurement, (continued)

Appendix B

Experimental procedures

Preparation of test sheets for drying

Uncalendered papermachine paper received from mills was stored to avoid yellowing. Sheets of 103 mm diameter were cut with the paper sandwiched between two blotter papers to avoid damaging the sheet at its edge. Blotters must initially be kept in conditioned air at about 50% humidity to provide adhesion with these papers. Each sheet was carefully checked over a light box to eliminate any visible cracks or damage. Sheets were wetted uniformly to a moisture content higher than the target initial moisture content, then the moisture content was allowed to drop to the target value. This reduction in sheet moisture content to that desired simulates industrial operation where fibres experience a higher moisture content before entering the dryer section. The sheet was then sandwiched between two plastic sheets and stored in a sealed bag for at least 24 hours prior to a drying experiment

Kraft handsheets were prepared from dry, unbleached, unbeaten laboratory pulp, 100% black spruce. TMP handsheets were made from wet mechanical pulp received from a paper mill and stored in a refrigerator. All handsheets were made according to CPPA Standard C.4. Freshly made handsheets were stacked, separated by thin plastic sheets, sealed in a plastic bag and stored in a refrigerator.

Calibration of the IR-Analyzer as an air humidity sensor

The IR analyzer is calibrated against an absolute measurement instrument, a chilled-mirror dew point meter (EG&G Model 660). During IR calibration, air of various levels of relative humidity, each fixed by equilibration with a saturated salt solution, is circulated continuously until equilibrium is attained in a closed system consisting of the IR-Analyzer measurement cell, the saturated salt solution container, the dew point meter and a circulation fan. The signals from IR Analyzer and from the dewpoint meter were acquired by computer. The dew point reading was converted to humidity according to the

humidification table given by Dean [1985]. The humidity of the laboratory compressed dry air supply and the ambient air were also determined. A second order polynomial correlation of humidity with voltage output of the IR analyzer was then obtained as a calibration curve using Quattro Pro software. The relative humidity of the salt solutions used in the calibration runs are listed in Table B.1. Equilibrium relative humidity is a strong function of ambient temperature for some salt solutions.

Table B.1 Relative humidity of salt solutions at 20 °C

Solid phase	Relative humidity, %
LiCl.H ₂ O	12.0
CH ₃ COOK.1.5H ₂ O	23.0
MgCl ₂ .6H ₂ O	33.0
Mg(NO ₃) ₂ .6H ₂ O	55.0
NaCl	75.7
KBr	84.0
KNO ₃	93.0
K ₂ SO ₄	97.0

Drying experiment procedure

- (1) Select the high or low flow rate air line and rotameter.
- (2) Open the main compressed air line and adjust the flow rate to the desired value. Monitor the humidity of the dry air both by the IR analyzer and, for calibration purposes, by the dew point meter.
- (3) Connect the IR analyzer cell to the calibration system, and follow the calibration procedure described above.
- (4) Upon the completion of the calibration runs, reconnect the measuring chamber of the IR analyzer to the drying apparatus with two T-valves.
- (5) Adjust the drying air temperature to desired value while monitoring the air temperature by running the data acquisition program.

- (6) Place the test sheet into the sample holder described in chapter 2. Weigh the sheet holder with and without wet paper before the drying experiment, then immediately insert the sheet into drying chamber.
- (7) Upon completion of drying, as judged from the on-line screen IR analyzer output, the air exit temperature and the pressure drop across the sheet, interrupt the data acquisition, retract the insertion-retraction plate, remove the sheet holder and weigh it again. Place the dried sheet in an oven at 104 °C for about 24 h, then weigh it again. These weighings provide the initial and final moisture content.
- (8) Check the mass balance from the IR humidity measurement against that of the electronic balance. Any experiment with an error in the mass balance higher than those values reported in previous chapters, between 5 to 10%, was rejected.
- (9) Further process the data from successful experiments using Lotus 123, Quattro Pro as well as SYSTAT as needed. The graphical output was prepared by Freelance Presentation for Windows.

Moisture diffusivity experiment procedure

Handsheets were prepared as described above. Blotter paper and superabsorber sheets were cut to annular rings of 20 mm wide for use as the moisture sink. These were kept in desiccator to maintain their moisture content as low as possible.

Calibration of IR sensor for paper moisture content

The IR moisture sensor was calibrated gravimetrically using an electronic balance of accuracy of 0.0001g. A special calibration rig consisting of the balance and an adjustable stand for fine tuning the distance of the sheet from two heads of IR sensor was used. The same type of paper as used for moisture diffusivity is placed in the sheet holder when wet and the decrease in weight of the wet paper, due to drying at room temperature, is measured precisely and the data recorded in a file. As such surface drying is very slow the calibration of moisture sensor takes about an hour from an initial moisture content of 2 kg water/kg fibre to dryness. Slow drying is essential in order that the thickness direction moisture gradient is negligible as the IR is used in Reflectance mode. When the

paper completely dries the sheet is removed to an oven at 104 °C for bone dry weight determination. The computer data stored is converted later to sheet moisture content as a function of IR voltage output. This sensor has low sensitivity at high sheet moisture content but has high sensitivity over the medium to low range of moisture content relevant to this work. As the spot size monitored by the moisture sensor is only 2.5 mm diameter an accurate calibration requires determination of the local grammage of each spot used. Such a calibration was repeated for several sheets and the average calibration curve obtained from the entire results. A third order polynomial could represent the calibration curve accurately.

Obtaining an in-plane moisture profile across the sheet

- (1) Enter the experimental setting, i.e. speed of scanning table, scanning time, returning speed number of scanning points, maximum distance traveled as well as the paper specifications in a file opened in the data acquisition program. The moisture profile across the sheet could then be determined as a function of time and position simply by pressing the RUN key.
- (2) Enter the calibration coefficients of the IR moisture sensor for the specific type of paper used.
- (3) Place sheet in the sheet holder with its edges sandwiched between the two annular rings of superabsorber paper.
- (4) Measure the weight of sheet holder and associated paper.
- (5) Place the sheet holder on the scanning table and press RUN key to start.
- (6) Immediately after the scanning table stops remove and weigh the sheet holder with the paper, then place the sheet alone in an oven for subsequent weighing with the paper bone dry.
- (7) The gravimetrical check of the moisture loss during scanning with that lost due to ambient drying must be in the range of 99% in order not to reject the data.
- (8) The data acquisition program automatically records the sheet local moisture profile as well as all experimental specifications in a file from which the moisture diffusivity is calculated.

Nonuniformity experiments by measuring local moisture content

The procedure for preparing sheets and running drying experiments was the same as described before. The interruption time at a particular moisture content was determined based on the entire drying history of an identical sheet from the same initial moisture content dried under the same drying conditions.

- (1) Prepare the sheet for drying and preset the drying conditions as well as the setting for the scanning table.
- (2) Start drying, measure the drying time with the timer. Interrupt drying at a specific sheet moisture content.
- (3) Measure the weight of sheet holder and paper immediately, before placing the sheet holder on the scanning table for scanning the sheet local moisture content.
- (4) Measure the weight of the sheet holder after scanning, for a gravimetric accuracy check.
- (5) Place the sheet in an oven for determination of bone dry weight, sheet initial and final moisture content.
- (6) The data acquisition program would provide the sheet local moisture content across the paper as a precise function of time and position.
- (7) Use further file processing to determine drying nonuniformity indices.

Nonuniformity experiments by measuring local exhaust air temperature

The only difference between this set of experiments and the procedure used in the main through drying experiments is on the further processing of data using several programs written either in Fortran or as a macro command in Quattro Pro spreadsheet.

Appendix C

Drying rate characteristics of TMP and TMP-kraft blends

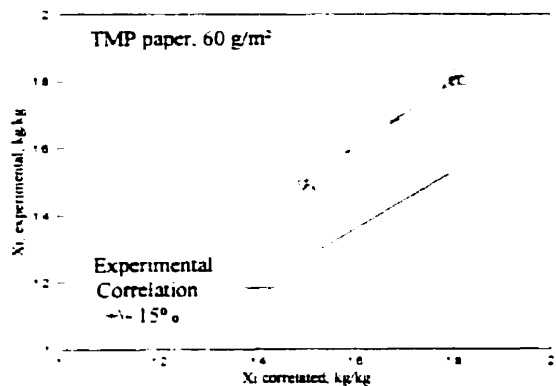


Fig. C.1 Comparison of experimental and correlated values of X_i

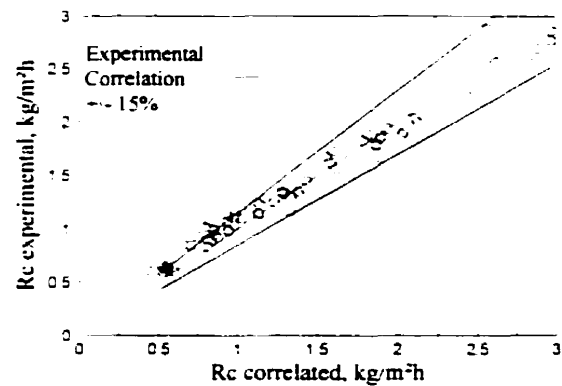


Fig. C.2 Comparison of experimental and correlated values of R_c

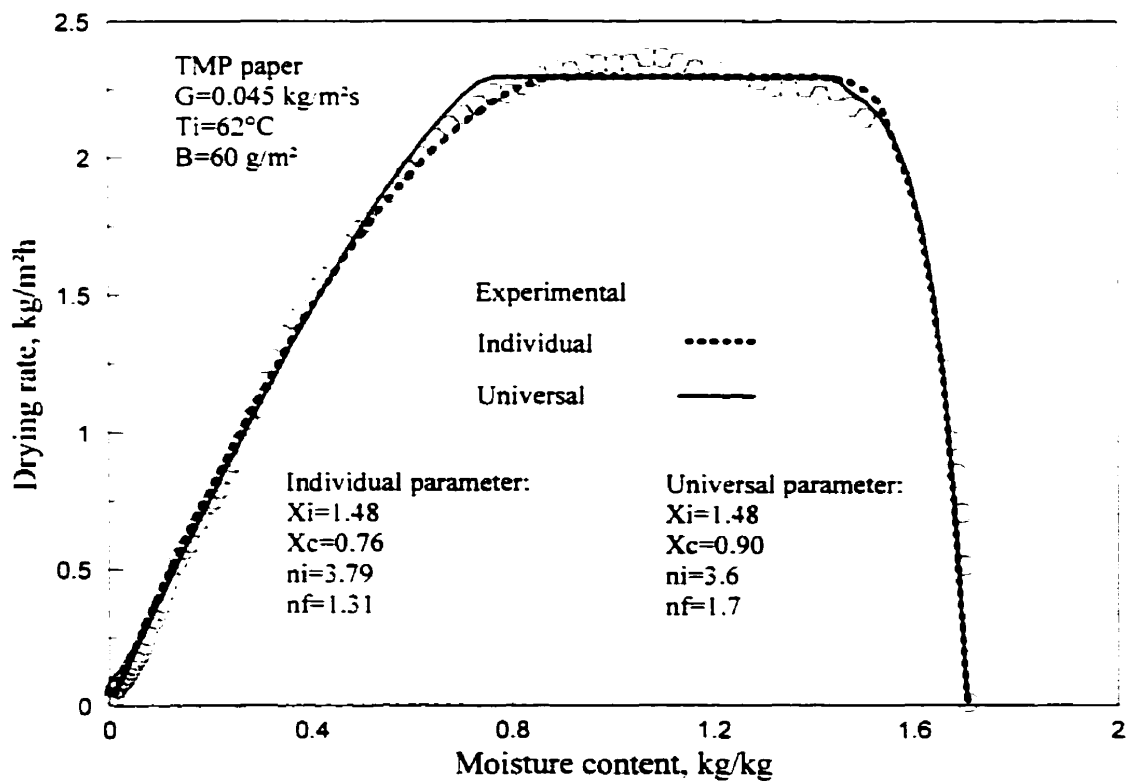


Fig. C.3 Drying rate curve from individual and universal parameters

Table C.1 Correlation parameters for falling rate drying period

Type of paper	c	σ_c	n_f	σ_{nf}
TMP	0.42	0.08	1.32	0.2
TMP ^{LF}	0.40	0.06	1.21	0.2
75%TMP+25%kraft	0.43	0.15	1.59	0.4
50%TMP+50%kraft	0.40	0.13	1.76	0.4
25%TMP+75%kraft	0.42	0.15	2.00	0.7
kraft	0.45	0.03	1.70	0.4

TMP^{LF}: TMP pulp with low (20%) fines content

Appendix D

Error analysis

Total rms error is expressed as $\delta f = \left[\sum_{i=1}^n \left(\frac{\partial f}{\partial x_i} \delta x_i \right)^2 \right]^{\frac{1}{2}}$

Basis weight

$$B = \frac{4W}{\pi D^2}$$

with W the bone dry weight
 D the sheet diameter

$$\frac{\delta B}{B} = \left[\left(\frac{\partial B}{\partial W} \frac{\delta W}{B} \right)^2 + \left(\frac{\partial B}{\partial D} \frac{\delta D}{B} \right)^2 \right]^{\frac{1}{2}} = \left[\left(\frac{\delta W}{W} \right)^2 + \left(-\frac{2\delta D}{D} \right)^2 \right]^{\frac{1}{2}}$$

As $\delta W = 0.0005$ g. $W > 0.21$ g
 $\delta D = 0.0005$ m. $D = 0.103$ m

Hence $\frac{\delta B}{B} < 1\%$

Inlet air mass flow rate

$$G = \rho V / A$$

and $\rho = \frac{PM}{RT}$, $V = V_s \sqrt{\frac{\rho_s}{\rho}}$

so $G = \frac{V_s \sqrt{\rho_s}}{A} \sqrt{\frac{PM}{RT}}$

with ρ air density
 ρ_s air density at standard conditions
 V volumetric flow rate from rotameter
 V_s volumetric flow rate from rotameter at standard conditions
 A cross section area of drying chamber
 P absolute pressure at rotameter
 M air molecular weight
 T air temperature at rotameter

$$\frac{\delta G}{G} = \left[\left(\frac{\partial G}{\partial P} \frac{\delta P}{G} \right)^2 + \left(\frac{\partial G}{\partial V_s} \frac{\delta V_s}{G} \right)^2 + \left(\frac{\partial G}{\partial T} \frac{\delta T}{G} \right)^2 \right]^{\frac{1}{2}}$$

$$\frac{\delta G}{G} = \left[\left(\frac{\delta P}{2P} \right)^2 + \left(\frac{\delta V_s}{V_s} \right)^2 + \left(-\frac{\delta T}{2T} \right)^2 \right]^{\frac{1}{2}}$$

as $\delta P = 0.13 \text{ kPa}$, $P > 101 \text{ kPa}$
 $\delta T = 0.5 \text{ K}$, $T > 290 \text{ K}$
 $\delta V_s/V_s < 0.7\%$ from calibration

Hence $\frac{\delta G}{G} < 0.8\%$

Porosity

$$\varepsilon = 1 - \frac{B}{L\rho_f}$$

$$\frac{\partial \varepsilon}{\partial B} = -\frac{1}{L\rho_f}; \quad \frac{\partial \varepsilon}{\partial L} = \frac{B}{L^2\rho_f}; \quad \frac{\partial \varepsilon}{\partial \rho_f} = \frac{B}{L\rho_f^2}$$

as $\delta B = 0.01B$
 $\delta L = 1 \text{ } \mu\text{m}$
 $\delta \rho_f = 50 \text{ g/m}^3$

Hence $\delta \varepsilon \leq 0.013\varepsilon$

Permeability

$$k = \frac{1}{\alpha}$$

$$\frac{\partial k}{\partial \alpha} = -\frac{1}{\alpha^2}$$

as $\delta \alpha \approx 0.06\alpha$ as given in chapters 2.3 and 7

Hence $\delta k \approx 0.06k$

Specific surface

$$a_p^2 = \frac{1}{\kappa} \frac{\varepsilon^3}{(1-\varepsilon)^2} \frac{1}{k}$$

$$\frac{\partial a_p}{\partial k} = -\frac{1}{2a_p \kappa k^2} \frac{\varepsilon^3}{(1-\varepsilon)^2}; \quad \frac{\partial a_p}{\partial \varepsilon} = -\frac{1}{2a_p \kappa k} \left[\frac{3\varepsilon^2}{(1-\varepsilon)^2} + \frac{2\varepsilon^3}{(1-\varepsilon)^3} \right]$$

as $\delta k = 0.06k$

$$\delta \varepsilon = 0.013\varepsilon$$

Hence $\delta a_p \approx 6.0\%$

Characteristic dimension

$$d_p = \frac{\beta}{\alpha}$$

$$\frac{\partial d_p}{\partial \alpha} = -\frac{\beta}{\alpha^2}; \quad \frac{\partial d_p}{\partial \beta} = \frac{1}{\alpha}$$

δd_p is $\sim 10-12\%$ for dry paper because both $\delta \alpha$ and $\delta \beta$ are about 10% as obtained in chapters 2, 3 and 7.

Reynolds number

$$Re = \frac{G d_p}{\mu}$$

$$\frac{\partial Re}{\partial G} = \frac{d_p}{\mu}; \quad \frac{\partial Re}{\partial d_p} = \frac{G}{\mu}; \quad \frac{\partial Re}{\partial \mu} = -\frac{G d_p}{\mu^2}$$

δRe is mainly controlled by δd_p , thus $\delta Re \approx 12\%$ for $\delta d_p \sim 10-12\%$

Drying rate

$$R_c = 3600G(Y_o - Y_i)$$

$$\frac{\partial R_c}{\partial G} = 3600(Y_o - Y_i); \quad \frac{\partial R_c}{\partial Y_o} = 3600G; \quad \frac{\partial R_c}{\partial Y_i} = -3600G$$

$\delta \Delta Y < 0.0001$ kg water/kg air and $\Delta Y > 0.006$ kg water/kg air, because the standard error on

Y measurements from the infra red calibration, hence $\frac{\delta R_c}{R_c} < 1.8\%$.

Appendix E

E.1 Through air drying of machine-formed paper: Detailed data

PM paper type 1, pure TMP. B=42.8 g/m²

G	T _i	T _s	X ₀	R _s	Chen's technique					Polat's Technique		
					X _i	X _c	R _c	n _i	n _f	X _i	X _c	R _c
0.013	22.5	8.3	1.61	0.32	-	-	-	-	-	1.37	0.6	0.32
0.013	22.3	8.3	1.64	0.32	-	-	-	-	-	1.44	0.82	0.32
0.013	40.8	16.3	1.51	0.53	-	-	-	-	-	1.45	0.87	0.50
0.013	44.5	18.2	1.60	0.60	-	-	-	-	-	1.53	0.87	0.48
0.013	59.7	22.5	1.57	0.78	1.36	0.77	0.70	3.81	1.55	1.38	0.81	0.72
0.013	59.7	22.5	1.54	0.78	1.33	0.69	0.67	3.77	1.19	1.37	0.80	0.70
0.013	58.8	22.5	1.49	0.79	1.29	0.69	0.79	3.79	1.36	1.38	0.79	0.79
0.013	58.4	23.3	1.44	0.82	1.32	0.89	0.74	2.97	1.55	1.41	0.86	0.75
0.019	22.5	8.0	1.50	0.49	-	-	-	-	-	1.35	0.80	0.49
0.019	21.3	7.8	1.81	0.48	-	-	-	-	-	1.75	0.91	0.45
0.019	21.2	7.7	1.56	0.47	-	-	-	-	-	1.35	0.73	0.44
0.019	27.1	11.2	1.60	0.60	-	-	-	-	-	1.40	1.20	0.60
0.019	27.2	11.4	1.64	0.60	-	-	-	-	-	1.41	0.96	0.60
0.019	44.5	17.6	1.48	0.88	-	-	-	-	-	1.34	0.88	0.76
0.019	40.0	15.4	1.60	0.77	-	-	-	-	-	1.35	0.86	0.71
0.019	62.7	23.5	1.73	1.28	1.55	1.16	0.92	2.95	1.95	1.45	1.08	0.96
0.019	63.6	24.5	1.54	1.35	1.33	1.00	1.09	3.25	1.23	1.39	0.88	1.10
0.019	63.3	24.4	1.55	1.35	1.30	0.66	1.12	3.72	1.36	1.39	0.79	1.15
0.023	60.6	22.8	1.61	1.44	1.41	0.92	1.08	3.70	1.39	1.45	0.82	1.08
0.023	61.4	23.1	1.64	1.46	1.43	0.95	1.14	3.16	2.20	1.50	0.85	1.16
0.023	60.7	23.4	1.32	1.49	1.15	0.66	1.14	3.73	1.27	1.21	0.65	1.15
0.023	60.7	23.4	1.24	1.49	1.07	0.60	1.16	3.75	1.19	1.18	0.72	1.18
0.023	61.7	23.5	1.89	1.50	1.63	0.89	1.18	3.78	1.58	1.64	0.90	1.19
0.023	62.2	23.6	2.01	1.51	1.83	1.32	1.10	3.06	1.97	1.92	1.10	1.10
0.026	21.5	7.5	1.55	0.64	-	-	-	-	-	1.20	0.81	0.61
0.026	21.4	7.5	1.50	0.63	-	-	-	-	-	1.35	0.80	0.58
0.026	41.4	16.4	1.66	1.11	-	-	-	-	-	1.55	1.00	0.99
0.026	41.2	16.3	1.69	1.10	-	-	-	-	-	1.58	0.90	1.00
0.026	62.6	23.6	1.45	1.74	1.34	0.86	1.48	2.12	1.50	1.33	0.80	1.44
0.026	62.5	23.7	1.63	1.75	1.47	0.87	1.49	3.39	1.19	1.50	0.95	1.52
0.026	69.6	25.1	1.77	1.91	1.54	1.05	1.39	3.08	2.11	1.55	1.00	1.42
0.026	69.1	25.1	1.75	1.90	1.54	1.12	1.37	2.73	1.96	1.54	1.00	1.38

G	T _i	T _s	X _o	R _s	Chen's technique					Polat's Technique		
					X _i	X _c	R _c	n _i	n _r	X _i	X _c	R _c
0.026	83.0	29.2	1.56	2.47	1.27	0.82	2.13	3.66	1.69	1.31	0.73	2.10
0.026	84.5	29.6	1.60	2.54	1.48	0.63	2.08	2.77	0.97	1.43	0.82	2.16
0.034	22.4	9.2	1.60	0.92	-	-	-	-	-	1.33	0.92	0.82
0.034	22.3	9.2	1.64	0.91	-	-	-	-	-	1.34	0.92	0.81
0.034	42.7	16.8	1.60	1.46	-	-	-	-	-	1.46	0.96	1.28
0.034	44.0	17.4	1.60	1.50	-	-	-	-	-	1.45	0.68	1.28
0.034	62.0	23.0	1.59	2.16	1.36	0.92	1.76	3.05	1.61	1.48	0.82	1.76
0.034	61.7	23.0	1.51	2.15	1.34	0.86	1.48	2.12	1.50	1.47	0.92	1.76
0.034	69.7	25.7	1.56	2.55	1.43	1.00	1.79	2.77	0.97	1.43	0.92	1.81
0.034	70.2	25.8	1.56	2.57	1.34	0.98	1.98	2.86	2.05	1.47	0.94	1.96
0.034	77.7	27.7	1.50	2.89	1.37	0.87	2.43	1.52	1.43	1.40	0.94	2.50
0.034	81.4	28.7	1.59	3.07	1.36	0.86	2.45	3.61	1.20	1.44	0.92	2.44
0.034	82.2	28.9	1.52	3.10	1.39	0.90	2.59	2.75	1.79	1.40	0.88	2.61

Note 1: The slight differences between R_c, X_i, X_c determined by these two techniques may disappear here as the data has been round off.

PM paper type 2, pure TMP, B=57.3 g/m², only Polat's technique was used

G	T _i	T _s	X _o	R _s	X _i	X _c	R _c
0.013	22.6	8.5	1.59	0.32	1.30	0.67	0.32
0.013	22.4	8.5	1.58	0.32	1.30	0.70	0.32
0.013	41.2	16.0	1.66	0.52	1.45	0.65	0.52
0.013	41.4	16.0	1.59	0.52	1.43	0.62	0.52
0.013	47.3	18.9	1.57	0.62	1.45	0.64	0.57
0.013	52.0	19.8	1.66	0.66	1.35	0.75	0.64
0.013	54.7	20.5	1.64	0.69	1.46	0.69	0.62
0.013	59.2	23.6	1.62	0.83	1.37	0.69	0.80
0.013	58.9	23.5	1.60	0.83	1.33	0.67	0.78
0.013	59.1	22.5	1.59	0.77	1.17	0.63	0.68
0.019	21.9	7.4	1.63	0.48	1.43	0.73	0.45
0.019	21.5	7.6	1.68	0.47	1.45	0.83	0.40
0.019	20.5	7.1	1.64	0.46	1.39	0.75	0.43
0.019	26.9	11.6	1.67	0.61	1.43	0.72	0.60
0.019	26.9	11.6	1.61	0.61	1.40	0.63	0.60
0.019	43.4	16.9	1.66	0.84	1.40	0.63	0.80
0.019	43.3	16.9	1.60	0.84	1.39	0.60	0.82

G	T _i	T _s	X _o	R _s	X _i	X _c	R _c
0.019	60.4	23.5	1.57	1.27	1.41	0.79	1.03
0.019	62.2	23.9	1.62	1.31	1.51	0.79	1.08
0.019	59.0	22.0	1.60	1.16	1.42	0.85	0.98
0.023	60.4	23.6	1.55	1.51	1.43	0.87	1.21
0.023	60.6	23.6	1.64	1.51	1.56	0.91	1.22
0.023	61.8	23.3	1.63	1.48	1.48	0.68	1.17
0.023	62.1	23.4	1.60	1.49	1.48	0.62	1.19
0.023	60.8	23.4	1.31	1.49	1.23	0.80	1.10
0.023	60.6	23.4	1.39	1.49	1.28	0.61	1.19
0.023	61.4	23.4	2.02	1.49	1.91	0.78	1.22
0.023	61.0	23.5	2.02	1.49	1.93	0.82	1.27
0.026	20.2	6.9	1.65	0.61	1.42	0.83	0.55
0.026	20.1	7.0	1.62	0.61	1.40	0.73	0.50
0.026	20.0	6.7	1.69	0.60	1.36	0.77	0.54
0.026	42.7	16.7	1.70	1.13	1.50	0.71	0.87
0.026	41.5	16.3	1.64	1.10	1.43	0.59	0.89
0.026	62.1	24.1	1.61	1.79	1.45	0.71	1.40
0.026	62.1	24.1	1.61	1.79	1.54	0.71	1.43
0.026	62.2	23.7	1.66	1.75	1.56	0.60	1.48
0.026	61.9	23.5	1.62	1.73	1.51	0.60	1.46
0.026	68.7	25.1	1.59	1.91	1.05	0.70	1.61
0.026	68.7	25.1	1.61	1.91	1.10	0.70	1.60
0.026	84.5	29.5	1.62	2.51	1.51	0.64	2.25
0.026	84.5	29.5	1.58	2.51	1.49	0.61	2.22
0.034	22.5	9.4	1.63	0.92	1.36	0.72	0.83
0.034	22.8	9.5	1.61	0.93	1.33	0.76	0.83
0.034	41.5	16.5	1.63	1.43	1.41	0.69	1.28
0.034	40.9	16.4	1.59	1.42	1.35	0.80	1.23
0.034	60.8	22.7	1.67	2.11	1.57	0.61	1.76
0.034	61.1	22.9	1.69	2.14	1.59	0.66	1.78
0.034	68.7	25.4	1.67	2.49	1.57	0.72	1.83
0.034	67.5	25.3	1.61	2.48	1.50	0.68	1.95
0.034	79.7	28.3	1.58	2.99	1.40	0.93	2.59
0.034	80.3	28.5	1.56	3.00	1.40	0.91	2.51

PM paper type 3, pure TMP, B=47.5 g/m², only Polat's technique was used

G	T _i	T _s	X ₀	R _s	X _i	X _c	R _c
0.013	21.2	6.8	1.58	0.29	1.40	0.60	0.29
0.013	21.3	6.7	1.54	0.29	1.38	0.70	0.29
0.013	41.7	16.2	1.52	0.52	1.44	0.70	0.52
0.013	41.7	16.1	1.55	0.52	1.48	0.55	0.52
0.019	26.9	11.2	1.63	0.59	1.41	0.86	0.59
0.019	27.0	10.4	1.58	0.60	1.38	0.84	0.60
0.019	43.5	16.9	1.54	0.84	1.44	0.70	0.84
0.019	43.6	17.0	1.63	0.84	1.54	0.78	0.84
0.023	62.5	23.5	1.53	1.50	1.40	0.77	1.16
0.023	62.4	23.5	1.58	1.50	1.34	0.61	1.23
0.023	61.3	23.6	1.33	1.51	1.23	0.59	1.22
0.023	61.3	23.5	1.32	1.50	1.22	0.62	1.26
0.023	60.1	23.2	1.93	1.47	1.80	0.99	1.18
0.023	60.3	23.2	1.86	1.47	1.79	0.90	1.21
0.025	63.1	23.6	1.61	1.62	1.46	0.75	1.22
0.025	60.5	22.7	1.61	1.53	1.46	0.78	1.23
0.026	21.4	7.5	1.61	0.64	1.39	0.73	0.64
0.026	22.8	8.3	1.59	0.67	1.42	0.85	0.67
0.026	41.4	16.4	1.61	1.11	1.52	0.92	1.03
0.026	41.4	16.5	1.67	1.12	1.61	0.90	1.03
0.026	62.7	23.8	1.64	1.76	1.51	0.80	1.50
0.026	62.5	23.8	1.61	1.76	1.48	0.82	1.50
0.026	69.9	25.4	1.64	1.94	1.35	0.54	1.59
0.026	69.9	25.4	1.58	1.95	1.28	0.62	1.58
0.023	85.0	29.6	1.58	2.52	1.43	0.63	2.24
0.023	84.5	29.5	1.56	2.52	1.40	0.75	2.22
0.034	23.7	10.1	1.55	0.96	1.36	0.79	0.91
0.034	23.5	10.0	1.46	0.96	1.25	0.81	0.90
0.034	41.2	16.5	1.56	1.43	1.33	0.70	1.28
0.034	41.6	16.7	1.55	1.44	1.37	0.80	1.28
0.034	61.6	23.0	1.56	2.14	1.50	0.67	1.77
0.034	62.0	23.1	1.54	2.16	1.43	0.75	1.85
0.034	68.6	25.3	1.63	2.48	1.50	0.69	1.95
0.034	69.1	25.6	1.67	2.53	1.56	0.83	1.89
0.034	81.9	28.8	1.55	3.09	1.42	0.77	2.62
0.034	83.2	29.0	1.64	3.13	1.49	1.07	2.73

G	T _i	T _s	X _o	R _s	X _i	X _c	R _c
0.036	60.8	22.8	1.61	2.26	1.49	0.91	1.74
0.036	61.7	23.0	1.57	2.29	1.45	0.89	1.75
0.044	62.3	23.4	1.60	2.88	1.45	0.91	2.09
0.044	61.3	22.9	1.64	2.78	1.49	0.85	2.11

PM paper type 4. pure TMP. B=43.8 g/m². only Polat's technique was used

G	T _i	T _s	X _o	R _s	X _i	X _c	R _c
0.013	21.2	6.7	1.55	0.29	1.39	0.71	0.29
0.013	21.2	6.7	1.52	0.29	1.41	0.67	0.29
0.013	41.8	16.1	1.55	0.52	1.42	0.68	0.52
0.013	41.8	16.2	1.56	0.52	1.45	0.68	0.52
0.013	57.7	23.1	1.54	0.81	1.40	0.72	0.72
0.013	58.0	23.1	1.54	0.81	1.33	0.58	0.74
0.019	26.6	11.2	1.55	0.59	1.37	0.70	0.59
0.019	26.7	11.3	1.57	0.59	1.39	0.80	0.59
0.019	43.3	16.9	1.56	0.84	1.49	0.72	0.84
0.019	43.3	16.9	1.54	0.84	1.45	0.70	0.83
0.019	61.3	23.8	1.54	1.30	1.39	0.70	1.10
0.019	60.5	23.5	1.54	1.27	1.38	0.61	1.06
0.023	62.0	23.4	1.59	1.49	1.39	0.61	1.17
0.023	61.8	23.3	1.51	1.48	1.39	0.61	1.16
0.023	61.9	23.7	1.30	1.52	1.21	0.60	1.19
0.023	61.6	23.7	1.23	1.52	1.18	0.60	1.23
0.023	60.0	23.4	1.85	1.49	1.74	0.98	1.16
0.023	60.5	23.4	1.91	1.49	1.81	1.00	1.24
0.026	23.4	8.8	1.51	0.69	1.37	0.80	0.69
0.026	23.3	8.7	1.54	0.69	1.36	0.82	0.69
0.026	41.4	16.4	1.55	1.11	1.42	0.69	1.01
0.026	41.3	16.5	1.54	1.11	1.42	0.69	0.99
0.026	62.0	23.6	1.53	1.74	1.46	0.61	1.51
0.026	62.6	23.8	1.58	1.76	1.49	0.91	1.50
0.026	69.6	25.3	1.54	1.94	0.89	0.57	1.77
0.026	69.4	25.3	1.60	1.93	1.51	0.88	1.29
0.026	83.9	29.4	1.52	2.49	1.39	0.70	2.26
0.026	83.9	29.3	1.58	2.49	1.44	0.85	2.23

G	T _i	T _s	X _o	R _s	X _i	X _c	R _c
0.034	23.3	9.7	1.51	0.94	1.30	0.73	0.90
0.034	23.1	9.7	1.54	0.94	1.30	0.70	0.88
0.034	42.5	17.1	1.53	1.48	1.49	0.80	1.35
0.034	42.7	17.3	1.55	1.50	1.42	0.82	1.37
0.034	61.4	22.8	1.54	2.13	1.43	0.64	1.79
0.034	61.3	22.8	1.52	2.14	1.41	0.71	1.76
0.034	69.0	25.4	1.59	2.50	1.45	0.61	1.87
0.034	68.5	25.2	1.63	2.47	1.52	0.63	1.95
0.034	83.2	29.1	1.51	3.15	1.40	0.67	2.69
0.034	82.9	29.0	1.55	3.12	1.43	0.64	2.75

PM paper type 5, pure TMP. B=44.0 g/m². only Polat's technique was used

G	T _i	T _s	X _o	R _s	X _i	X _c	R _c
0.013	23.2	8.0	1.48	0.31	1.32	0.61	0.31
0.013	21.2	6.7	1.54	0.29	1.41	0.67	0.29
0.013	41.9	16.2	1.43	0.52	1.35	0.57	0.52
0.013	41.8	16.2	1.52	0.52	1.44	0.60	0.52
0.013	57.9	23.2	1.48	0.81	1.29	0.59	0.79
0.013	57.7	23.1	1.45	0.81	1.25	0.62	0.78
0.019	26.1	10.8	1.51	0.58	1.32	0.55	0.58
0.019	26.3	11.0	1.47	0.58	1.28	0.61	0.58
0.019	42.8	16.7	1.51	0.83	1.35	0.53	0.82
0.019	43.0	16.8	1.48	0.84	1.41	0.54	0.82
0.019	63.2	24.5	1.52	1.35	1.14	0.49	1.12
0.019	63.4	24.5	1.60	1.35	1.35	0.57	1.18
0.023	61.3	23.2	1.44	1.47	1.33	0.57	1.18
0.023	61.3	23.2	1.51	1.47	1.39	0.53	1.21
0.023	61.5	23.6	1.28	1.51	1.18	0.51	1.24
0.023	61.7	23.7	1.25	1.52	1.12	0.49	1.23
0.023	60.7	23.4	1.81	1.49	1.69	0.78	1.30
0.023	60.9	23.7	1.80	1.51	1.70	0.72	1.21
0.026	22.7	8.5	1.50	0.68	1.31	0.62	0.67
0.026	22.6	8.4	1.50	0.67	1.27	0.54	0.67
0.026	40.9	16.3	1.49	1.10	1.32	0.60	1.01
0.026	40.9	16.3	1.46	1.10	1.32	0.58	0.99

G	T _i	T _f	X _o	R _i	X _i	X _c	R _c
0.026	61.9	23.5	1.45	1.73	1.33	0.60	1.53
0.026	61.9	23.5	1.53	1.73	1.41	0.55	1.51
0.026	68.9	25.3	1.51	1.93	1.35	0.49	1.43
0.026	69.3	25.2	1.59	1.92	1.02	0.60	1.77
0.026	82.6	29.1	1.50	2.45	1.33	0.49	2.15
0.026	82.1	28.9	1.52	2.42	1.38	0.49	2.16
0.034	19.3	7.1	1.49	0.79	1.32	0.60	0.76
0.034	19.6	7.3	1.48	0.80	1.30	0.56	0.77
0.034	42.5	17.2	1.50	1.49	1.24	0.55	1.32
0.034	42.8	17.3	1.49	1.51	1.30	0.61	1.33
0.034	60.9	22.8	1.51	2.12	1.39	0.65	1.81
0.034	60.7	22.7	1.50	2.10	1.37	0.56	1.79
0.034	67.6	24.8	1.55	2.40	1.35	0.51	1.93
0.034	68.2	25.1	1.52	2.46	1.38	0.57	1.90
0.034	82.2	28.8	1.44	3.09	1.31	0.59	2.71
0.034	82.2	28.8	1.46	3.10	1.37	0.65	2.78

PM paper type 6. 33%TMP+59%GW+8%kraft. B=44.2 g/m²

G	T _i	T _f	X _o	R _i	Chen's technique					Polat's Technique		
					X _i	X _c	R _c	n _i	n _f	X _i	X _c	R _c
0.013	23.2	8.1	1.53	0.32	-	-	-	-	-	1.41	0.59	0.32
0.013	23.2	8.0	1.53	0.32	-	-	-	-	-	1.33	0.63	0.32
0.013	41.9	16.1	1.56	0.52	-	-	-	-	-	1.49	0.51	0.52
0.013	41.8	16.1	1.61	0.52	-	-	-	-	-	1.54	0.49	0.52
0.013	58.9	23.4	1.53	0.82	1.34	0.62	0.80	3.92	1.24	1.31	0.61	0.82
0.013	58.1	23.2	1.53	0.82	1.34	0.47	0.73	3.98	1.29	1.24	0.50	0.76
0.019	25.9	10.7	1.60	0.57	-	-	-	-	-	1.38	0.67	0.57
0.019	26.2	11.0	1.55	0.58	-	-	-	-	-	1.39	0.63	0.58
0.019	42.7	16.7	1.51	0.83	-	-	-	-	-	1.42	0.57	0.82
0.019	42.9	16.7	1.59	0.83	-	-	-	-	-	1.54	0.59	0.83
0.019	59.9	23.2	1.66	1.25	1.49	0.72	1.06	3.92	1.54	1.49	0.88	1.09
0.019	59.7	23.3	1.67	1.25	1.47	0.56	1.08	3.79	1.28	1.48	0.51	1.09
0.023	61.6	23.3	1.63	1.48	1.47	0.68	1.18	3.97	1.62	1.49	0.64	1.21
0.023	61.6	23.2	1.62	1.48	1.43	0.62	1.20	3.96	1.18	1.41	0.67	1.23
0.023	61.5	23.6	1.31	1.51	1.22	0.46	1.16	3.94	1.60	1.22	0.48	1.20
0.023	61.7	23.6	1.24	1.52	1.12	0.45	1.21	4.19	1.32	1.11	0.54	1.25

G	T _i	T _s	X _o	R _s	Chen's technique					Polat's Technique		
					X _i	X _c	R _c	n _i	n _f	X _i	X _c	R _c
0.023	61.5	23.7	1.89	1.52	1.74	0.96	1.24	3.81	1.73	1.77	0.81	1.23
0.023	62.1	23.9	1.89	1.54	1.72	0.78	1.30	3.83	1.84	1.79	0.69	1.31
0.026	22.4	8.4	1.53	0.67	-	-	-	-	-	1.41	0.70	0.67
0.026	22.5	8.4	1.54	0.67	-	-	-	-	-	1.31	0.59	0.67
0.026	41.0	16.3	1.55	1.10	-	-	-	-	-	1.46	0.59	1.00
0.026	41.2	16.4	1.54	1.11	-	-	-	-	-	1.40	0.61	1.01
0.026	61.7	23.5	1.52	1.73	1.41	0.58	1.52	3.75	1.11	1.42	0.58	1.46
0.026	62.4	23.7	1.54	1.75	1.45	0.45	1.47	3.90	1.19	1.42	0.50	1.50
0.026	70.1	25.6	1.63	1.97	1.42	0.61	1.53	4.07	1.77	1.21	0.55	1.60
0.026	70.6	25.7	1.56	1.99	1.37	0.47	1.54	3.95	1.44	1.19	0.50	1.66
0.026	81.4	28.8	1.60	2.41	1.35	0.60	2.81	3.79	1.31	1.47	0.59	2.15
0.026	81.0	28.8	1.62	2.40	1.46	0.53	2.12	3.80	0.99	1.40	0.59	2.17
0.034	19.2	7.1	1.54	0.80	-	-	-	-	-	1.44	0.62	0.73
0.034	19.3	7.3	1.50	0.80	-	-	-	-	-	1.38	0.73	0.76
0.034	43.6	17.6	1.59	1.53	-	-	-	-	-	1.37	0.64	1.37
0.034	44.0	17.8	1.52	1.55	-	-	-	-	-	1.35	0.59	1.38
0.034	61.7	23.0	1.56	2.14	1.46	0.49	1.76	3.85	1.07	1.46	0.49	1.78
0.034	61.8	23.0	1.54	2.15	1.43	0.49	1.80	3.85	0.99	1.42	0.52	1.82
0.034	70.5	25.6	1.64	2.54	1.48	0.47	1.96	3.95	1.00	1.47	0.51	2.00
0.034	70.3	25.6	1.64	2.53	1.51	0.60	1.95	3.80	1.30	1.54	0.56	1.96
0.034	82.8	30.0	1.49	3.13	1.35	0.64	2.77	3.79	1.50	1.38	0.61	2.78
0.034	83.0	29.8	1.50	3.13	1.35	0.60	2.81	3.79	1.31	1.33	0.61	2.89

PM paper type 7, 48%TMP and 52%Deinked pulp. B=44.5 g/m²

G	T _i	T _s	X _o	R _s	Chen's technique					Polat's Technique		
					X _i	X _c	R _c	n _i	n _f	X _i	X _c	R _c
0.013	23.1	7.9	1.50	0.31	-	-	-	-	-	1.43	0.54	0.31
0.013	23.1	8.0	1.51	0.31	-	-	-	-	-	1.42	0.69	0.31
0.013	41.8	16.1	1.56	0.52	-	-	-	-	-	1.49	0.66	0.52
0.013	41.7	16.1	1.51	0.52	-	-	-	-	-	1.41	0.50	0.52
0.013	59.1	23.5	1.50	0.83	1.25	0.49	0.72	4.93	1.43	1.29	0.43	0.79
0.013	59.1	23.5	1.48	0.83	1.28	0.54	0.78	3.99	1.00	1.27	0.59	0.80
0.019	25.5	10.4	1.54	0.56	-	-	-	-	-	1.32	0.65	0.56
0.019	25.7	10.6	1.52	0.57	-	-	-	-	-	1.25	0.64	0.57
0.019	40.6	16.0	1.51	0.80	-	-	-	-	-	1.45	0.61	0.79

G	T _i	T _s	X _o	R _s	Chen's technique					Polat's Technique		
					X _i	X _c	R _c	n _i	n _f	X _i	X _c	R _c
0.019	42.2	16.5	1.53	0.82	-	-	-	-	-	1.48	0.59	0.80
0.019	60.9	23.7	1.55	1.29	1.34	0.60	1.02	3.84	1.28	1.43	0.55	1.03
0.019	60	23.5	1.56	1.27	1.34	0.66	1.08	3.84	1.43	1.41	0.67	1.09
0.023	61.2	23.1	1.55	1.47	1.37	0.78	1.21	3.80	1.81	1.48	0.58	1.21
0.023	61.4	23.1	1.49	1.46	-	-	-	-	-	1.37	0.74	1.21
0.023	60.9	23.5	1.24	1.50	1.09	0.56	1.24	3.82	1.37	1.13	0.55	1.29
0.023	61.2	23.5	1.24	1.50	1.10	0.50	1.20	3.82	1.61	1.18	0.48	1.22
0.023	62.1	23.8	1.76	1.53	1.63	1.11	1.36	1.64	2.03	1.67	0.85	1.35
0.023	62.2	24.0	1.80	1.55	1.60	1.03	1.27	3.73	1.79	1.73	0.87	1.26
0.026	20.3	7.1	1.52	0.62	-	-	-	-	-	1.34	0.72	0.62
0.026	20.5	7.2	1.55	0.62	-	-	-	-	-	1.32	0.64	0.59
0.026	40.7	16.2	1.50	1.09	-	-	-	-	-	1.42	0.54	0.99
0.026	40.5	16.1	1.51	1.09	-	-	-	-	-	1.41	0.69	1.01
0.026	61.3	23.4	1.52	1.72	1.37	0.66	1.45	2.96	1.47	1.43	0.56	1.44
0.026	61.2	23.3	1.50	1.71	1.36	0.54	1.49	3.76	0.97	1.40	0.55	1.50
0.026	69.5	25.3	1.49	1.94	1.23	0.76	1.45	3.77	1.12	1.35	0.66	1.39
0.026	69.4	25.3	1.48	1.93	1.26	0.73	1.45	3.84	1.93	1.35	0.73	1.48
0.026	80.4	28.7	1.60	2.39	1.50	0.73	2.16	2.67	1.19	1.51	0.69	2.18
0.026	80.7	28.8	1.48	2.40	1.35	0.62	2.05	2.18	1.20	1.37	0.64	2.06
0.034	23.2	10.0	1.53	0.96	-	-	-	-	-	1.34	0.61	0.85
0.034	23.2	10.0	1.49	0.95	-	-	-	-	-	1.30	0.64	0.86
0.034	42.9	17.4	1.48	1.52	-	-	-	-	-	1.31	0.65	1.39
0.034	42.5	17.2	1.49	1.49	-	-	-	-	-	1.32	0.74	1.39
0.034	60.1	22.5	1.50	2.08	1.38	0.61	1.73	3.75	1.22	1.43	0.59	1.73
0.034	59.9	22.3	1.52	2.06	1.36	0.64	1.73	3.78	1.56	1.40	0.57	1.74
0.034	70.3	25.6	1.53	2.53	1.32	0.83	1.86	3.30	2.21	1.36	0.65	1.89
0.034	70.2	25.5	1.50	2.51	1.32	0.72	1.94	3.42	1.43	1.39	0.63	1.92
0.034	82.6	29.0	1.50	3.12	1.30	0.74	2.90	3.61	1.95	1.40	0.63	2.88
0.034	82.4	29.0	1.51	3.13	1.40	0.55	2.73	2.73	1.22	1.39	0.58	2.77

PM paper type 8. 71.5%SGW and 28.5%bleached kraft. B=47.7 g/m²

G	T _i	T _s	X _n	R _s	Chen's technique					Polat's Technique		
					X _i	X _c	R _c	n _i	n _f	X _i	X _c	R _c
0.013	22.3	8.6	1.58	0.33	-	-	-	-	-	1.39	0.59	0.33
0.013	22.3	8.6	1.57	0.33	-	-	-	-	-	1.45	0.59	0.33

G	T _i	T _s	X _o	R _s	Chen's technique					Polat's Technique		
					X _i	X _c	R _c	n _i	n _f	X _i	X _c	R _c
0.013	41.7	16.1	1.63	0.52	-	-	-	-	-	1.42	0.71	0.52
0.013	41.7	16.2	1.56	0.52	-	-	-	-	-	1.45	0.66	0.52
0.013	58.8	23.4	1.60	0.82	1.39	0.66	0.80	3.72	1.24	1.49	0.64	0.79
0.013	58.7	23.4	1.58	0.82	1.43	0.63	0.78	2.23	1.41	1.46	0.63	0.79
0.019	23.8	9.6	1.57	0.54	-	-	-	-	-	1.28	0.56	0.54
0.019	25.2	10.5	1.52	0.57	-	-	-	-	-	1.29	0.66	0.55
0.019	40.9	16.0	1.59	0.80	-	-	-	-	-	1.45	0.73	0.78
0.019	40.4	15.8	1.58	0.79	-	-	-	-	-	1.48	0.74	0.78
0.019	61.4	23.9	1.59	1.31	1.31	0.77	1.05	3.77	1.98	1.30	0.62	1.06
0.019	62.4	24.1	1.60	1.32	1.37	0.67	1.09	3.79	1.02	1.33	0.71	1.12
0.023	61.3	23.2	1.58	1.47	1.43	0.79	1.12	2.52	2.59	1.48	0.79	1.16
0.023	61.2	23.2	1.59	1.47	1.42	0.70	1.21	2.90	1.65	1.49	0.63	1.21
0.023	61.0	23.5	1.30	1.50	1.18	0.50	1.22	2.54	1.06	1.21	0.48	1.25
0.023	61.1	23.5	1.34	1.50	1.17	0.65	1.22	3.49	1.53	1.23	0.55	1.23
0.023	60.7	23.5	1.91	1.50	1.81	1.32	1.14	2.77	2.04	1.59	0.82	1.08
0.023	62.0	23.8	1.93	1.53	1.74	0.74	1.00	3.47	1.73	1.53	0.59	1.00
0.026	20.3	7.4	1.58	0.63	-	-	-	-	-	1.36	0.57	0.59
0.026	20.5	7.5	1.59	0.63	-	-	-	-	-	1.38	0.67	0.60
0.026	41.0	15.9	1.55	1.07	-	-	-	-	-	1.37	0.73	1.01
0.026	40.0	15.5	1.57	1.05	-	-	-	-	-	1.37	0.67	1.03
0.026	61.1	23.3	1.62	1.71	1.41	0.68	1.42	3.69	2.07	1.50	0.56	1.42
0.026	61.2	23.4	1.63	1.71	1.45	0.98	1.51	3.32	2.05	1.55	0.77	1.48
0.026	69.0	25.2	1.58	1.92	1.28	0.65	1.58	3.96	1.81	1.19	0.62	1.46
0.026	80.1	28.5	1.74	2.37	1.60	0.96	2.11	3.00	2.34	1.60	0.65	2.06
0.026	80.3	28.7	1.58	2.40	1.46	0.74	2.11	2.55	1.52	1.48	0.68	2.11
0.034	23.2	9.9	1.54	0.95	-	-	-	-	-	1.33	0.64	0.84
0.034	18.8	6.9	1.55	0.78	-	-	-	-	-	1.27	0.71	0.71
0.034	42.3	17.1	1.56	1.49	-	-	-	-	-	1.32	0.64	1.32
0.034	41.9	17.1	1.51	1.49	-	-	-	-	-	1.27	0.61	1.28
0.034	59.9	22.4	1.57	2.07	1.48	0.71	1.73	2.23	1.41	1.48	0.66	1.73
0.034	60.0	22.4	1.60	2.07	1.43	0.61	1.76	1.49	1.67	1.51	0.61	1.77
0.034	70.2	25.6	1.56	2.52	1.42	0.82	1.82	3.12	2.35	1.46	0.55	1.79
0.034	70.2	25.7	1.66	2.54	1.51	0.75	1.87	3.65	1.84	1.58	0.59	1.88

- (1) Both Polat's and Chen's techniques were used to analyze drying rate curves of machine-formed paper types 1,6,7 and 8.
- (2) Only Polat's technique was used to analyze drying rate curves for paper types 2,3,4 and 5

E.2 Effect of papermaking parameters: Detailed drying data

1- Pulping process: Effect of beating

Pure kraft handsheet, B=60 g/m², Freeness=683 ml

G	T _i	T _s	X ₀	R _s	X _i	X _c	R _c
0.207	21.0	7.6	2.19	5.0	1.90	0.68	4.3
0.207	21.5	6.8	1.80	4.8	1.76	0.70	4.6
0.207	20.8	7.4	1.67	4.9	1.50	0.55	4.3
0.207	20.9	7.5	1.67	5.0	1.51	0.58	4.4
0.207	44.8	17.6	1.67	9.4	1.58	0.53	7.9
0.207	44.7	17.6	1.64	9.3	1.60	0.60	7.8
0.207	40.9	16.4	1.28	8.7	1.21	0.45	7.3
0.207	41.9	16.8	2.40	8.9	2.20	0.98	7.5
0.207	64.3	23.9	1.90	13.9	1.75	0.64	10.7
0.207	62.4	23.4	1.74	13.4	1.65	0.68	10.6
0.207	62.5	23.4	1.83	13.5	1.78	0.70	10.3
0.207	62.5	23.3	1.81	13.4	1.68	0.68	10.6
0.207	83.6	28.9	1.42	18.8	1.37	0.37	13.3
0.207	81.7	28.3	1.37	18.3	1.31	0.38	13.7
0.207	82.6	28.5	1.70	18.6	1.45	0.45	13.7
0.207	82.6	28.5	1.82	18.6	1.59	0.53	13.4
0.402	21.0	7.6	1.74	9.7	1.60	0.68	8.3
0.402	40.0	15.8	1.83	16.2	1.61	0.43	13.5
0.402	40.2	15.8	1.72	16.3	1.50	0.57	13.1
0.402	60.1	22.7	1.90	25.0	1.82	0.80	19.1
0.402	59.8	22.6	1.35	24.9	1.30	0.40	19.3
0.402	62.0	24.1	1.82	27.4	1.60	0.70	20.7
0.402	63.8	23.8	1.85	26.8	1.76	0.67	20.0
0.402	81.6	28.2	1.42	35.4	1.30	0.47	27.4
0.402	82.6	28.5	1.38	35.9	1.32	0.37	26.7
0.402	84.6	29.0	1.81	37.2	1.70	0.61	27.2
0.402	84.6	29.0	1.85	37.1	1.71	0.62	27.5

Note 1: Polat's technique has been used to analyze drying rate results.

Note 2: For comparison purposes with other types of paper only results of similar range of initial moisture content were used.

Note 3: Whenever was needed some of these experiments were analyzed using Chen's technique

Pure kraft handsheet, B=60 g/m², Freeness=435 ml

G	T _i	T _s	X ₀	R _i	X _i	X _c	R _c
0.025	21.1	7.8	1.69	0.65	1.67	0.45	0.64
0.025	20.3	8.1	1.66	0.63	1.64	0.48	0.61
0.025	20.2	8.1	1.76	0.63	1.74	0.69	0.63
0.025	40.0	15.6	2.05	0.98	1.93	0.62	0.88
0.025	40.0	15.6	1.94	0.98	1.80	0.50	0.88
0.025	61.0	22.8	2.03	1.54	1.83	0.34	1.24
0.025	60.3	22.6	1.88	1.52	1.62	0.41	1.25
0.036	21.2	7.7	1.61	0.88	1.43	0.82	0.85
0.036	41.0	15.8	1.88	1.46	1.77	0.52	1.14
0.036	40.0	15.4	1.82	1.42	1.72	0.52	1.18
0.036	60.4	22.7	1.83	2.24	1.64	0.53	1.76
0.036	60.4	22.4	1.68	2.21	1.49	0.39	1.81
0.036	81.0	28.1	1.54	3.14	1.33	0.57	2.45
0.036	83.9	28.8	1.78	3.30	1.55	0.59	2.67
0.044	20.0	7.9	1.69	1.10	1.65	0.69	1.01
0.044	20.3	7.9	1.89	1.09	1.84	0.72	1.07
0.044	20.4	8.5	2.03	1.06	1.96	0.58	1.03
0.044	40.0	15.5	1.87	1.76	1.73	0.81	1.42
0.044	42.0	16.2	1.83	1.83	1.64	0.59	1.44
0.044	60.5	22.6	1.74	2.73	1.53	0.54	2.16
0.044	60.3	22.5	1.93	2.72	1.69	0.54	2.20
0.044	81.1	27.9	1.71	3.80	1.36	0.72	3.06
0.044	82.4	28.3	1.86	3.90	1.28	0.71	3.59
0.044	82.9	28.4	1.73	3.94	1.39	0.61	3.17
0.051	20.5	8.4	1.90	1.30	1.88	0.78	1.19
0.051	20.6	8.4	2.17	1.30	2.15	0.91	1.12
0.051	41.0	15.5	1.83	2.02	1.68	0.48	1.58
0.051	41.0	15.5	1.74	2.02	1.64	0.55	1.58
0.051	60.0	22.6	1.74	3.13	1.64	0.48	2.44
0.051	62.0	23.0	1.75	3.23	1.63	0.53	2.54
0.051	81.5	27.9	1.73	4.39	1.47	0.56	3.28
0.051	80.9	27.8	1.66	4.36	1.44	0.53	3.18

Pure kraft handsheet, B=60 g/m², Freeness=258 ml

G	T _i	T _s	X _o	R _s	X _i	X _c	R _c
0.025	22.4	8.2	1.66	0.62	1.48	0.58	0.57
0.025	21.7	8.0	1.60	0.61	1.57	0.45	0.57
0.025	40.0	15.5	1.75	1.46	1.65	0.47	1.10
0.025	58.7	22.0	1.60	1.46	1.47	0.61	1.20
0.025	60.0	22.5	1.82	1.50	1.60	0.44	1.24
0.036	21.8	7.8	1.56	0.88	1.53	0.60	0.82
0.036	41.1	15.7	1.87	1.42	1.65	0.52	1.10
0.036	63.2	23.5	1.64	2.37	1.51	0.60	1.78
0.036	62.9	23.3	1.63	2.29	1.49	0.60	1.77
0.044	22.2	8.1	1.45	1.10	1.40	0.60	0.97
0.044	21.9	8.0	1.59	1.10	1.55	0.53	0.96
0.044	39.9	15.9	1.67	1.79	1.62	0.70	1.51
0.044	59.3	22.4	1.62	2.69	1.52	0.50	2.08
0.044	60.0	22.4	1.60	2.71	1.50	0.49	2.10
0.051	23.3	8.9	1.10	1.34	1.06	0.40	1.34
0.051	20.5	8.4	1.85	1.28	1.80	0.75	1.18
0.051	41.0	15.5	1.82	2.02	1.67	0.48	1.55
0.051	67.2	25.0	1.39	3.65	1.21	0.46	2.77

2- Bleach plant: Effect of bleaching

Bleached kraft handsheet, B=60g/m²

G	T _i	T _s	X _o	R _s	X _i	X _c	R _c
0.207	23.0	8.8	1.47	5.4	1.33	0.58	4.6
0.207	22.3	8.4	1.67	5.3	1.53	0.77	4.3
0.207	42.8	17.0	1.63	9.0	1.53	0.64	7.4
0.207	42.4	16.5	1.85	8.8	1.79	0.78	6.6
0.207	41.2	16.5	1.81	8.7	1.64	0.89	7.4
0.207	62.4	23.3	1.91	13.4	1.86	0.94	9.9
0.207	65.0	24.1	1.54	14.1	1.48	0.63	10.8
0.207	61.7	23.0	2.16	13.1	2.12	1.15	9.6
0.207	82.1	28.2	1.72	18.1	1.45	0.45	13.5
0.207	82.3	28.3	1.70	18.2	1.45	0.47	13.6
0.402	22.0	8.3	1.68	10.1	1.55	0.68	8.6
0.402	22.0	8.1	1.43	10.1	1.29	0.56	9.0
0.402	42.0	16.7	1.82	17.2	1.62	0.72	14.7

G	T _i	T _s	X _o	R _s	X _i	X _c	R _c
0.402	42.5	16.5	2.04	16.9	1.79	1.06	13.4
0.402	64.6	23.9	1.46	26.9	1.37	0.68	21.9
0.402	61.8	23.0	1.90	25.5	1.83	1.09	19.9
0.402	61.7	23.2	1.83	25.7	1.77	0.8	18.4
0.402	81.0	27.7	1.45	34.9	1.29	0.52	26.7

3- Paper mill: Wet pressing

Pure kraft handsheet. B=60 g/m². Wet pressed at 150 psi. Representative results

G	T _i	T _s	X _o	R _s	X _i	X _c	R _c
0.207	20.7	9.0	1.86	5.0	1.83	0.73	4.3
0.207	44.5	17.5	1.66	9.2	1.57	0.52	9.3
0.207	57.0	22.7	1.78	12.9	1.68	0.55	10.5
0.207	82.9	28.9	1.77	19.0	1.54	0.84	13.5
0.207	80.0	28.4	1.74	18.4	1.60	0.77	13.1
0.402	21.0	7.6	1.73	9.7	1.59	0.67	8.3
0.402	39.4	17.6	1.74	18.2	1.62	0.65	13.9
0.402	59.7	23.7	1.79	26.6	1.40	0.81	22.0
0.402	59.6	23.5	1.71	26.2	1.45	0.80	21.6
0.402	81.7	28.8	1.78	36.5	1.52	0.87	26.2
0.402	78.8	27.7	1.77	34.3	1.49	0.80	27.5

Pure kraft handsheet. B=60 g/m². Wet pressed at 300 psi. Representative results

G	T _i	T _s	X _o	R _s	X _i	X _c	R _c
0.207	22.5	10.5	1.70	5.0	1.60	0.50	4.3
0.207	40.2	16.9	1.71	9.0	1.66	0.69	7.1
0.207	59.3	23.1	1.93	13.3	1.84	1.1	10.2
0.207	80.4	28.5	1.97	18.5	1.64	0.71	13.9
0.207	82.0	28.9	1.84	19.0	1.60	0.49	14.5
0.402	22.7	10.0	1.77	11.3	1.68	0.65	7.7
0.402	38.9	16.7	1.91	16.7	1.76	0.79	13.5
0.402	59.0	23.1	1.80	25.5	1.63	0.70	19.3
0.402	77.6	28.2	1.82	35.2	1.55	1.08	24.7
0.402	79.9	28.5	1.88	36.0	1.58	0.69	27.0

Pure kraft handsheet. B=60 g/m². Wet pressed at 600 psi. Representative results

G	T _i	T _s	X _o	R _s	X _i	X _c	R _c
0.207	21.1	7.7	1.72	4.9	1.60	0.65	4.3
0.207	40.1	17.1	1.98	9.1	1.94	0.99	7.1
0.207	59.2	23.2	1.81	13.3	1.70	0.93	10.8
0.207	78.8	27.5	1.90	17.4	1.54	0.95	14.2
0.207	79.2	28.4	1.90	18.5	1.72	1.26	14.9
0.402	22.6	10.5	1.75	11.7	1.71	0.72	7.5
0.402	37.9	16.0	1.80	16.4	1.71	0.60	13.2
0.402	58.7	23.2	1.78	25.7	1.63	0.90	20.0
0.402	81.8	28.6	1.89	36.7	1.61	0.87	26.9
0.402	79.8	28.4	1.74	35.7	1.50	0.91	26.4

4-Paper mill: Formation

Pure kraft handsheet. B=60 g/m². Retention time=10s

G	T _i	T _s	X _o	R _s	X _i	X _c	R _c
0.207	23.3	9.1	1.85	5.5	1.82	0.59	4.6
0.207	20.5	6.8	1.87	4.8	1.85	0.73	4.6
0.207	42.2	16.9	1.89	9.0	1.82	0.9	7.5
0.207	42.9	17.0	2.00	9.0	1.93	0.71	7.5
0.207	60.5	22.7	1.93	12.9	1.81	0.81	10.1
0.207	59.0	22.5	1.76	12.7	1.67	0.78	10.5
0.207	80.1	28.1	1.92	18.0	1.74	0.99	13.0
0.207	79.6	27.9	2.25	17.8	2.01	0.78	15.9
0.402	19.7	6.5	1.83	9.0	1.74	0.58	8.9
0.402	19.6	6.5	2.00	9.0	1.95	0.65	8.7
0.402	40.4	16.6	2.04	17.0	1.83	0.99	14.3
0.402	41.0	16.7	2.06	17.2	1.93	0.91	14.0
0.402	60.0	22.9	1.88	25.2	1.70	0.78	21.1
0.402	60.4	23.1	2.02	25.6	1.65	1.12	20.2
0.402	80.3	28.1	1.91	35.2	1.55	1.45	29.9
0.402	80.6	28.1	1.93	35.0	1.52	1.50	30.0

Pure kraft handsheet, B=60 g/m². Retention time=100s

G	T _i	T _r	X _o	R _i	X _i	X _c	R _c
0.207	22.7	9.0	1.77	5.4	1.75	0.52	4.4
0.207	22.8	9.0	1.94	5.4	1.91	0.68	3.3
0.207	41.1	16.3	1.77	8.6	1.70	0.48	7.4
0.207	41.0	16.2	1.70	8.5	1.67	0.50	7.4
0.207	62.0	23.0	1.93	13.1	1.73	0.91	10.5
0.207	62.7	23.1	1.69	13.1	1.56	0.63	10.9
0.207	83.2	28.7	1.87	18.7	1.73	0.93	15.0
0.207	84.9	28.9	1.77	19.0	1.67	0.92	15.5
0.402	23.1	9.1	1.69	10.7	1.63	0.72	8.8
0.402	20.2	7.0	1.72	9.3	1.66	0.70	7.7
0.402	40.7	15.9	1.75	16.3	1.63	0.75	14.6
0.402	40.8	16.3	1.84	16.7	1.71	0.86	14.3
0.402	60.3	22.7	1.76	25.0	1.56	0.80	19.7
0.402	60.6	22.8	1.65	25.1	1.42	0.89	21.0
0.402	79.4	27.7	1.73	34.1	1.53	0.72	28.0

5- Blending

Pure TMP handsheet, B=60 g/m². Fines content=26.4%

G	T _i	T _r	X _o	R _i	Chen's technique					Polar's Technique		
					X _i	X _c	R _c	n _i	n _r	X _i	X _c	R _c
0.025	22.0	8.3	1.71	0.62	-	0.69	0.60	-	1.45	1.55	0.60	0.60
0.025	21.8	8.1	1.67	0.62	-	0.65	0.59	-	1.51	1.52	0.64	0.60
0.025	41.0	17.2	1.79	0.95	1.67	0.83	0.95	3.72	1.10	1.74	0.74	0.95
0.025	41.3	17.3	1.75	0.96	1.65	0.92	0.94	3.61	1.21	1.62	0.85	0.95
0.025	61.0	23.4	1.68	1.60	1.49	0.52	1.35	3.95	1.55	1.49	0.49	1.59
0.025	61.4	23.5	1.64	1.61	1.48	0.56	1.34	3.63	1.54	1.48	0.55	1.58
0.036	21.0	7.7	1.58	0.88	-	0.63	0.85	-	1.64	1.43	0.54	0.84
0.036	21.1	7.7	1.60	0.88	-	0.71	0.85	-	1.62	1.44	0.81	0.85
0.036	41.0	17.0	1.76	1.58	1.68	0.73	1.35	4.11	1.09	1.71	0.74	1.38
0.036	42.1	17.5	1.67	1.65	1.55	0.70	1.37	3.62	1.19	1.53	0.68	1.42
0.036	61.5	23.5	1.78	2.37	1.56	0.68	1.88	3.86	1.38	1.64	0.61	1.90
0.036	61.5	23.5	1.77	2.37	1.58	0.72	1.99	3.62	1.42	1.55	0.62	2.09
0.044	21.0	7.8	1.78	1.08	-	0.58	1.00	-	1.02	1.64	0.57	1.00
0.044	21.5	8.0	1.75	1.15	-	0.70	1.05	-	1.17	1.61	0.65	1.09
0.044	41.5	17.4	1.68	1.51	1.53	0.60	1.28	3.61	1.23	1.49	0.57	1.35

G	T _i	T _s	X _o	R _s	X _i	X _c	R _c	n _i	n _f	X _i	X _c	R _c
0.044	42.1	18.0	1.69	1.61	1.52	0.65	1.31	3.29	1.33	1.56	0.61	1.39
0.044	62.0	23.7	1.71	2.94	1.48	0.76	2.30	3.79	1.31	1.55	0.70	2.29
0.044	61.5	23.3	1.69	2.90	1.45	0.77	2.29	3.62	1.35	1.43	0.67	2.33
0.051	21	7.7	1.60	1.24	-	0.59	1.11	-	1.40	1.59	0.55	1.11
0.051	20	8.9	1.72	1.34	-	1.10	1.08	-	1.61	1.55	0.85	1.08
0.051	43.0	19.3	1.83	2.34	1.79	0.89	1.79	2.32	1.05	1.81	0.85	1.82
0.051	43.0	18.8	1.78	2.34	1.58	0.80	1.80	3.86	1.38	1.75	0.83	1.83
0.051	62.0	23.6	2.01	3.35	1.80	0.89	2.56	3.86	1.16	1.98	0.85	2.58
0.051	61.5	23.3	1.69	3.28	1.45	0.69	2.65	3.67	1.23	1.43	0.65	2.68

Note 1: The slight differences between R_c, X_i, X_c determined by these two techniques may disappear here as the data has been round off.

Pure TMP handsheet, B=60 g/m², Fines content=20%. Representative results

G	T _i	T _s	X _o	R _s	Chen's technique					Polat's Technique		
					X _i	X _c	R _c	n _i	n _f	X _i	X _c	R _c
0.025	22.5	10.5	1.66	0.72	-	0.68	0.61	-	1.64	1.51	0.59	0.62
0.025	40.0	17.2	1.80	1.08	1.75	0.77	0.90	3.65	1.10	1.79	0.73	0.90
0.025	62.0	24.0	1.69	1.66	1.52	0.47	1.32	3.83	1.26	1.59	0.48	1.32
0.036	23.0	10.7	1.76	1.07	-	0.87	0.86	-	1.38	1.54	0.73	0.86
0.036	43.0	18.6	1.67	1.74	1.62	0.70	1.34	4.25	1.23	1.64	0.65	1.36
0.036	62.0	24.0	1.75	2.44	1.62	0.60	1.94	3.89	1.09	1.65	0.50	1.95
0.044	23.0	10.6	1.72	1.30	-	0.70	1.02	-	1.14	1.56	0.68	1.03
0.044	43.0	18.6	1.72	2.14	1.66	0.71	1.63	4.24	1.36	1.69	0.63	1.65
0.044	61.0	23.7	1.60	2.94	1.50	0.55	2.26	3.90	1.19	1.53	0.51	2.26
0.051	23.0	10.3	1.70	1.47	-	0.74	1.07	-	1.05	1.46	0.67	1.09
0.051	42.5	18.4	1.72	2.42	1.62	0.61	1.83	3.10	1.01	1.67	0.55	1.83
0.051	63.0	24.2	1.65	3.44	1.47	0.69	2.69	3.76	1.08	1.53	0.66	2.69

TMP-kraft blend handsheet, 75% TMP+25% kraft, B=60 g/m², Representative results

G	T _i	T _s	X _o	R _s	Chen's technique					Polat's Technique		
					X _i	X _c	R _c	n _i	n _r	X _i	X _c	R _c
0.025	24.5	9.8	1.85	0.69	-	1.14	0.64	-	1.14	1.70	0.65	0.61
0.025	43.5	17.7	1.91	1.12	1.85	0.48	0.98	4.31	1.08	1.88	0.47	0.98
0.025	63.0	24.0	2.03	1.66	1.90	0.84	1.45	3.99	2.08	1.86	0.67	1.46
0.036	23.5	9.7	1.65	0.98	-	0.55	0.93	-	1.11	1.60	0.53	0.95
0.036	42.0	17.0	1.86	1.58	1.81	0.80	1.31	4.39	1.62	1.80	0.65	1.30
0.036	63.5	24.0	2.01	2.43	1.89	1.07	2.04	3.79	1.71	1.93	0.96	2.03
0.044	23.5	9.3	1.86	1.19	-	0.57	1.14	-	1.51	1.68	0.53	1.14
0.044	42.0	17.0	2.04	1.93	1.99	0.95	1.56	4.41	1.41	1.98	0.81	1.56
0.044	63.5	23.9	1.95	2.97	1.84	0.76	2.88	3.80	1.32	1.88	0.74	2.89
0.051	25.0	9.7	1.83	1.41	-	0.55	1.15	-	1.20	1.65	0.53	1.16
0.051	43.0	17.4	1.89	2.27	1.85	0.70	1.88	3.06	1.43	1.86	0.63	1.86
0.051	63.5	24.0	1.76	3.45	1.61	0.61	2.77	3.85	1.41	1.58	0.51	2.81

TMP-kraft blend handsheet, 50% TMP+50% kraft, B=60 g/m², Representative results

G	T _i	T _s	X _o	R _s	Chen's technique					Polat's Technique		
					X _i	X _c	R _c	n _i	n _r	X _i	X _c	R _c
0.025	23.5	9.5	1.99	0.67	-	0.56	0.67	-	1.66	1.82	0.38	0.66
0.025	41.0	17.1	2.08	1.07	2.02	1.23	0.92	4.23	2.28	2.05	1.1	0.94
0.025	62.8	23.9	1.90	1.66	1.79	0.78	1.46	3.87	2.10	1.76	0.57	1.46
0.036	23.5	9.4	1.82	0.98	-	0.51	0.93	-	1.07	1.66	0.53	0.95
0.036	40.0	16.8	1.81	1.56	1.76	0.79	1.25	4.31	2.29	1.79	0.72	1.25
0.036	64.0	24.2	1.95	2.47	1.84	0.56	2.00	4.03	1.73	1.86	0.55	2.03
0.044	23.5	9.2	1.96	1.19	-	0.60	1.14	-	1.47	1.78	0.57	1.14
0.044	42.0	17.2	1.91	1.95	1.84	0.76	1.73	3.95	1.69	1.87	0.71	1.74
0.044	63.5	23.9	2.04	2.99	1.93	0.90	2.37	4.05	1.77	1.87	0.78	2.41
0.051	21.0	7.6	1.96	1.23	-	0.79	1.14	-	1.90	1.83	0.61	1.14
0.051	42.5	17.3	1.96	2.26	1.93	1.34	1.67	1.87	2.14	1.45	0.81	1.44
0.051	64.0	24.0	1.86	3.45	1.73	0.61	2.77	3.92	1.33	1.68	0.58	2.81

TMP-kraft blend handsheet. 25% TMP+75% kraft. B=60 g/m². Representative results

G	T _i	T _s	X _o	R _s	Chen's technique					Polar's Technique		
					X _i	X _c	R _c	n _i	n _f	X _i	X _c	R _c
0.025	25.5	10.2	1.69	0.70	-	0.48	0.65	-	1.39	1.61	0.44	0.65
0.025	40.0	16.8	1.75	1.06	1.72	0.98	0.99	3.92	2.36	1.72	0.72	0.97
0.025	60.0	23.8	1.92	1.64	1.88	0.63	1.17	2.54	2.85	1.88	0.49	1.15
0.036	25.5	10.2	1.94	1.04	-	0.62	0.91	-	1.21	1.83	0.58	0.90
0.036	41.5	17.4	1.86	1.62	1.81	0.48	1.34	4.23	1.55	1.83	0.48	1.33
0.036	62.3	24.1	1.84	2.46	1.78	0.80	1.91	2.96	2.59	1.78	0.71	1.91
0.044	25.5	10.2	1.76	1.27	-	0.42	1.04	-	1.05	1.56	0.45	1.09
0.044	41.5	17.4	1.79	1.99	1.77	0.73	1.68	4.17	1.93	1.76	0.58	1.65
0.044	63.0	22.7	1.70	2.76	1.63	0.91	2.56	3.80	2.31	1.63	0.79	2.57
0.051	25.5	10.1	1.79	1.45	-	0.62	1.24	-	2.46	1.70	0.41	1.24
0.051	42.0	17.5	1.79	2.30	1.77	1.31	1.89	2.94	2.02	1.78	0.80	1.65
0.051	64.5	24.5	1.91	3.54	1.84	1.05	2.86	3.40	2.37	1.82	0.87	2.84

Appendix F

Characterization of pulp and specifications of PM paper

The freeness of unbleached laboratory kraft pulp, 100% black spruce, and the physical properties of the kraft handsheets are as follows:

Canadian standard freeness, ml	685
Basis weight, g/m ² (O.D.)	59.8
Caliper, μm	120.1
Bulk, cm ³ /g	2.01
Burst index, kPam ² /g	1.96
Tear index, mNm ² /g	21.05
Breaking length, km	3.30
Stretch, %	1.77
Toughness index, mJ	37
Stress-strain factor, mJ/g	417
Zero-span breaking length, km (Pulmac)	16.84
Tensile index, Nm/g	32.38
TEA, J/m ²	24.97

The physical properties of the handsheets made from the ThermoMechanical Pulp received from Donohue Normick mill in Amos, Quebec are reported below. This pulp was taken from the disc filter segments prior to any sulphite or hydrosulfite addition. EDTA (a sequestering agent) had been added.

Canadian standard freeness, ml	168
Basis weight, g/m ² (O.D.)	60.0
Caliper, μm	205
Bulk, cm ³ /g	3.82
Burst index, kPam ² /g	1.12
Tear index, mNm ² /g	6.3

Stretch, %	1.7
Zero-span breaking length, km (Pulmac)	10.2
Tensile index, Nm/g	24.6
TEA, J/m ²	233

Tables F.1, F.2 and F.3 show the physical properties of the machine-formed paper as received.

Table F.1 Physical properties of uncalendered papermachine papers

Physical property	Paper Types									
	1	2	3	4	5	6	7	8	9	10
Caliper	129	170	158	136	137	148	123	108	104	122
Basis weight, g m ⁻²	42.8	57.3	47.5	43.8	44.0	44.2	44.5	47.7	68.5	81.7
Tear Index(MD), mNm ² /g	7.1	7.7	7.5	7.7	7.8	7.9	6.6	6.2	7.6	7.6
Tear Index(MD), mNm ² /g	6.8	7.7	7.8	7.5	6.4	7.3	6.4	7.5	8.9	7.9
Bulk, cm ³ /g	2.83	2.84	3.12	2.91	2.91	3.17	2.62	2.14	1.50	1.43
T.E.A.(CD), mJ/g	443	513	301	228	364	256	246	218	708	834
T.E.A.(MD), mJ/g	619	276	621	535	555	514	340	418	1019	862
Stretch(MD), %	2.54	2.42	2.13	2.03	1.27	1.88	2.11	1.69	3.00	3.32
Stretch(CD), %	0.29	0	1.50	0	0	1.33	1.25	1.15	2.07	2.31
Tensile(MD), kN/m	3.31	4.96	3.37	3.79	3.68	3.01	2.74	3.05	5.82	6.64
Tensile(CD), kN/m	1.11	1.84	1.04	0.76	1.27	0.96	0.82	0.92	2.15	2.76
Breaking length(MD), km	7.90	8.88	7.23	8.81	8.53	6.94	6.69	6.52	8.67	8.30
Breaking length(CD), km	2.60	3.27	2.38	1.77	2.95	2.23	2.09	1.96	3.21	3.45

Table F.2 Suppliers of papermachine paper used in chapter 2

Paper type	Paper company
1	Soucy (Riviere du Loup)
2	Abitibi (Beaupre)
3	Domtar (Donnacona)
4	Kruger (Bromptonville)
5	Kruger (Corner Brook)
6	Kruger
7	Quebec & Ontario (Thorold)
8	Boise Cascade (Fort Frances)
9	Domtar (Windsor)
10	Domtar (Windsor)

Table F.3 Physical properties of sack paper

Paper type		1	2	3	4	5	6	7	8	9	10	11	12	13	14
Property	Units														
Grammage	g/m ²	53.0	78.5	44.7	46.9	42.6	52.4	46.7	79.7	45.7	47.3	100.3	95.6	54.7	61.0
Caliper	µm	111	138	72	101	97	103	102	138	100	98	188	156	112	122
Specific volume	cm ³ /g	2.09	1.76	1.61	2.16	2.27	1.97	2.19	1.73	2.18	2.07	1.87	1.63	2.05	1.99
Apparent density	g/cm ³	0.48	0.57	0.62	0.46	0.44	0.51	0.46	0.58	0.46	0.48	0.53	0.61	0.49	0.50
Bendtsen air per.	ml/min	898	316	506	440	772	440	1485	303	816	584	1100	440	656	660
Air resist., Gurley	s/100	11.4	34.8	18.1	22.6	10.9	23.8	6.4	35.1	11.9	14.5	8.1	21.4	12.8	14.5
Freeness	ml	394	489	598	474	321	322	357	484	348	460	603	588	406	506
Fibre sat. point	kg/kg	0.88	0.85	0.68	0.91	0.94	0.89	0.88	0.83	0.91	0.92	0.99	0.83	0.87	0.88
Lt. Abs. coeff.	m ² /kg	18.8	16.7	0.78	27.0	22.8	20.5	21.6	16.2	21.8	20.7	17.3	12.5	19.3	23.2
Lt Scat. coeff.	m ² /kg	28.5	26.1	32.7	26.1	26.3	30.0	28.8	28.8	25.6	25.6	16.1	23.5	26.9	28.3
Fines content	100	14.4	34.8	18.1	22.6	10.9	23.8	6.4	35.1	11.9	14.5	8.1	21.4	12.8	14.5

Appendix G

Drying air properties for permeability calculation

Physical properties of air are calculated at the mean pressure, i.e. $\frac{1}{2}(P_i + P_o) = P_o + \frac{\Delta P}{2}$ where $P_o \approx 101.325$ kPa. The physical properties of air and water vapor are calculated at the mean conditions. The viscosity of moist air is calculated using the semiempirical formula of Wilke given by Bird et al. [1960].

$$\mu_{mix} = \frac{\sum_{i=1}^n \frac{x_i \mu_i}{\sum_{j=1}^n x_j \Omega_{ij}}}$$

in which

$$\Omega_{ij} = \frac{1}{\sqrt{8}} \left(1 + \frac{M_i}{M_j}\right)^{-\frac{1}{2}} \left[1 + \left(\frac{\mu_i}{\mu_j}\right)^{\frac{1}{2}} \left(\frac{M_j}{M_i}\right)^{\frac{1}{4}}\right]^2$$

where n is the number of chemical species in the mixture: x_i and x_j are the mole fractions of species i and j ; μ_i and μ_j are the viscosities of species i and j ; and M_i and M_j are the corresponding molecular weights. Ω_{ij} is dimensionless and, when $i=j$, $\Omega_{ij}=1$. However the viscosity difference between moist and dry air is always less than 2% for the present experimental conditions.

Appendix H

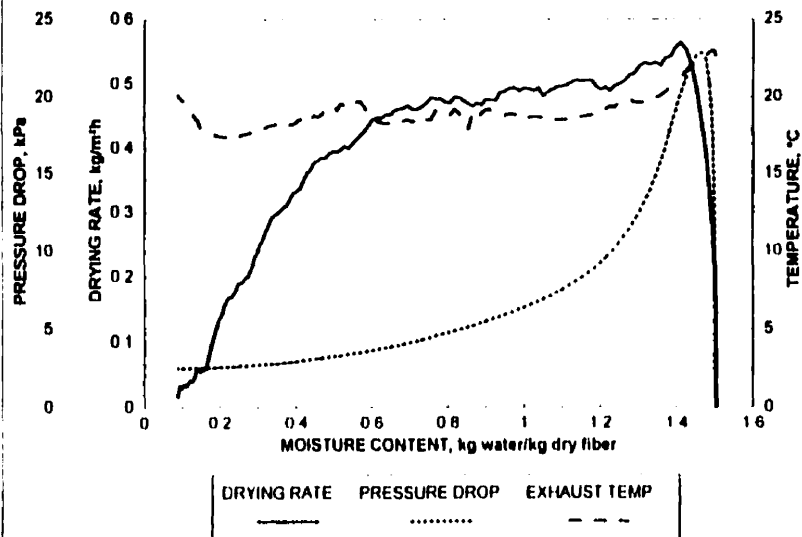
Values of exponent “n” in Eqn. 2.1 for PM paper

Table H.1 Values of exponent n in Equation 2.1 for machine-formed printing paper

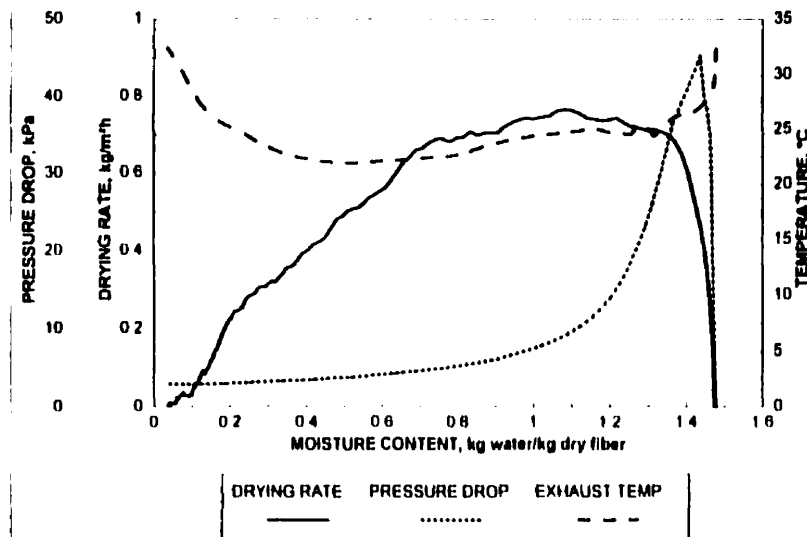
Moisture Content [kg/kg]	Paper Type 1			Paper Type 2			Paper Type 3			Paper Type 4			Paper Type 5		
	n	σ_n	R ²	n	σ_n	R ²	n	σ_n	R ²	n	σ_n	R ²	n	σ_n	R ²
0	0.968	0.054	0.887	0.976	0.054	0.892	0.979	0.061	0.915	0.938	0.064	0.885	1.207	0.036	0.968
0.1	0.964	0.049	0.902	0.972	0.050	0.905	0.980	0.061	0.916	0.947	0.060	0.899	1.028	0.035	0.970
0.2	0.952	0.043	0.936	0.963	0.046	0.917	0.986	0.059	0.921	0.956	0.045	0.943	1.026	0.034	0.971
0.3	0.952	0.045	0.93	0.968	0.045	0.919	0.989	0.058	0.923	0.962	0.043	0.948	1.028	0.034	0.971
0.4	0.949	0.048	0.935	0.979	0.046	0.918	0.991	0.058	0.925	0.964	0.042	0.950	1.024	0.033	0.972
0.5	0.943	0.051	0.936	0.991	0.048	0.916	0.994	0.056	0.929	0.959	0.041	0.951	1.022	0.034	0.972
0.6	0.955	0.046	0.958	1.006	0.050	0.912	0.998	0.054	0.935	0.958	0.040	0.953	1.026	0.035	0.970
0.7	0.949	0.048	0.954	1.020	0.052	0.906	1.009	0.051	0.942	0.953	0.040	0.954	1.035	0.037	0.966
0.8	0.946	0.049	0.951	1.039	0.057	0.895	1.029	0.051	0.945	0.949	0.041	0.951	1.051	0.040	0.962
0.9	0.963	0.046	0.966	1.057	0.064	0.874	1.061	0.051	0.948	0.947	0.042	0.947	1.076	0.045	0.956
1.0	0.968	0.053	0.954	1.071	0.078	0.831	1.106	0.054	0.946	0.952	0.043	0.945	1.119	0.051	0.949
1.1	0.992	0.079	0.908				1.172	0.065	0.935	0.965	0.047	0.937	1.182	0.067	0.923
1.2							1.245	0.82	0.912	0.993	0.06	0.909	1.270	0.093	0.880
1.3							1.337	0.112	0.867	1.020	0.098	0.811	1.254	0.112	0.844

Moisture Content [kg/kg]	Paper Type 6			Paper Type 7			Paper Type 8			Paper Type 9			Paper Type 10		
	n	σ_n	R ²	n	σ_n	R ²	n	σ_n	R ²	n	σ_n	R ²	n	σ_n	R ²
0	0.912	0.042	0.944	0.959	0.043	0.946	0.951	0.042	0.866	0.847	0.051	0.904	0.843	0.041	0.932
0.1	0.908	0.039	0.951	0.967	0.043	0.948	0.948	0.039	0.959	0.845	0.048	0.914	0.846	0.038	0.943
0.2	0.910	0.037	0.955	0.976	0.043	0.976	0.941	0.038	0.959	0.853	0.047	0.919	0.854	0.038	0.944
0.3	0.920	0.036	0.958	0.981	0.043	0.949	0.944	0.037	0.959	0.858	0.057	0.919	0.859	0.039	0.940
0.4	0.923	0.036	0.960	0.983	0.042	0.950	0.944	0.064	0.962	0.904	0.045	0.904	0.872	0.044	0.928
0.5	0.931	0.036	0.961	0.983	0.043	0.953	0.945	0.034	0.964	0.854	0.046	0.928	0.910	0.067	0.860
0.6	0.947	0.037	0.960	0.986	0.045	0.951	0.947	0.034	0.967	0.887	0.063	0.930			
0.7	0.957	0.038	0.957	0.988	0.047	0.947	0.943	0.034	0.968	0.938	0.105	0.889			
0.8	0.966	0.038	0.959	0.990	0.049	0.940	0.955	0.035	0.966						
0.9	0.980	0.037	0.961	1.003	0.052	0.938	0.964	0.037	0.964						
1.0	0.987	0.035	0.966	1.026	0.070	0.934	0.988	0.043	0.953						
1.1	1.006	0.037	0.964	1.074	0.131	0.897	1.045	0.070	0.898						
1.2	1.026	0.040	0.960												
1.3	1.052	0.050	0.944												

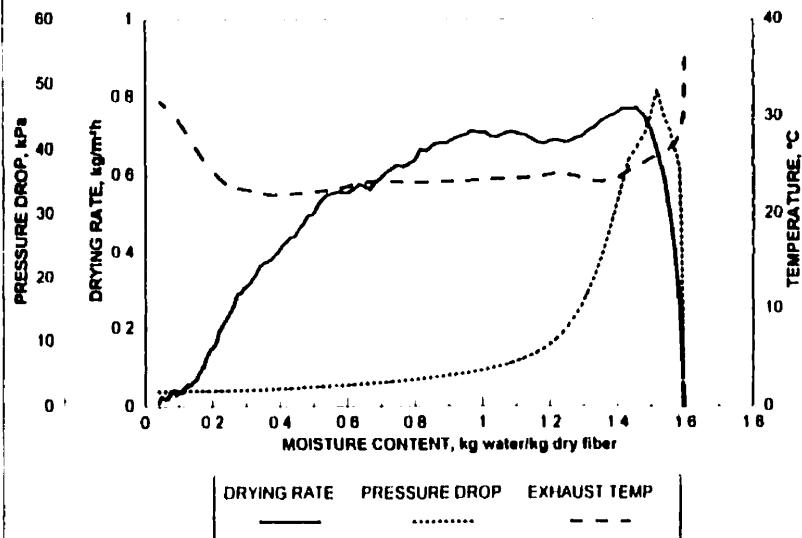
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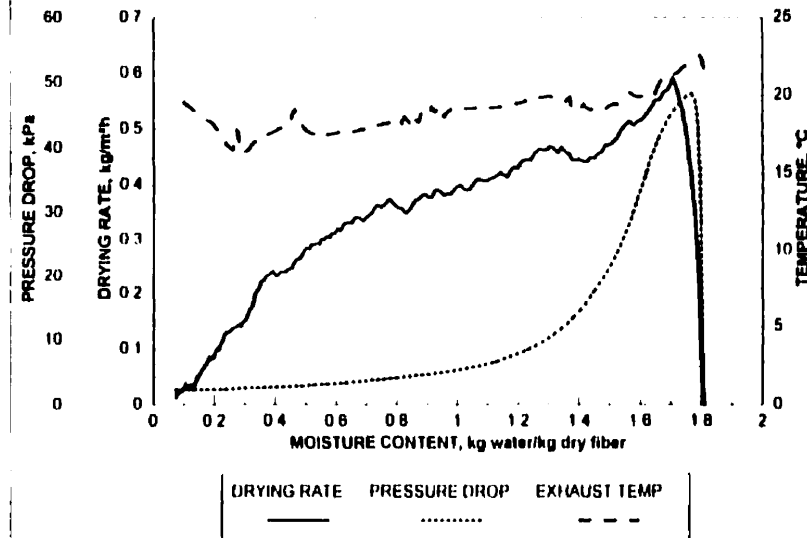
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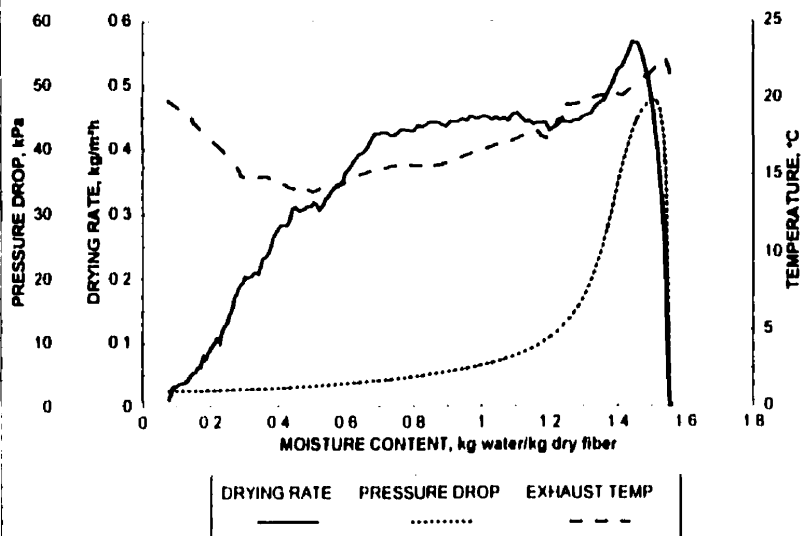
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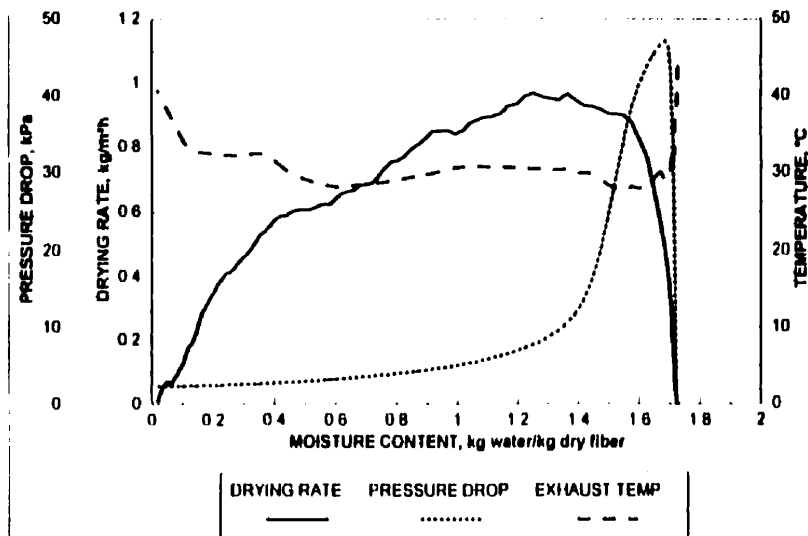
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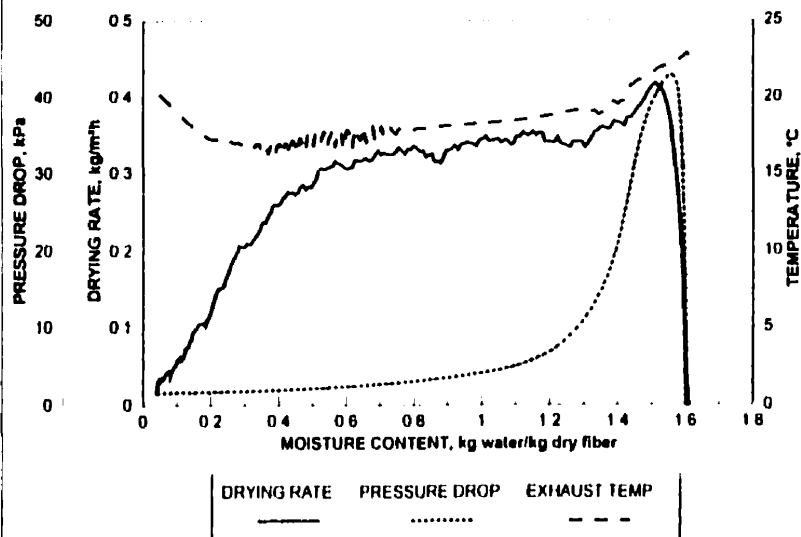
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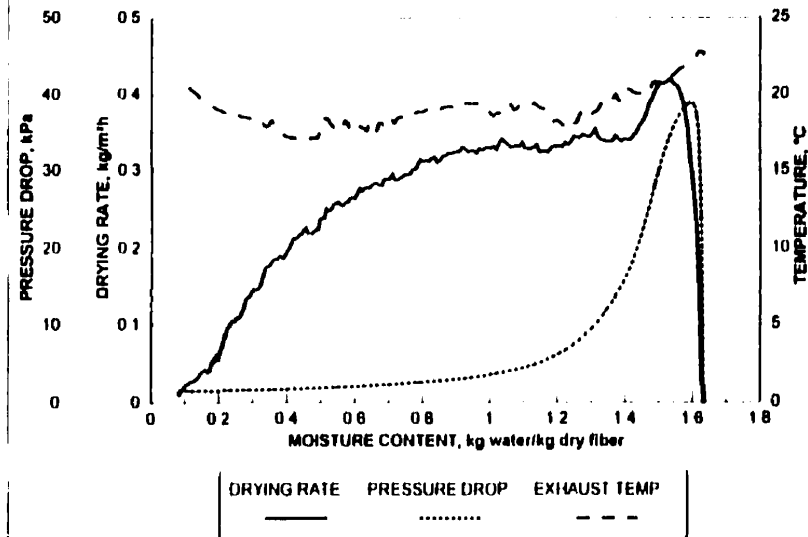
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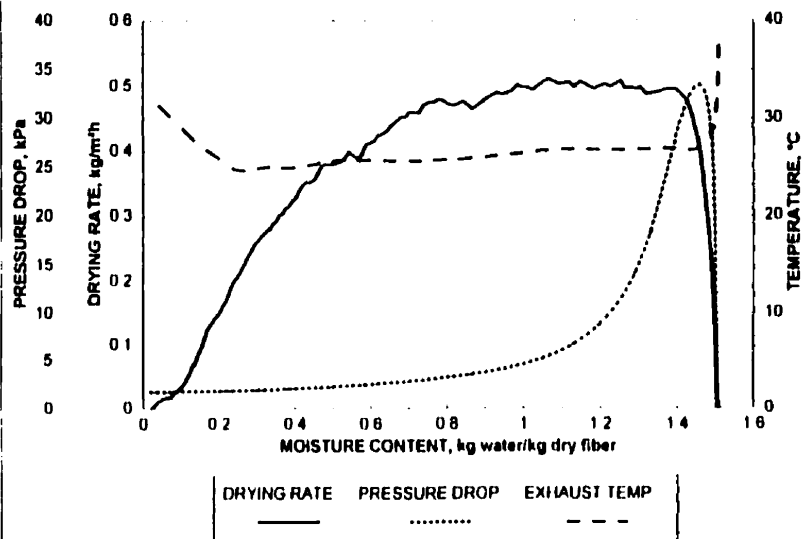
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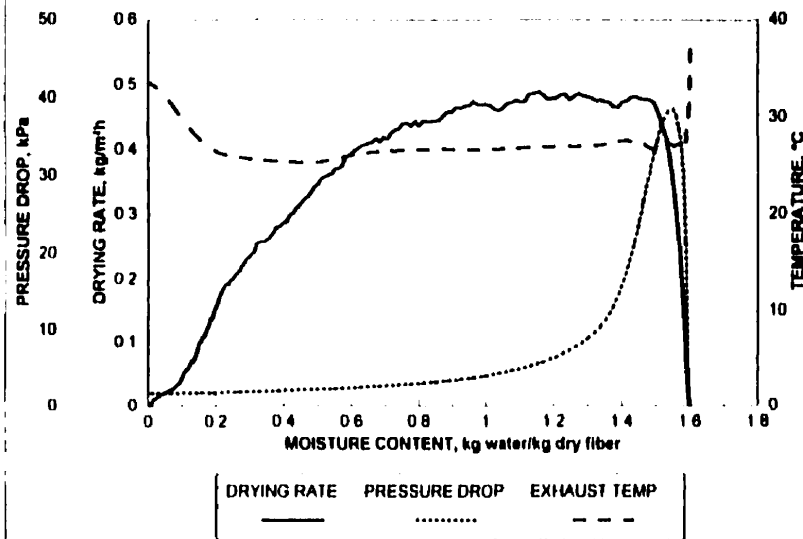
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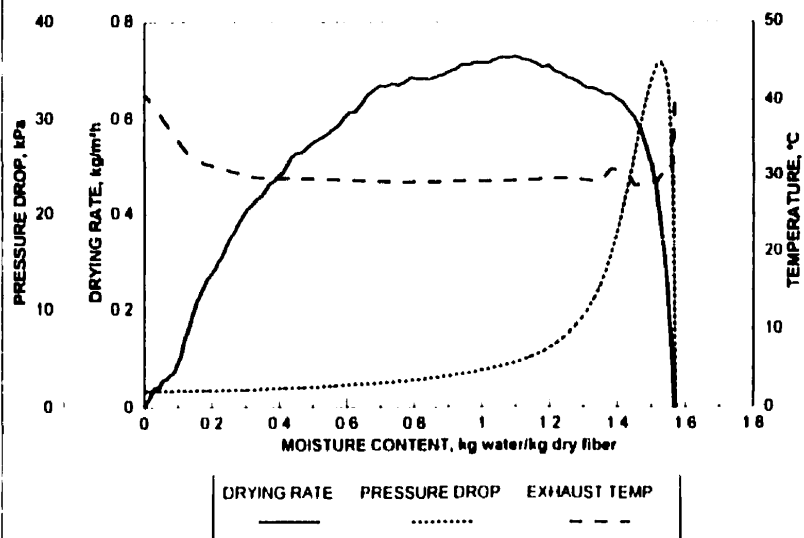
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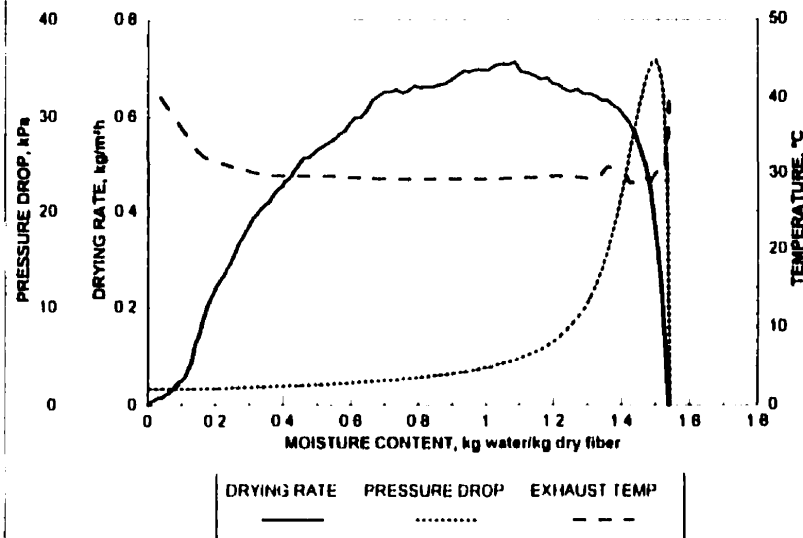
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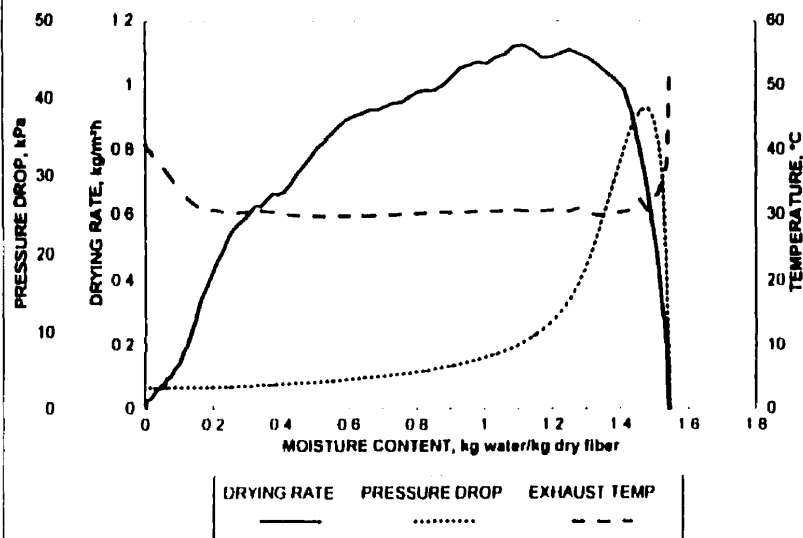
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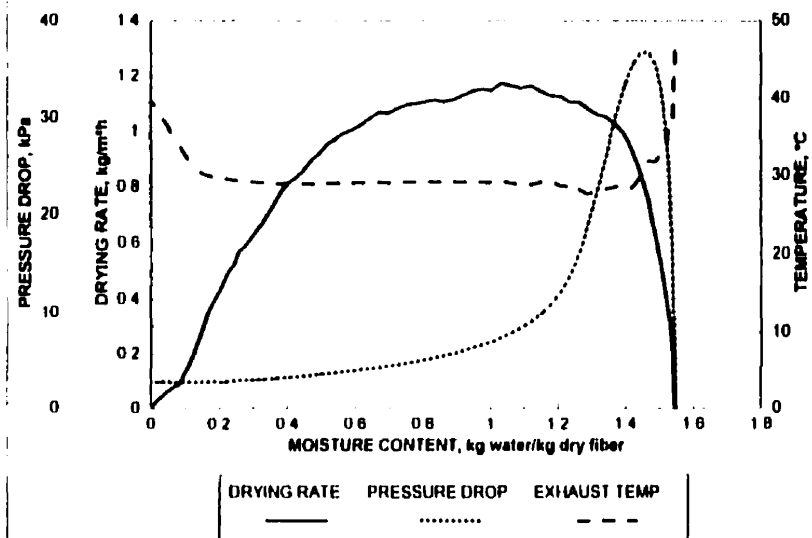
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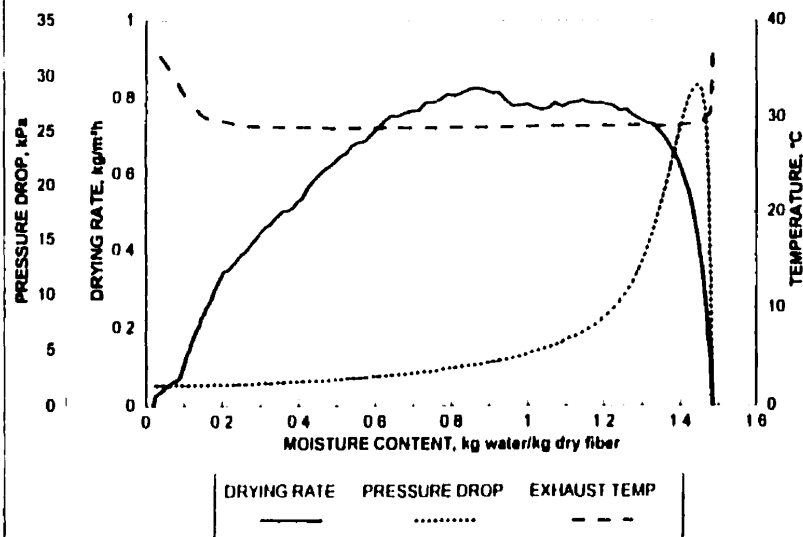
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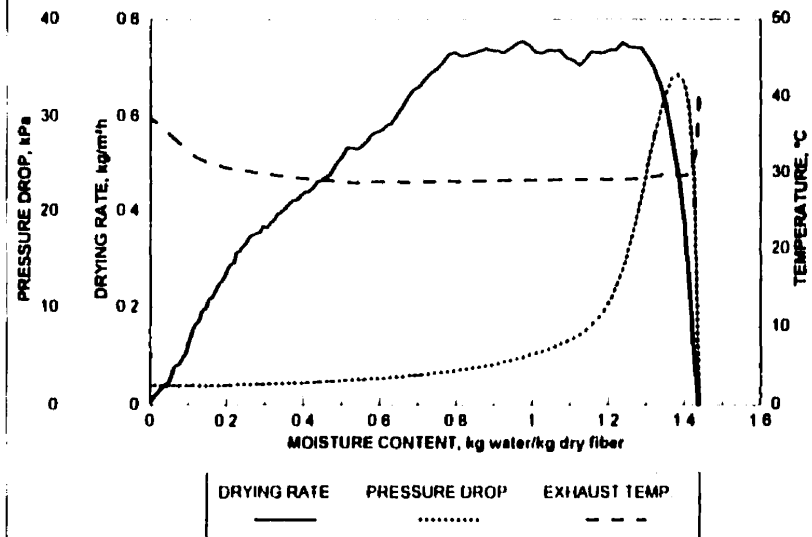
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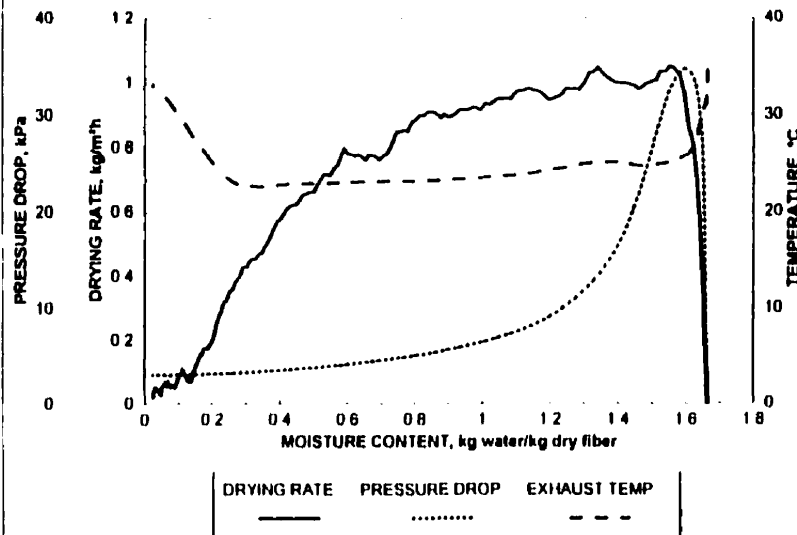
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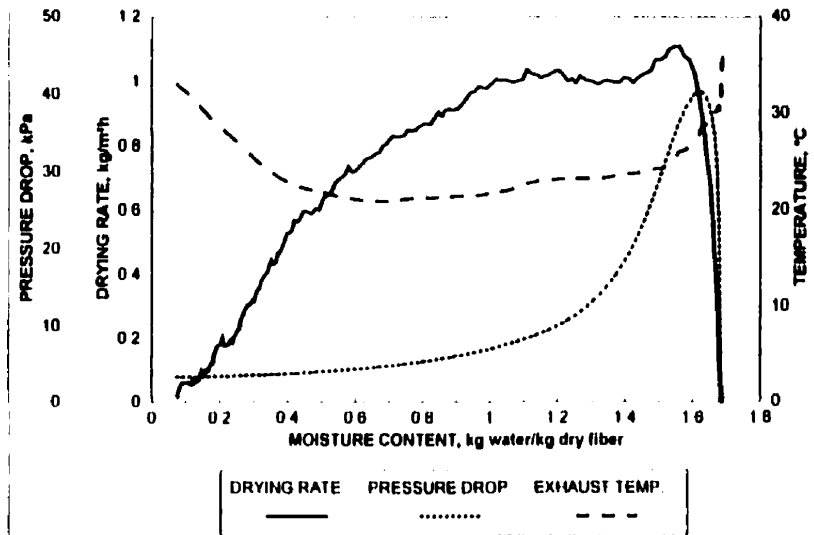
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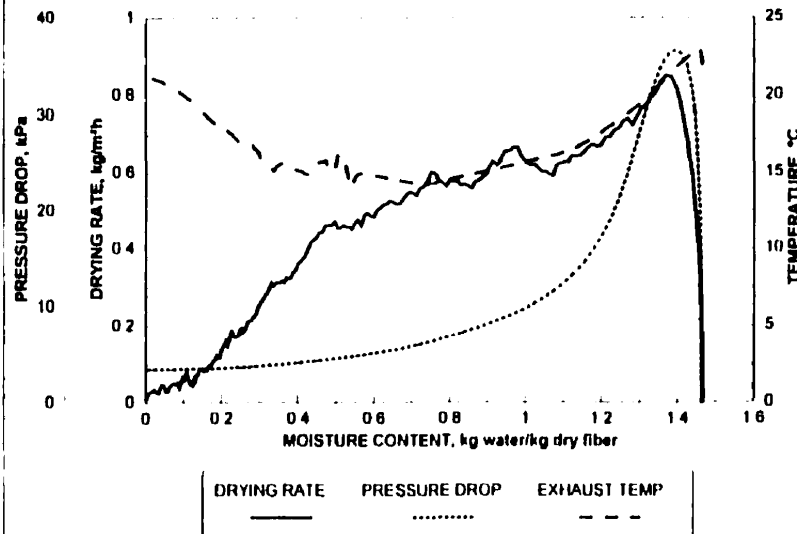
PAPER TYPE #1, B=42.8g/m², Ti=41.4°C, G=0.0265kg/m²s



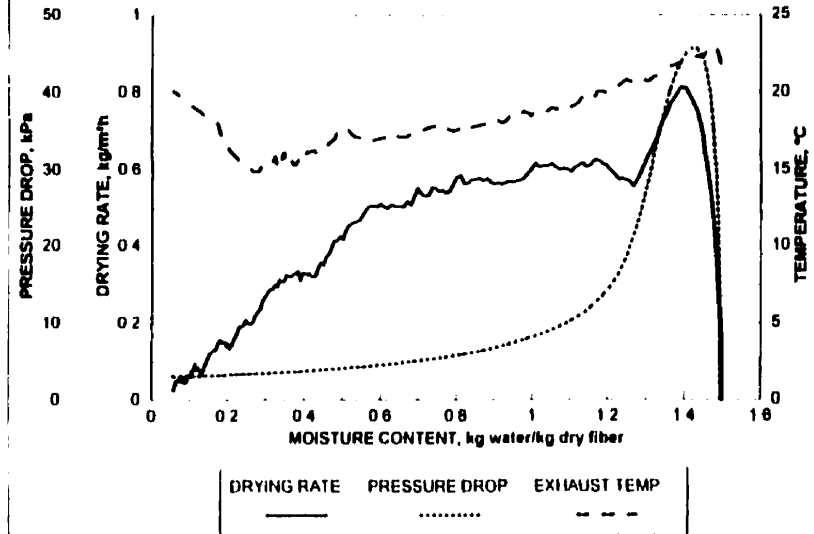
PAPER TYPE #1, B=42.8g/m², Ti=41.2°C, G=0.0265kg/m²s



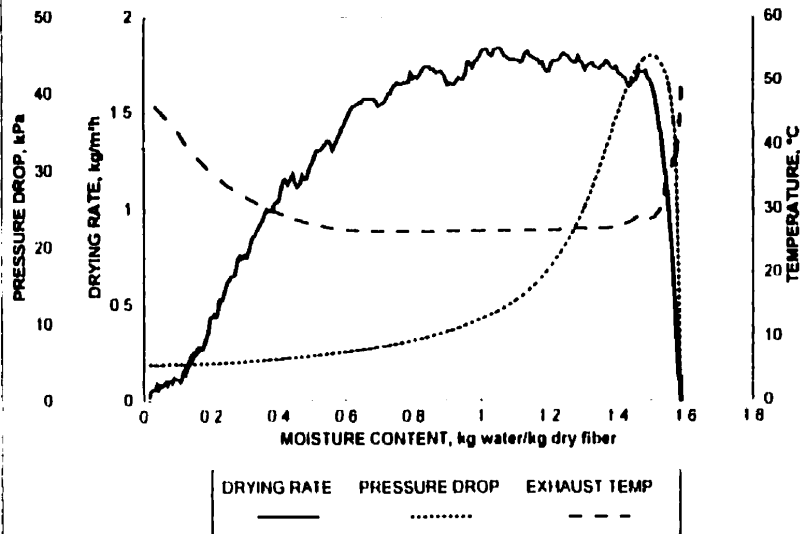
PAPER TYPE #1, B=42.8g/m², Ti=21.5°C, G=0.0265kg/m²s



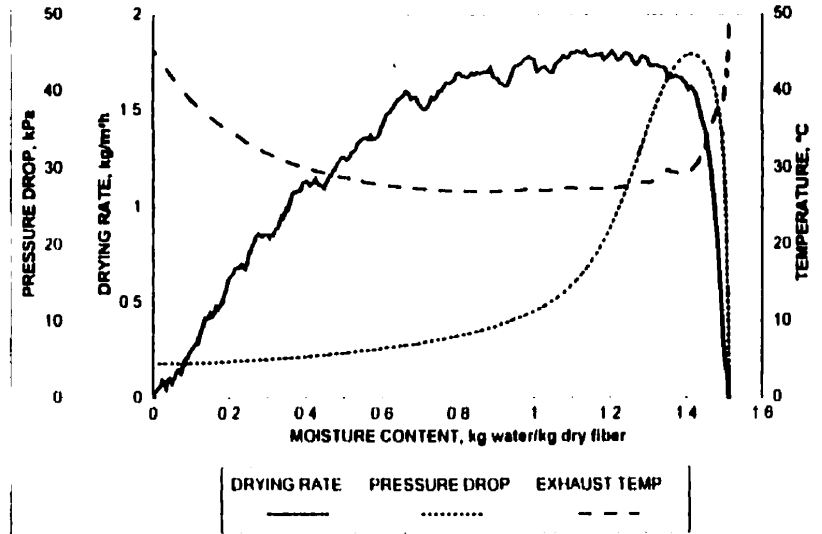
PAPER TYPE #1, B=42.8g/m², Ti=21.4°C, G=0.0265kg/m²s



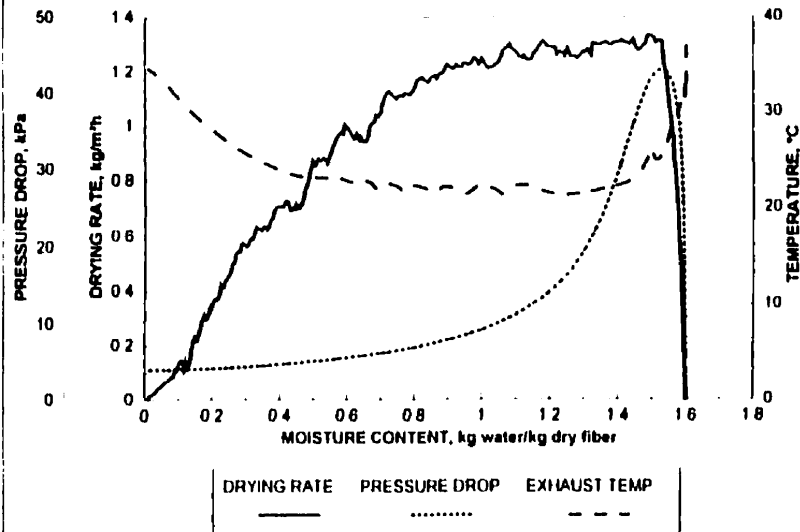
PAPER TYPE #1, B=42.8g/m², Ti=62.0°C, G=0.034kg/m²s



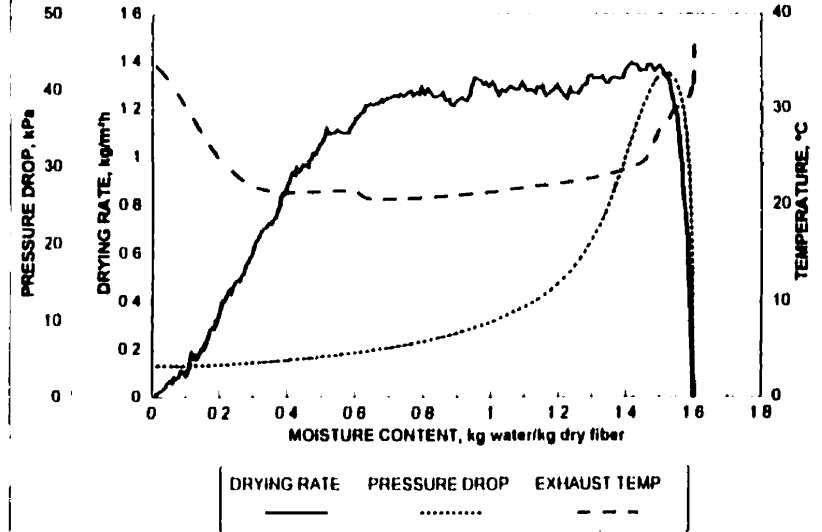
PAPER TYPE #1, B=42.8g/m², Ti=61.7°C, G=0.034kg/m²s



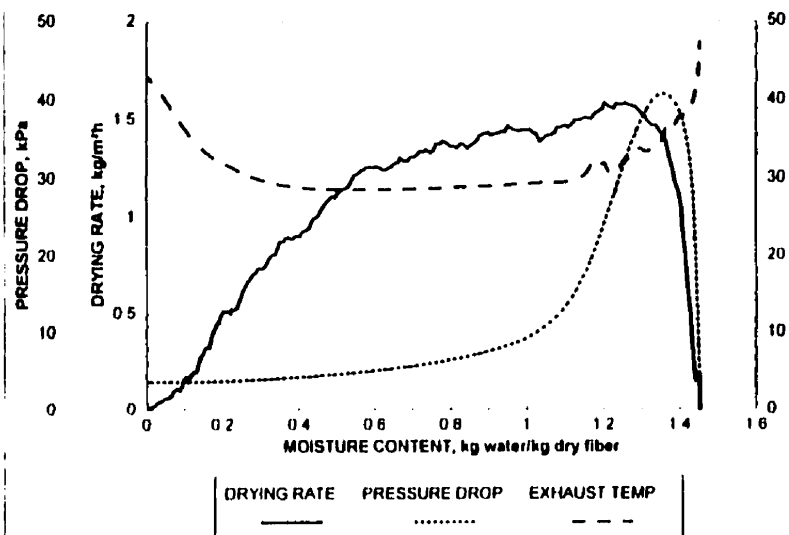
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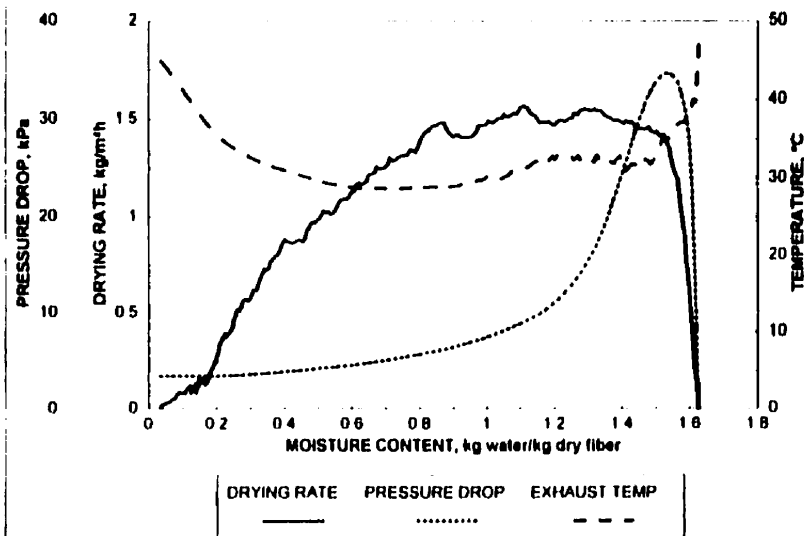
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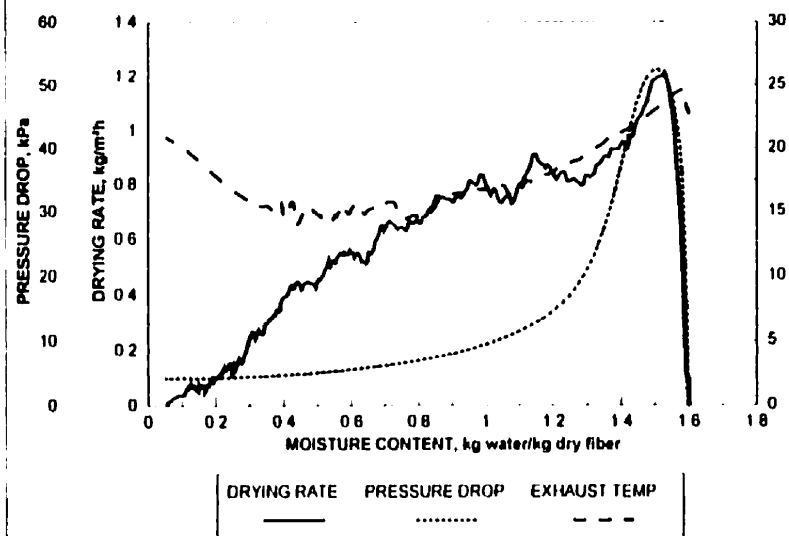
PAPER TYPE #1, B=42.8g/m², Ti=62.6°C, G=0.0265kg/m²s



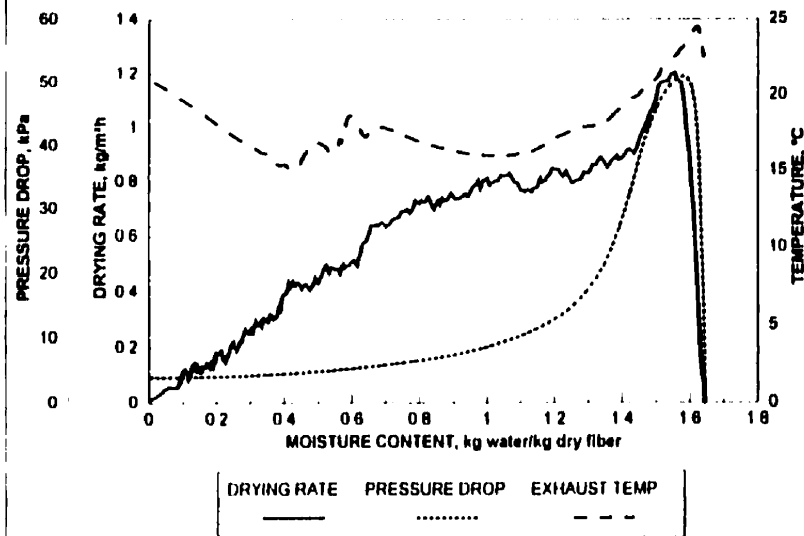
PAPER TYPE #1, B=42.8g/m², Ti=62.5°C, G=0.0265kg/m²s



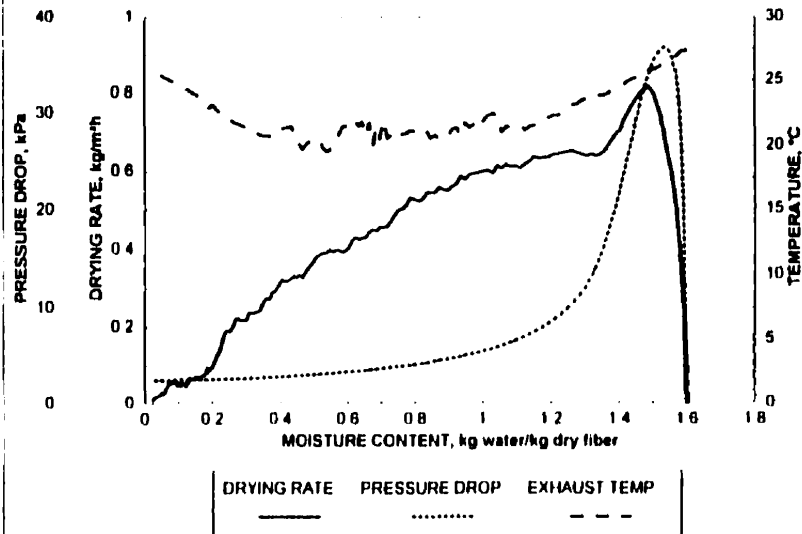
PAPER TYPE #1, B=42.8g/m², Ti=22.4°C, G=0.034kg/m²s



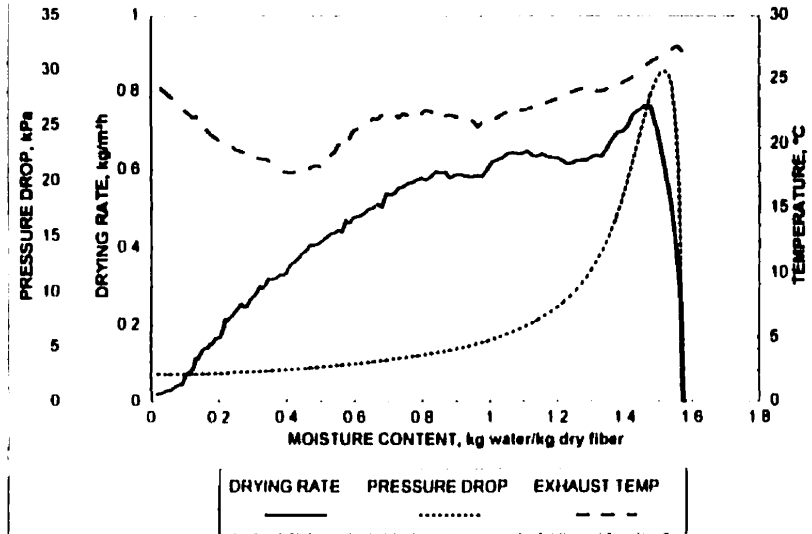
PAPER TYPE #1, B=42.8g/m², Ti=22.3°C, G=0.034kg/m²s



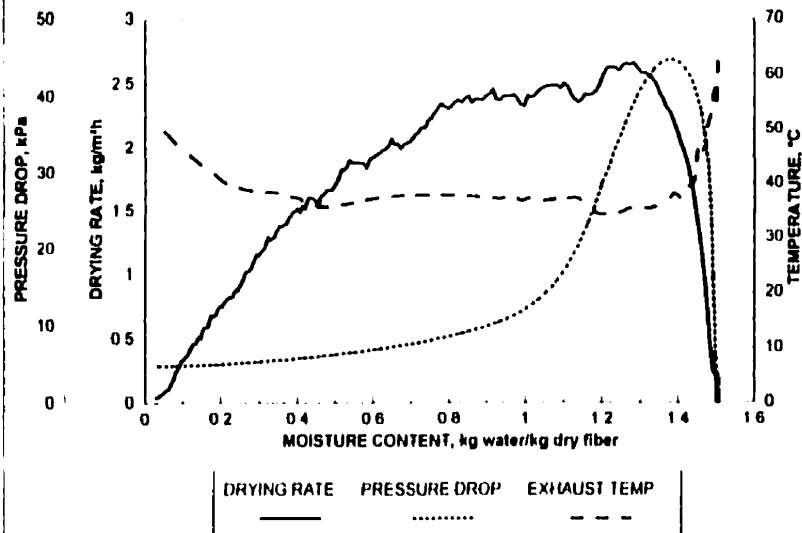
PAPER TYPE #1, $B=42.8\text{g/m}^2$, $T_i=27.1^\circ\text{C}$, $G=0.0195\text{kg/m}^2\text{s}$



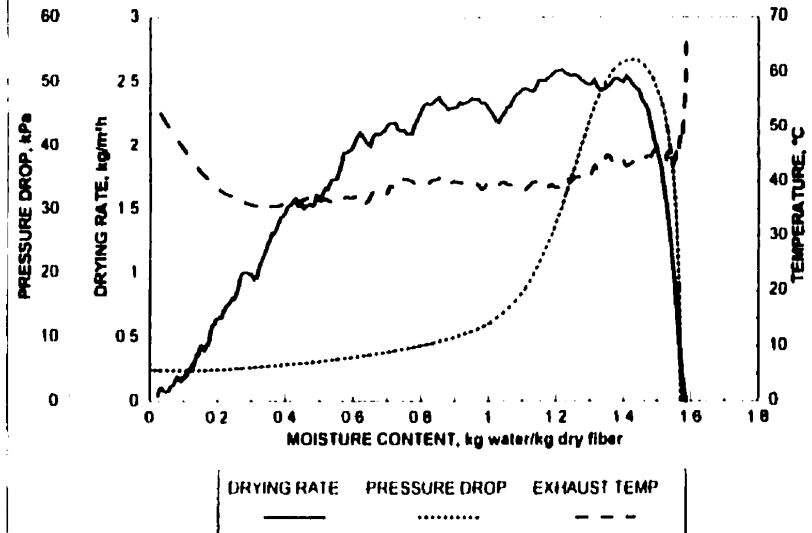
PAPER TYPE #1, $B=42.8\text{g/m}^2$, $T_i=27.2^\circ\text{C}$, $G=0.0195\text{kg/m}^2\text{s}$



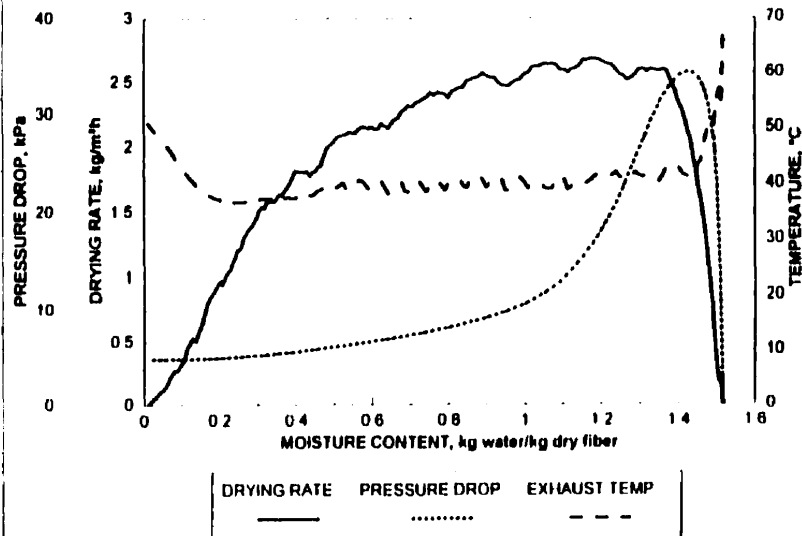
PAPER TYPE #1, $B=42.8\text{g/m}^2$, $T_i=77.7^\circ\text{C}$, $G=0.034\text{kg/m}^2\text{s}$



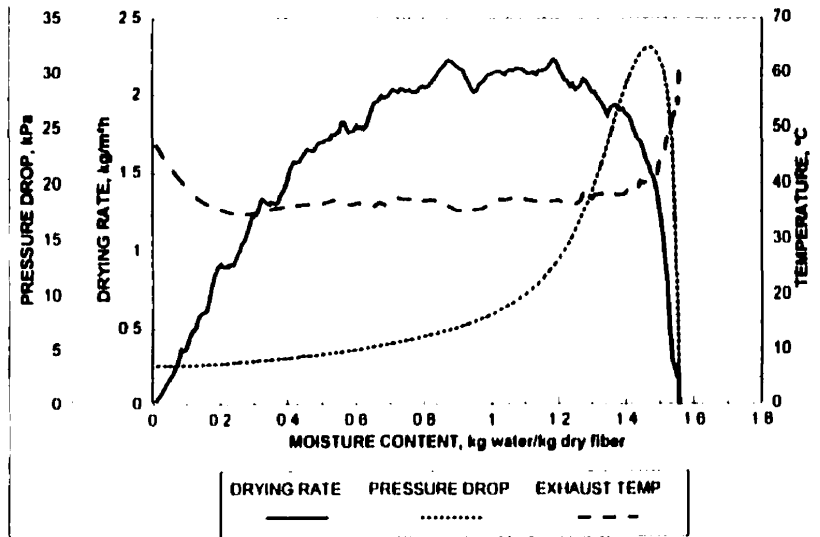
PAPER TYPE #1, $B=42.8\text{g/m}^2$, $T_i=81.4^\circ\text{C}$, $G=0.034\text{kg/m}^2\text{s}$



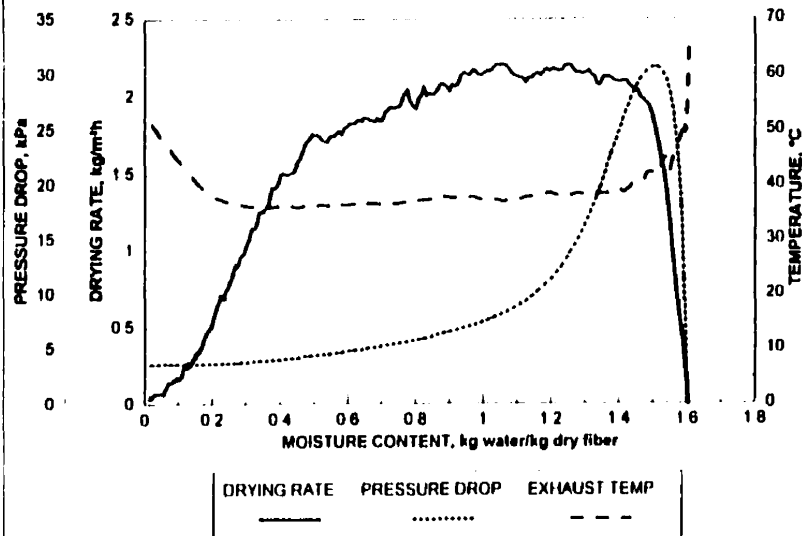
PAPER TYPE #1, B=42.8g/m², Ti=82.2°C, G=0.034kg/m²s



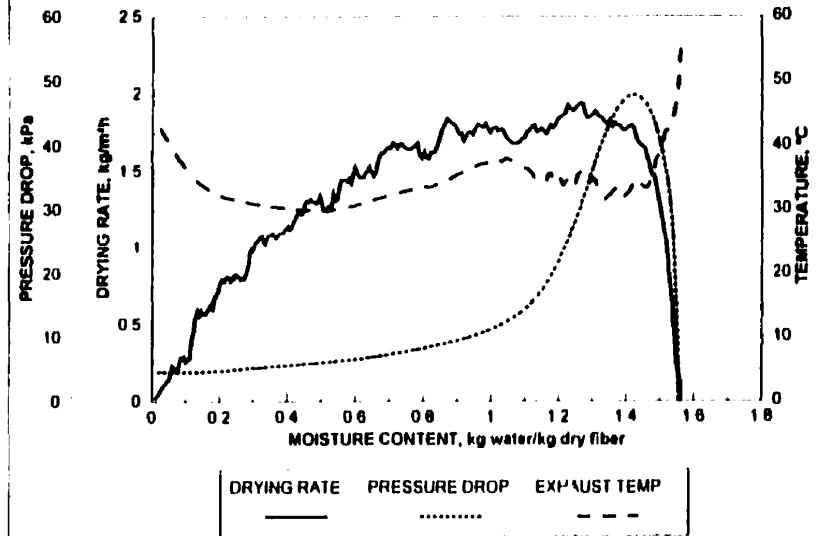
PAPER TYPE #1, B=42.8g/m², Ti=83.0°C, G=0.0265kg/m²s



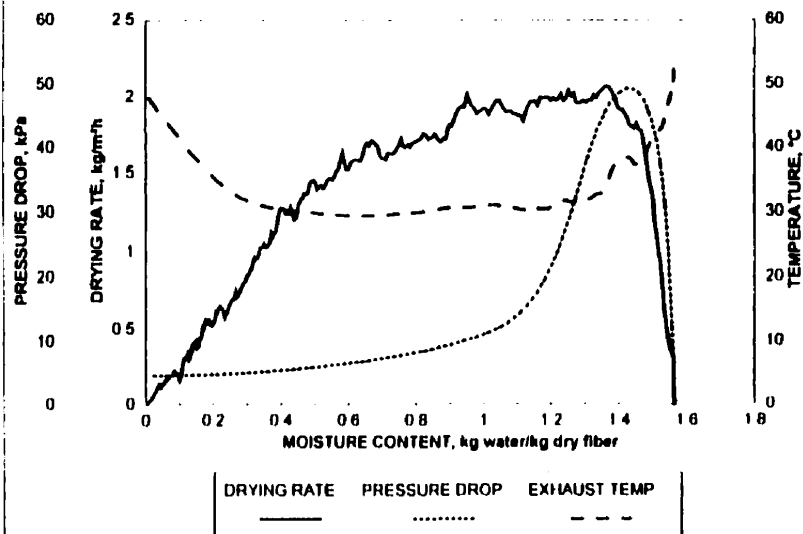
PAPER TYPE #1, B=42.8g/m², Ti=84.5°C, G=0.0265kg/m²s



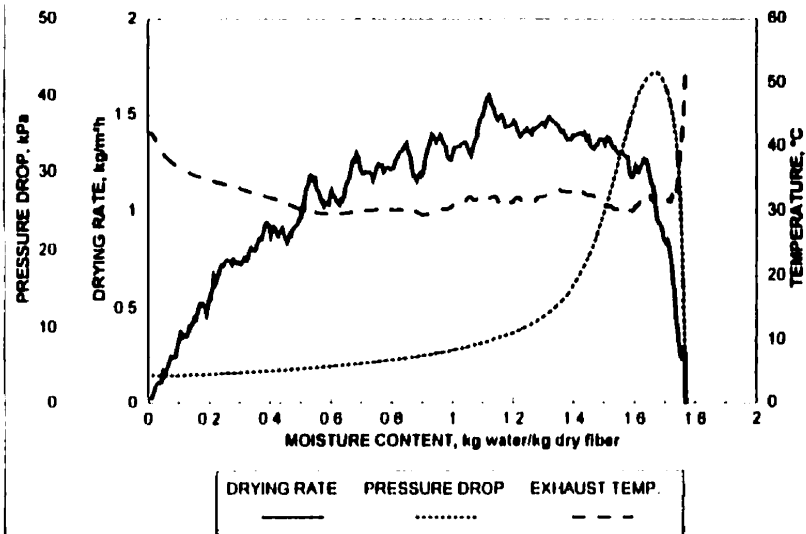
PAPER TYPE #1, B=42.8g/m², Ti=69.7°C, G=0.034kg/m²s



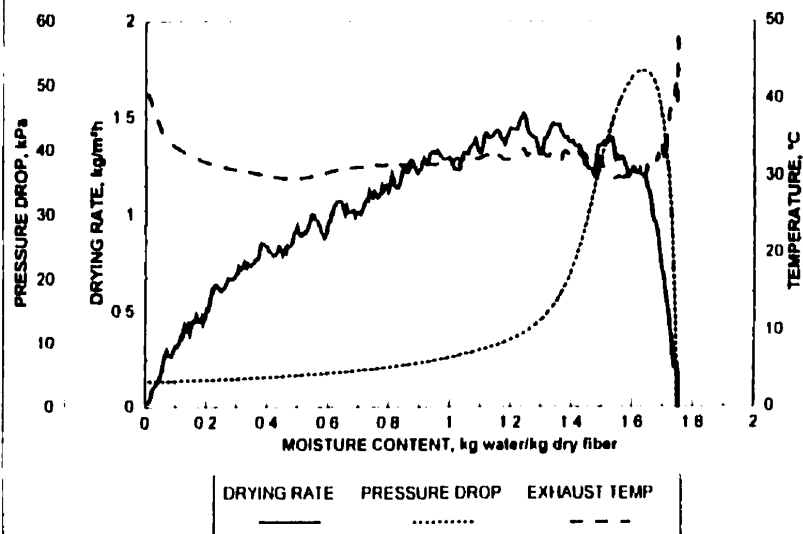
PAPER TYPE #1, B=42.8g/m², Ti=70.2°C, G=0.0265kg/m²s



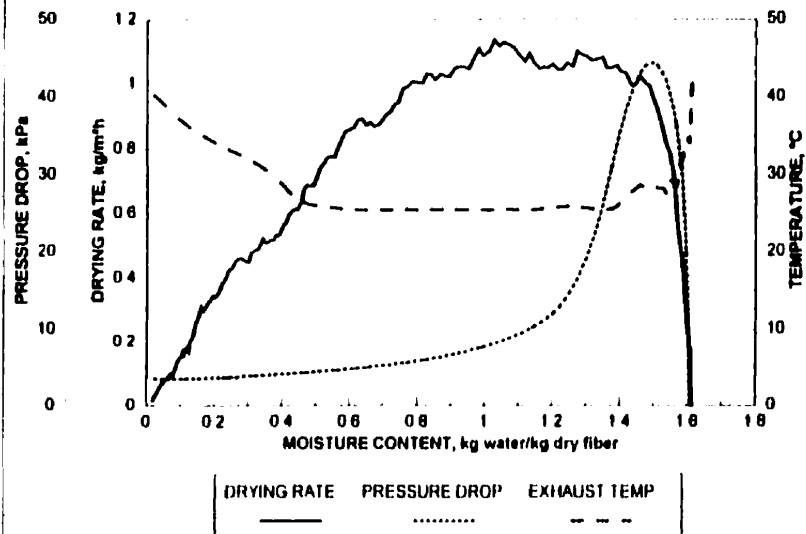
PAPER TYPE #1, B=42.8g/m², Ti=69.6°C, G=0.0265kg/m²s



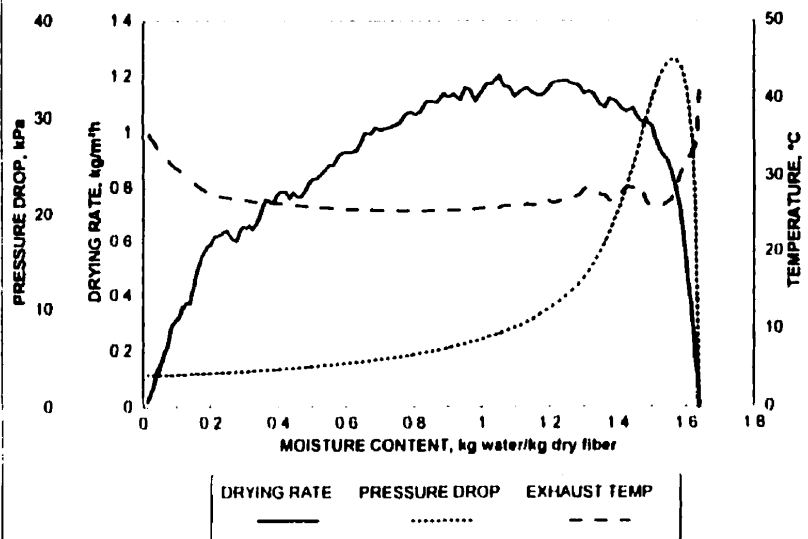
PAPER TYPE #1, B=42.8g/m², Ti=69.1°C, G=0.0265kg/m²s



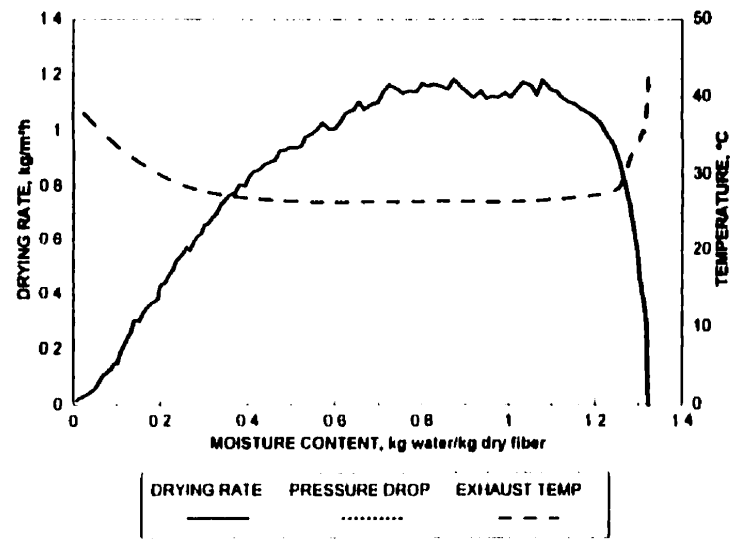
PAPER TYPE #1, B=42.8g/m², Ti=60.6°C, G=0.023kg/m²s



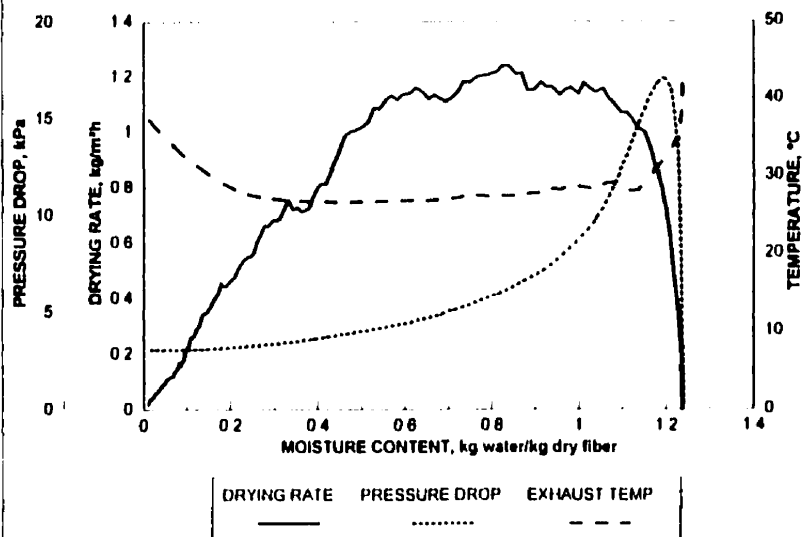
PAPER TYPE #1, B=42.8g/m², Ti=61.4°C, G=0.023kg/m²s



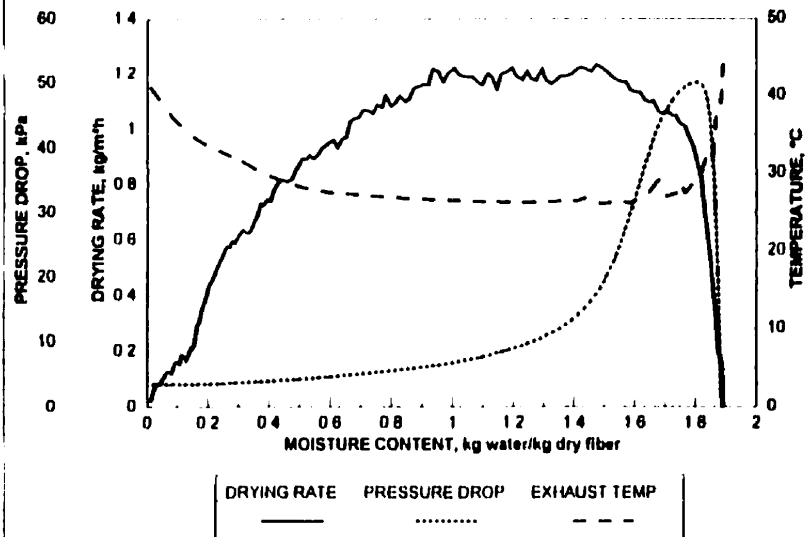
PAPER TYPE #1, B=42.8g/m², Ti=60.7°C, G=0.023kg/m²s



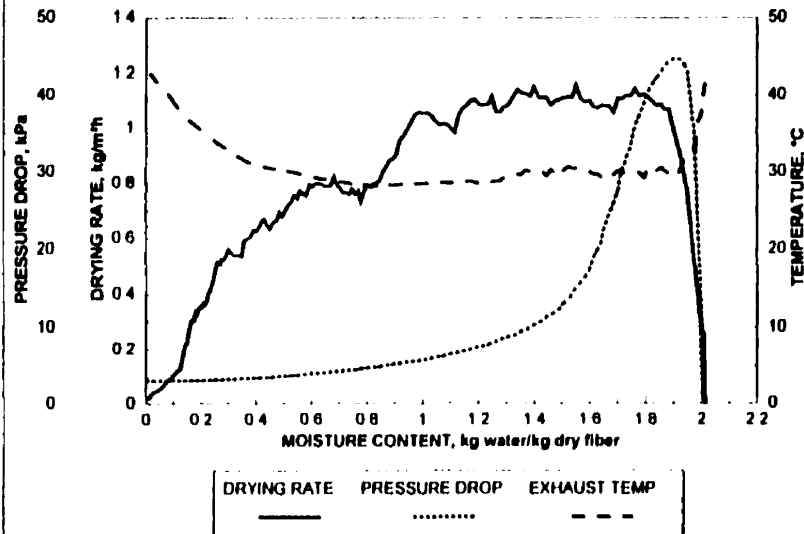
PAPER TYPE #1, B=42.8g/m², Ti=60.7°C, G=0.023kg/m²s



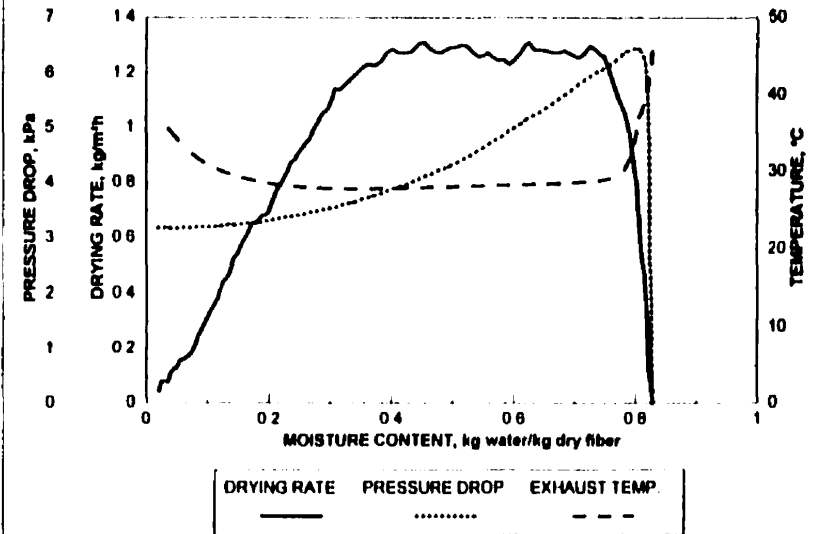
PAPER TYPE #1, B=42.8g/m², Ti=61.7°C, G=0.023kg/m²s



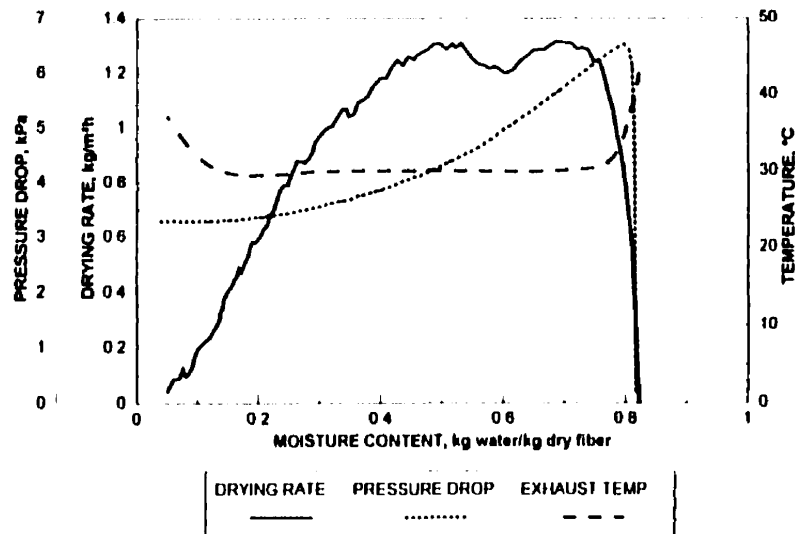
PAPER TYPE #1, B=42.8g/m², Ti=62.2°C, G=0.023kg/m²s



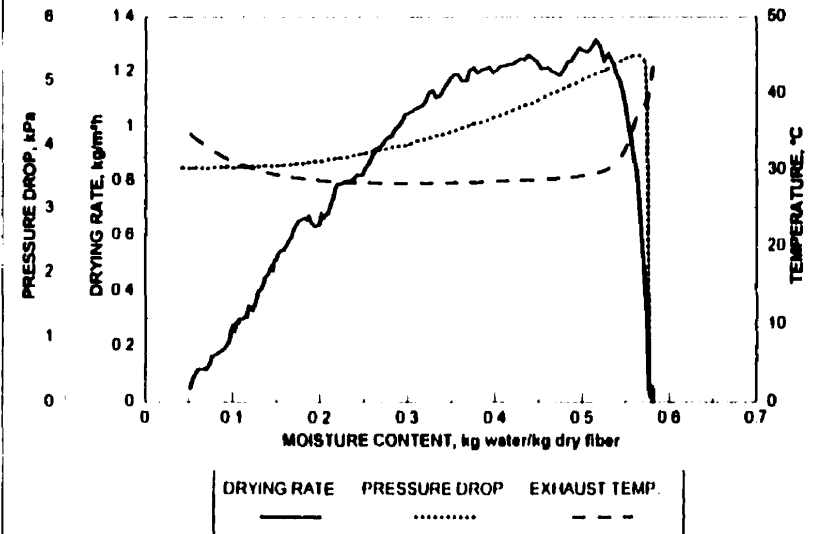
PAPER TYPE #1, B=42.8g/m², Ti=62.0°C, G=0.023kg/m²s



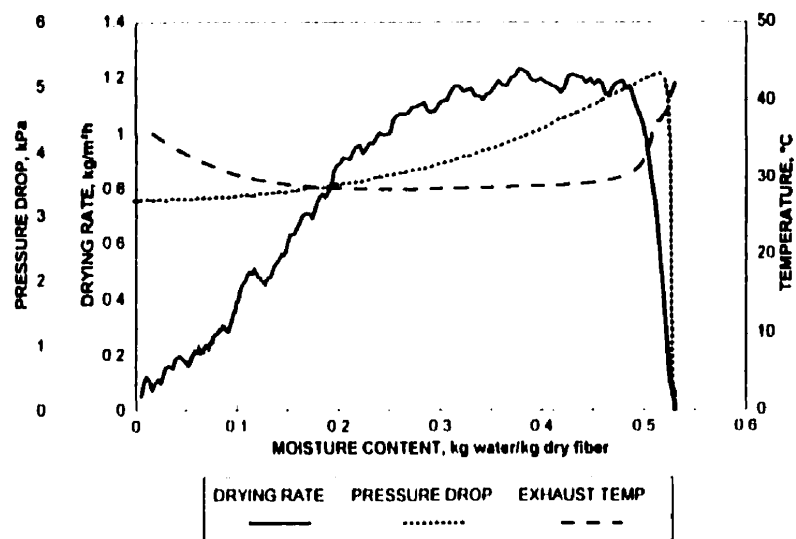
PAPER TYPE #1, B=42.8g/m², Ti=60.8°C, G=0.023kg/m²s



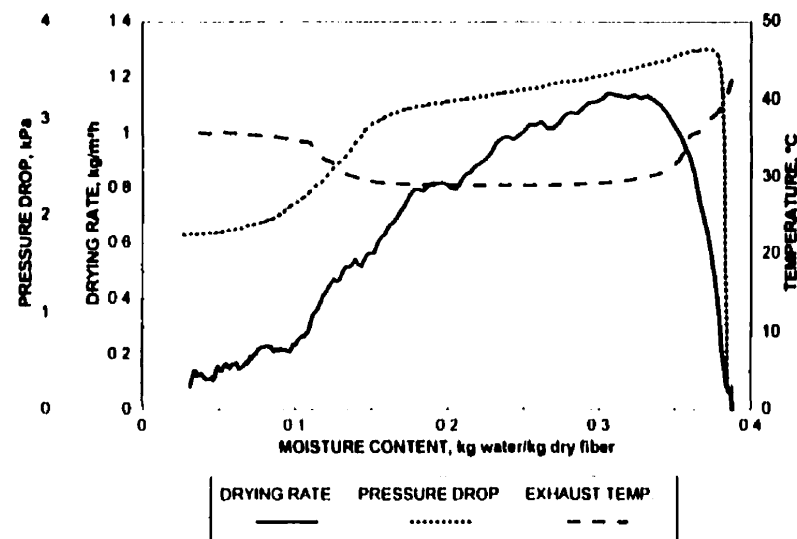
PAPER TYPE #1, B=42.8g/m², Ti=60.0°C, G=0.023kg/m²s



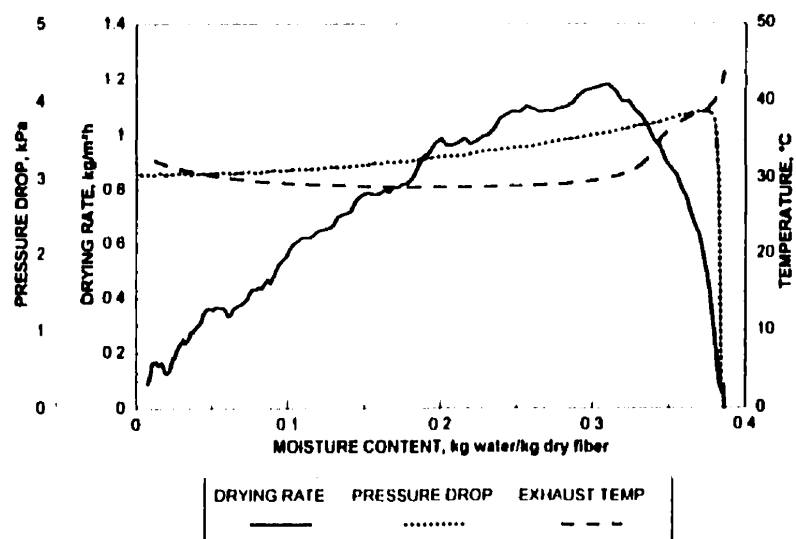
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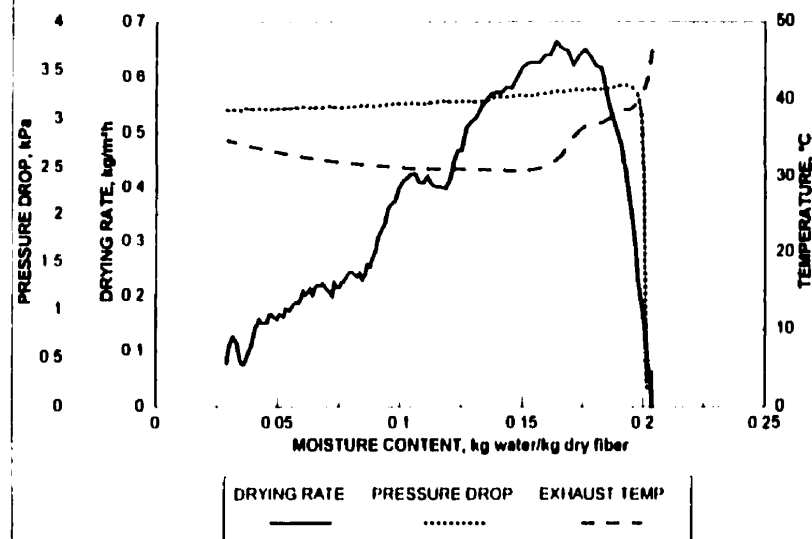
PAPER TYPE #1, B=42.8g/m², Ti=59.5°C, G=0.023kg/m²s



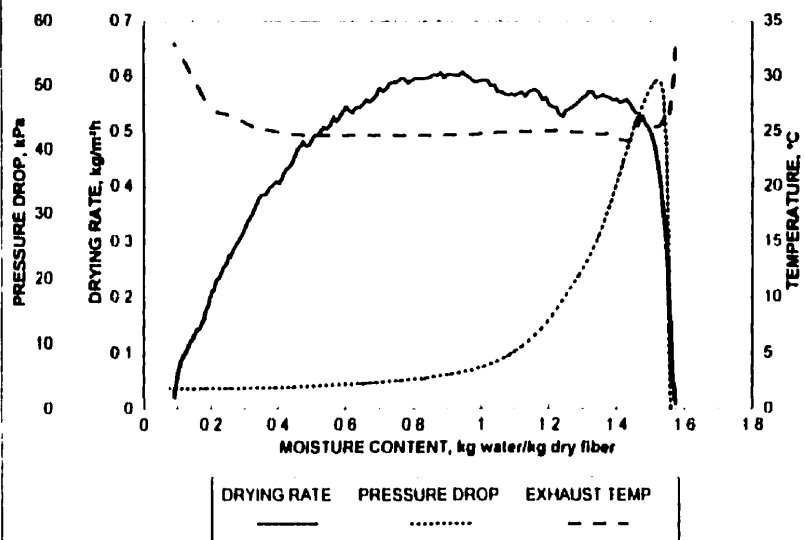
PAPER TYPE #1, B=42.8g/m², Ti=60.5°C, G=0.023kg/m²s



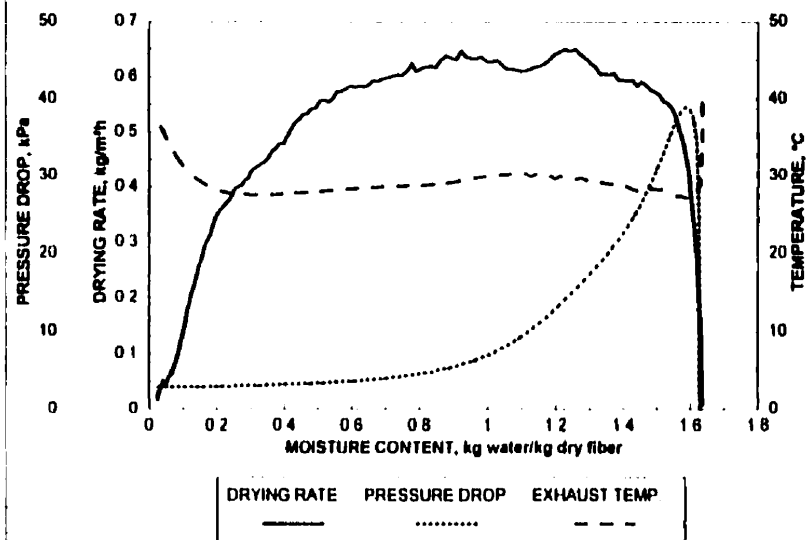
PAPER TYPE #1, B=42.8g/m², Ti=61.3°C, G=0.023kg/m²s



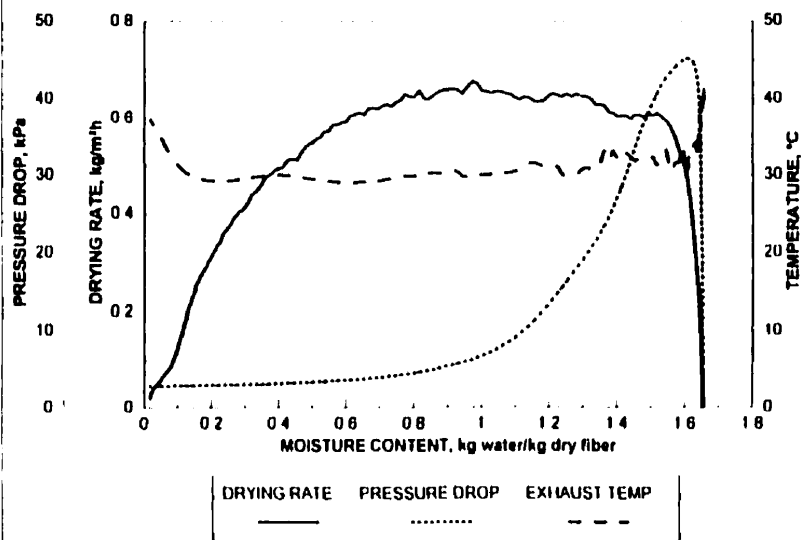
PAPER TYPE #2, B=57.3g/m², Ti=47.3°C, G=0.0127kg/m²s



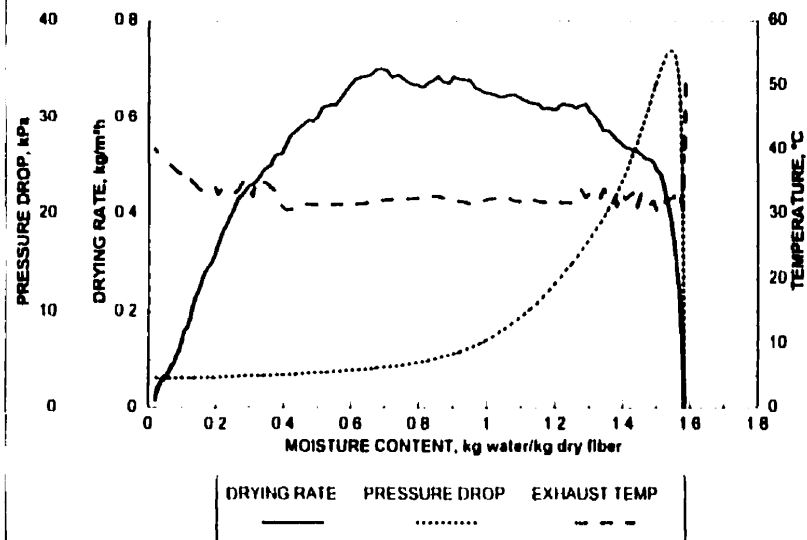
PAPER TYPE #2, B=57.3g/m², Ti=54.7°C, G=0.0127kg/m²s



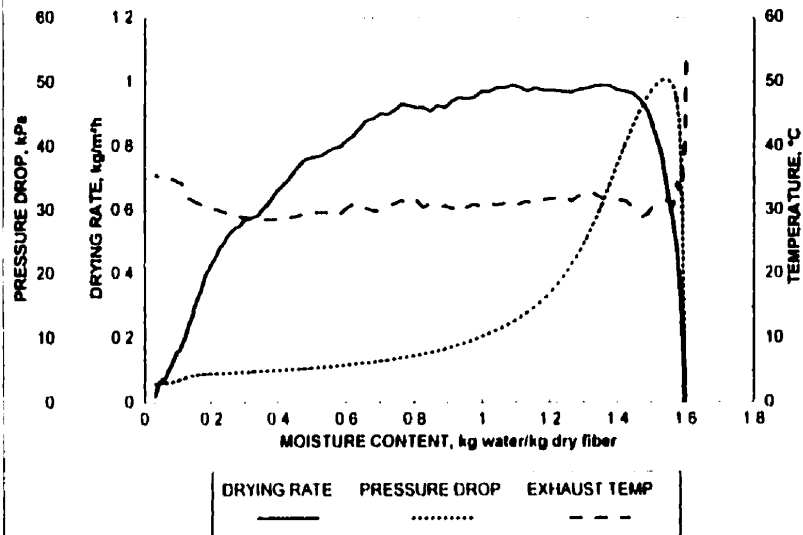
PAPER TYPE #2, B=57.3g/m², Ti=52.0°C, G=0.0127kg/m²s



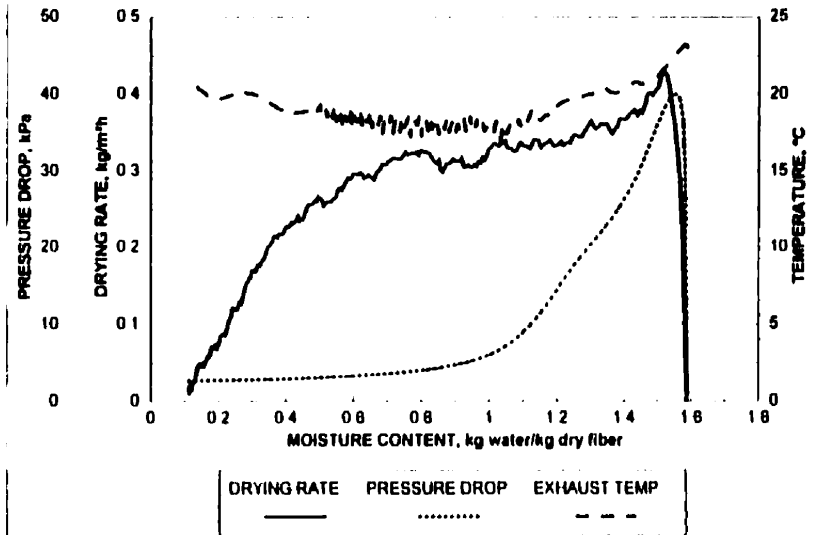
PAPER TYPE #2, B=57.3g/m², Ti=59.1°C, G=0.0127kg/m²s



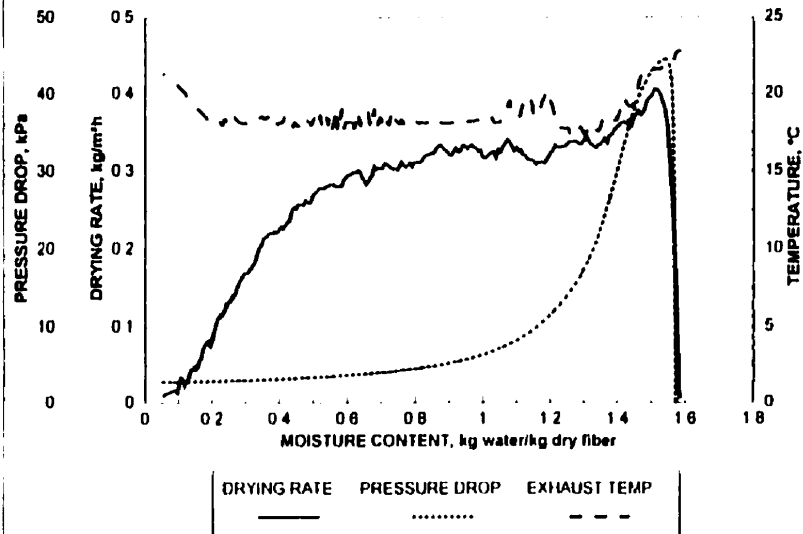
PAPER TYPE #2, B=57.3g/m², Ti=59.0°C, G=0.0195kg/m²s



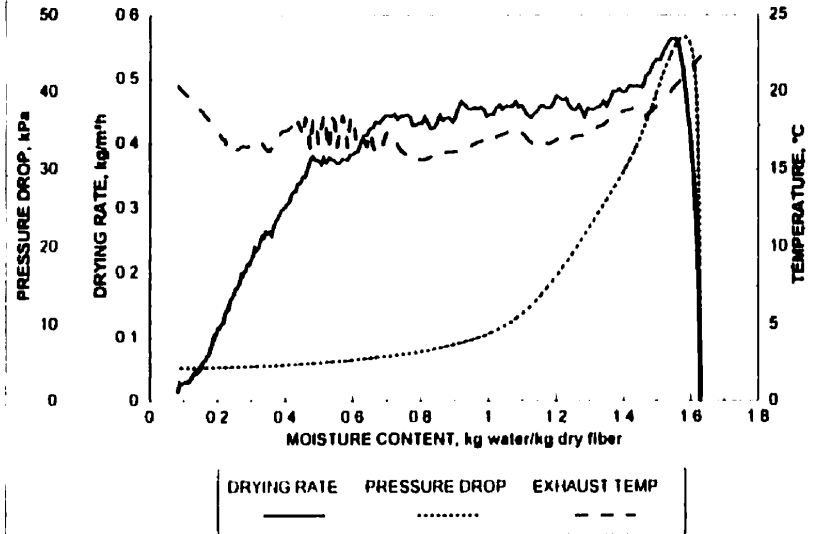
PAPER TYPE #2, B=57.3g/m², Ti=22.6°C, G=0.0127kg/m²s



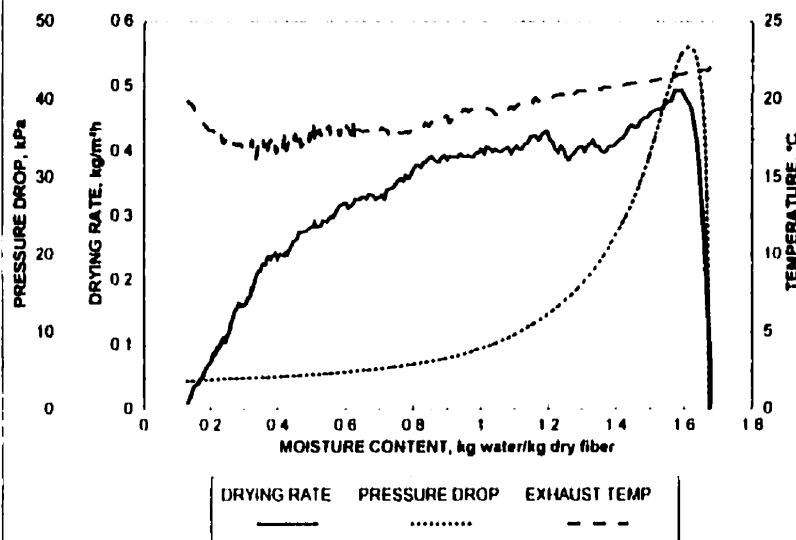
PAPER TYPE #2, B=57.3g/m², Ti=22.4°C, G=0.0127kg/m²s



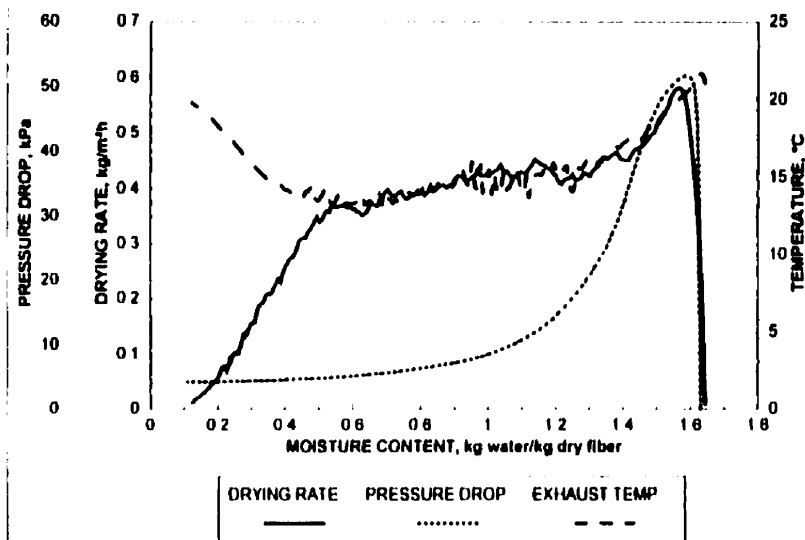
PAPER TYPE #2, B=57.3g/m², Ti=21.9°C, G=0.0195kg/m²s



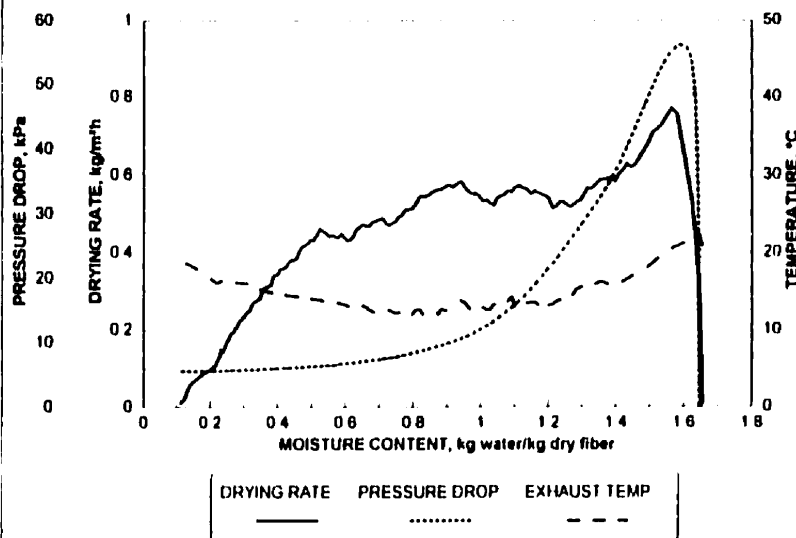
PAPER TYPE #2, $B=57.3\text{g/m}^2$, $T_i=21.5^\circ\text{C}$, $G=0.0195\text{kg/m}^2\text{s}$



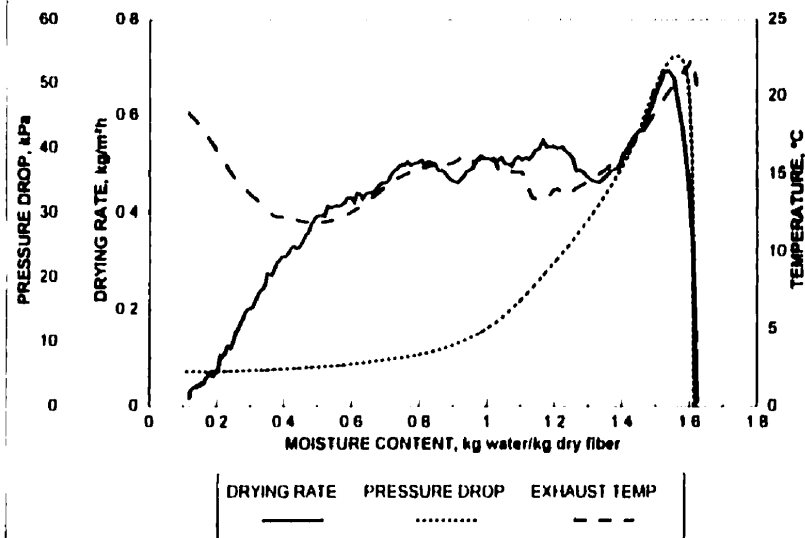
PAPER TYPE #2, $B=57.3\text{g/m}^2$, $T_i=20.5^\circ\text{C}$, $G=0.0195\text{kg/m}^2\text{s}$



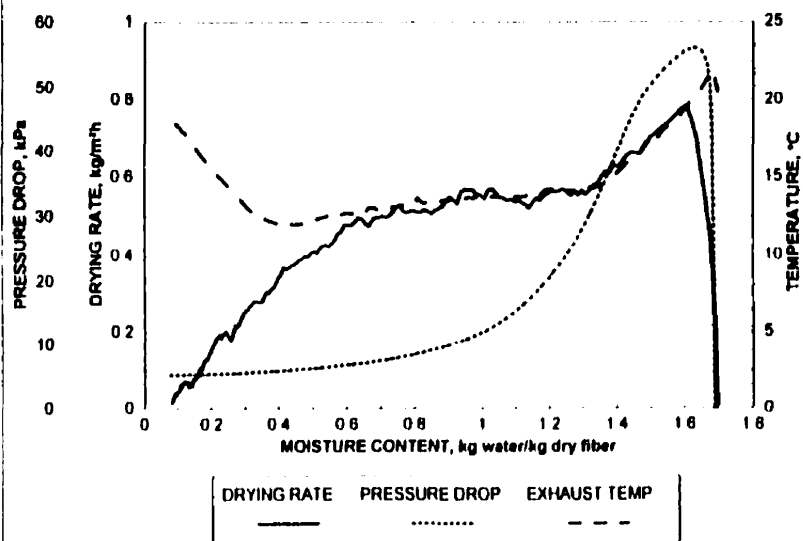
PAPER TYPE #2, $B=57.3\text{g/m}^2$, $T_i=20.2^\circ\text{C}$, $G=0.0265\text{kg/m}^2\text{s}$



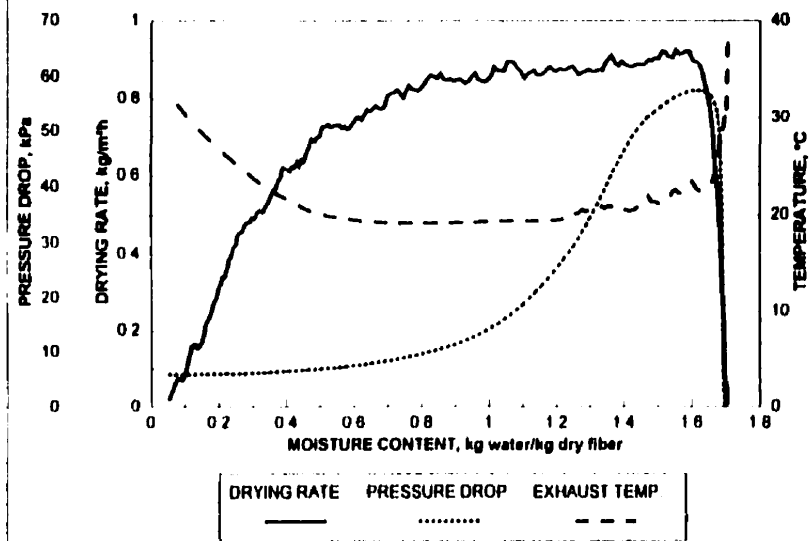
PAPER TYPE #2, $B=57.3\text{g/m}^2$, $T_i=20.1^\circ\text{C}$, $G=0.0265\text{kg/m}^2\text{s}$



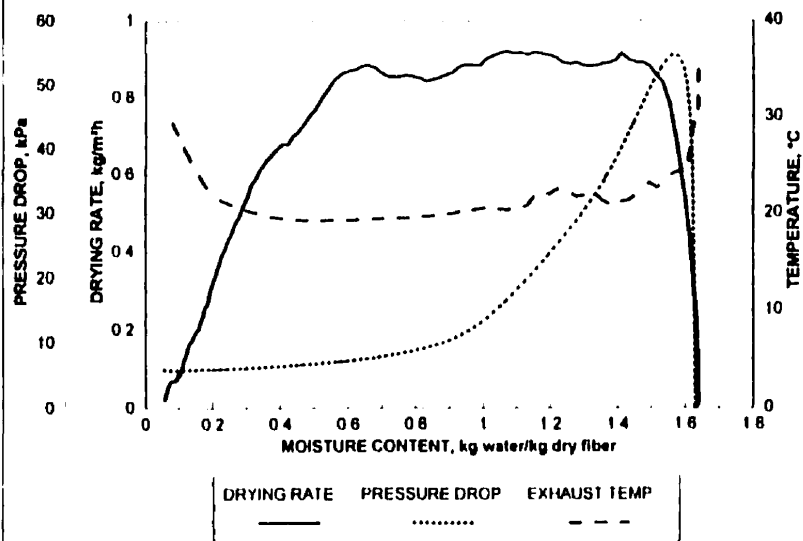
PAPER TYPE #2, B=57.3g/m², T_i=20.0°C, G=0.0265kg/m²s



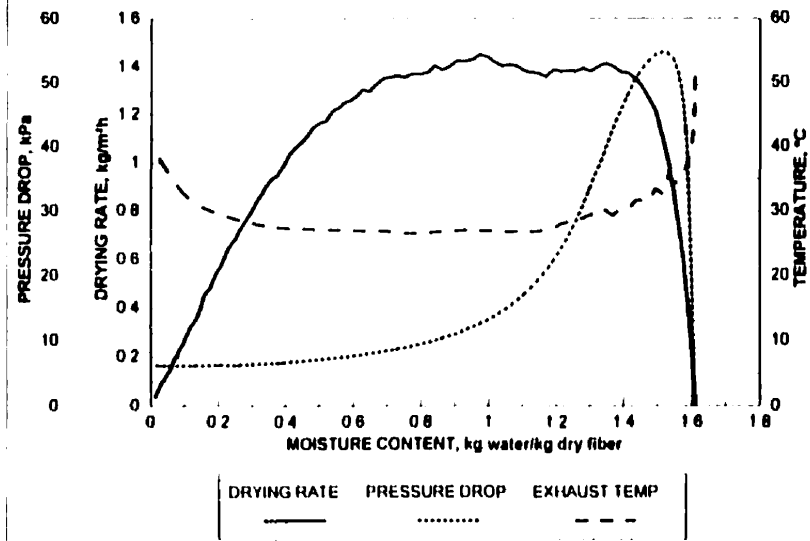
PAPER TYPE #2, B=57.3g/m², T_i=42.7°C, G=0.0265kg/m²s



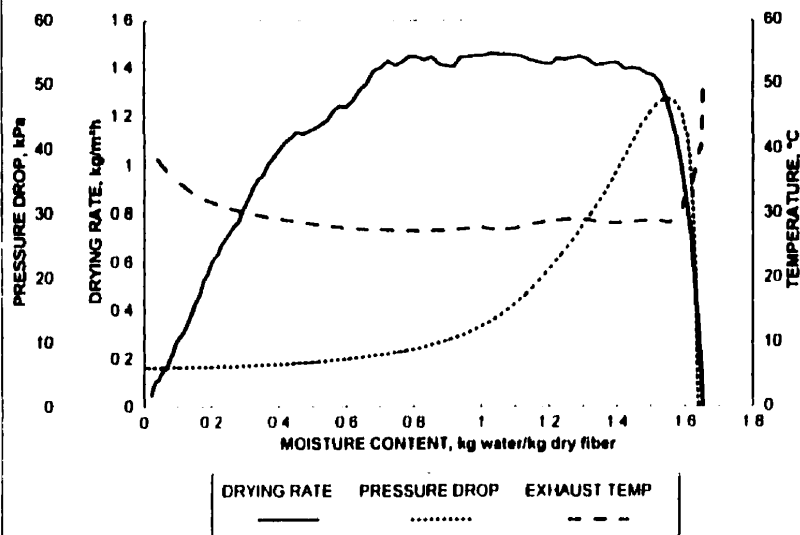
PAPER TYPE #2, B=57.3g/m², T_i=41.5°C, G=0.0265kg/m²s



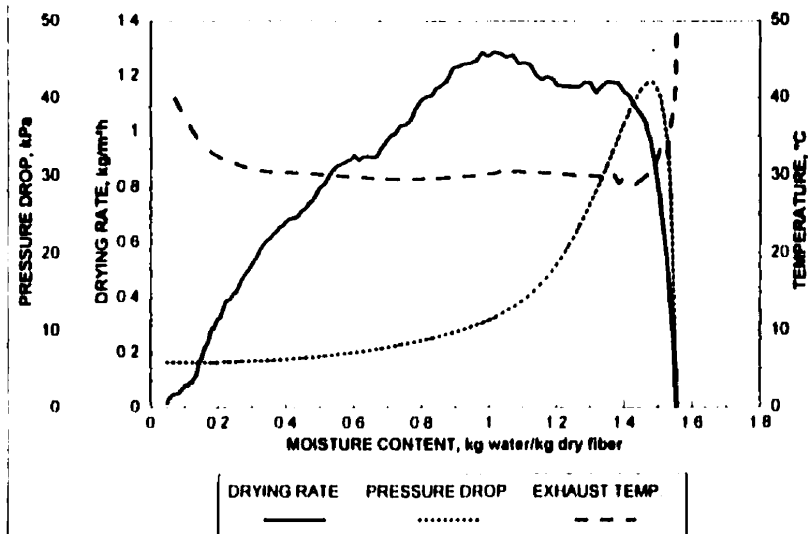
PAPER TYPE #2, B=57.3g/m², T_i=62.1°C, G=0.0265kg/m²s



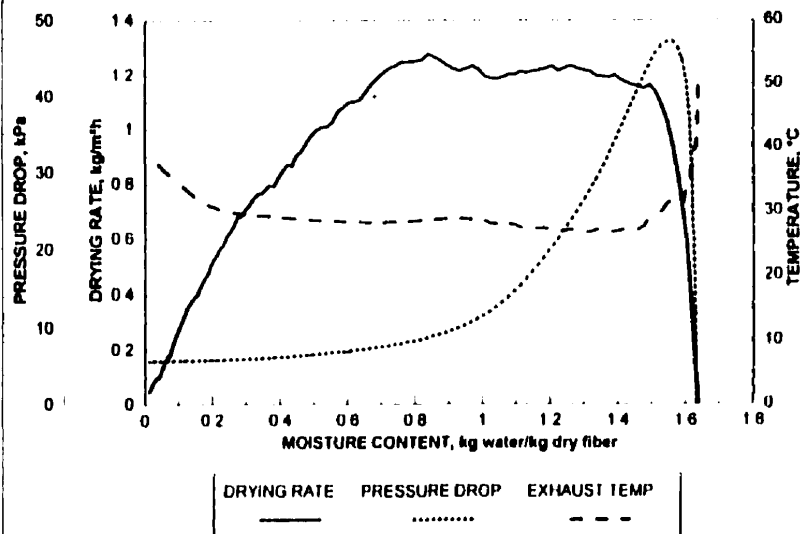
PAPER TYPE #2, B=57.3g/m², Ti=62.1°C, G=0.0265kg/m²s



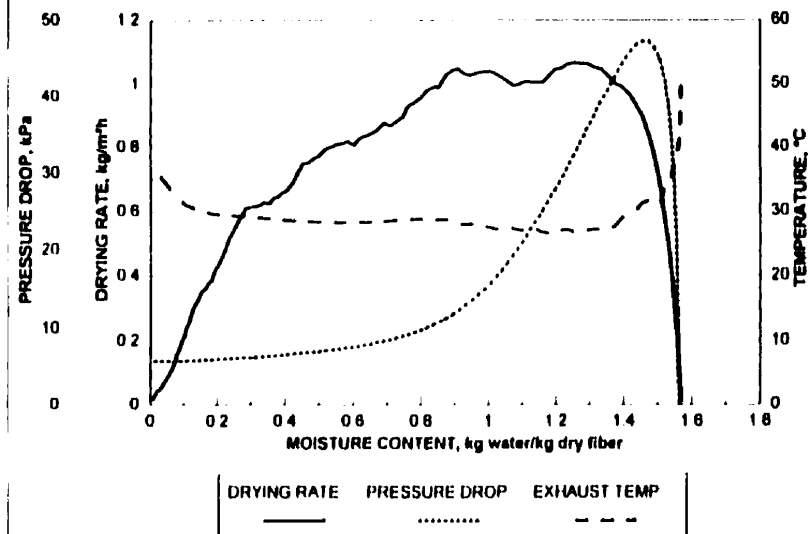
PAPER TYPE #2, B=57.3g/m², Ti=60.4°C, G=0.023kg/m²s



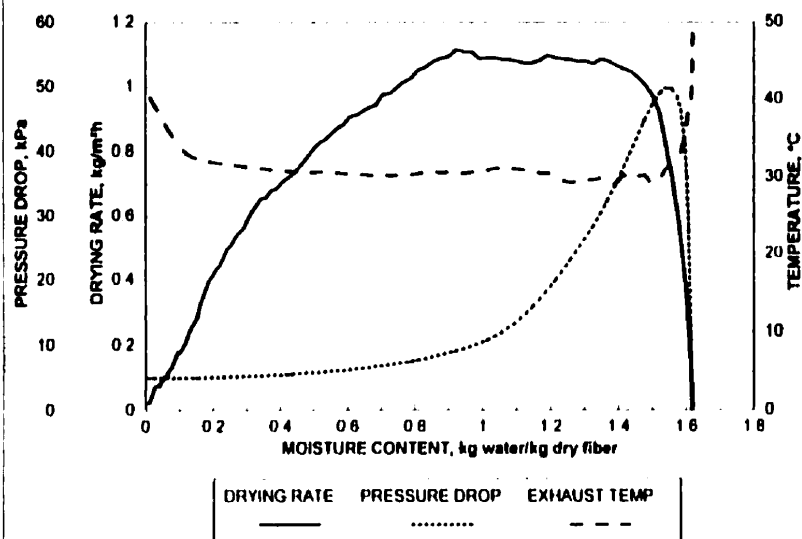
PAPER TYPE #2, B=57.3g/m², Ti=60.6°C, G=0.023kg/m²s



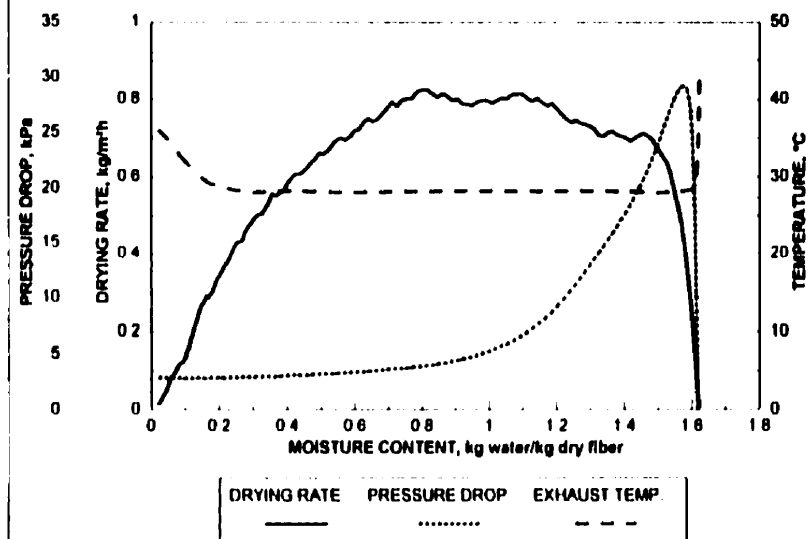
PAPER TYPE #2, B=57.3g/m², Ti=60.4°C, G=0.0195kg/m²s



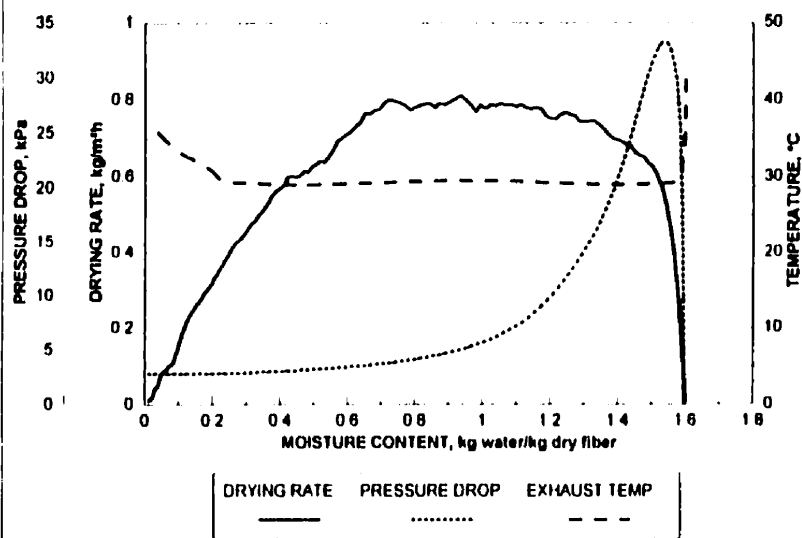
PAPER TYPE #2, B=57.3g/m², Ti=62.2°C, G=0.0195kg/m²s



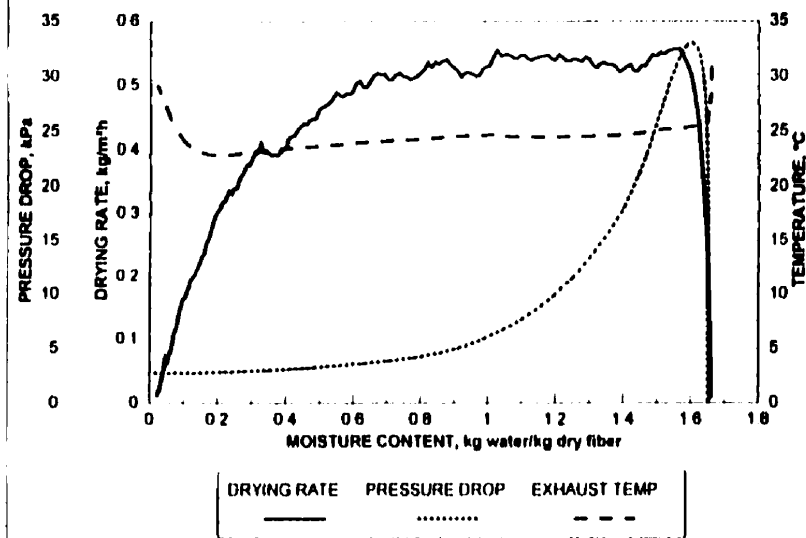
PAPER TYPE #2, B=57.3g/m², Ti=59.2°C, G=0.0127kg/m²s



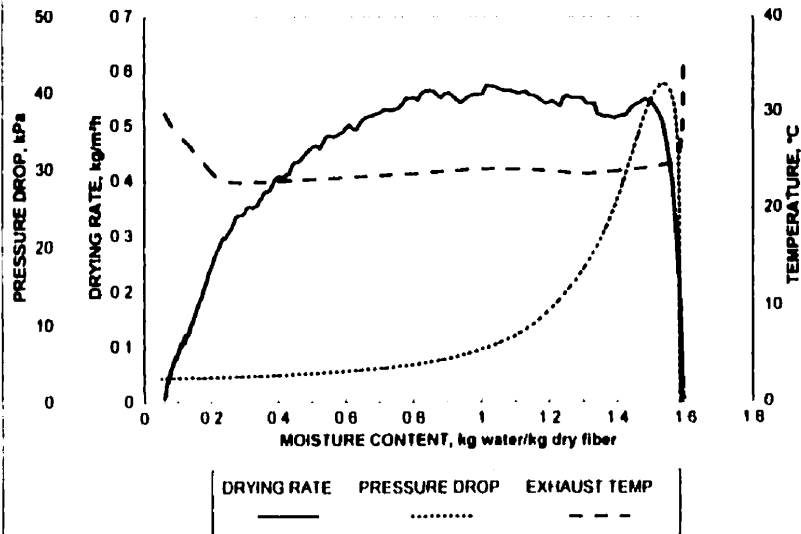
PAPER TYPE #2, B=57.3g/m², Ti=58.9°C, G=0.0127kg/m²s



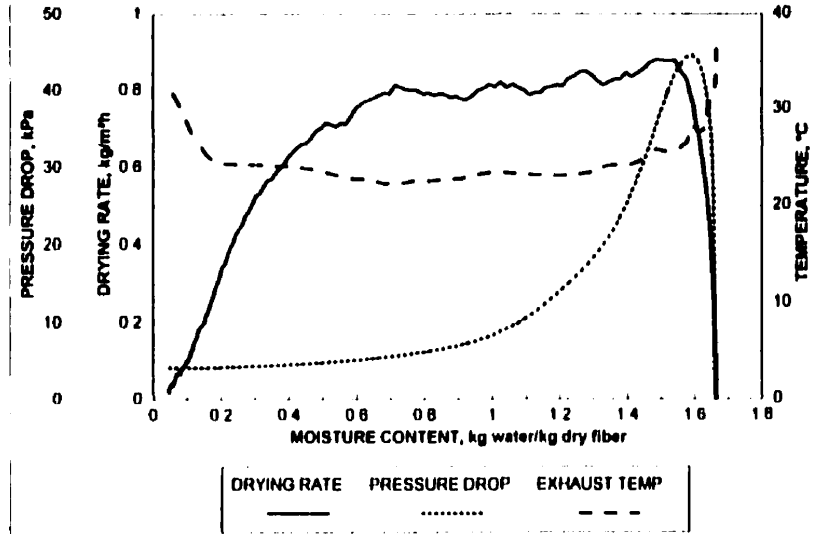
PAPER TYPE #2, B=57.3g/m², Ti=41.2°C, G=0.0127kg/m²s



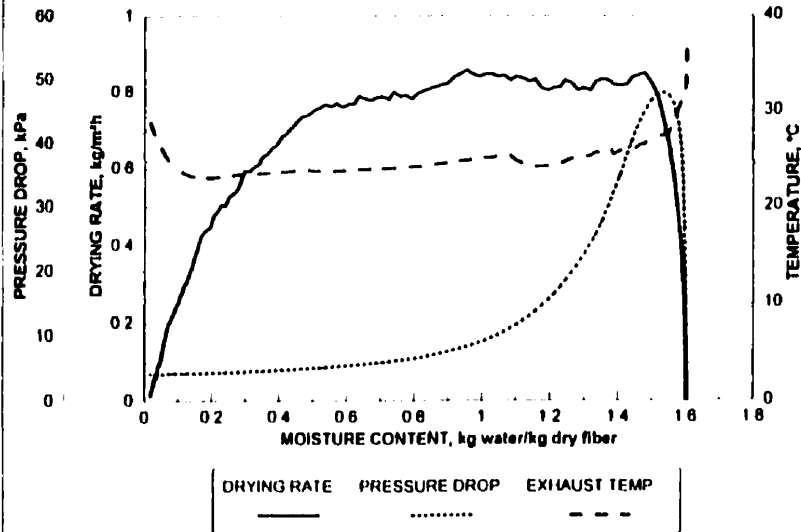
PAPER TYPE #2, B=57.3g/m², Ti=41.4°C, G=0.0127kg/m²s



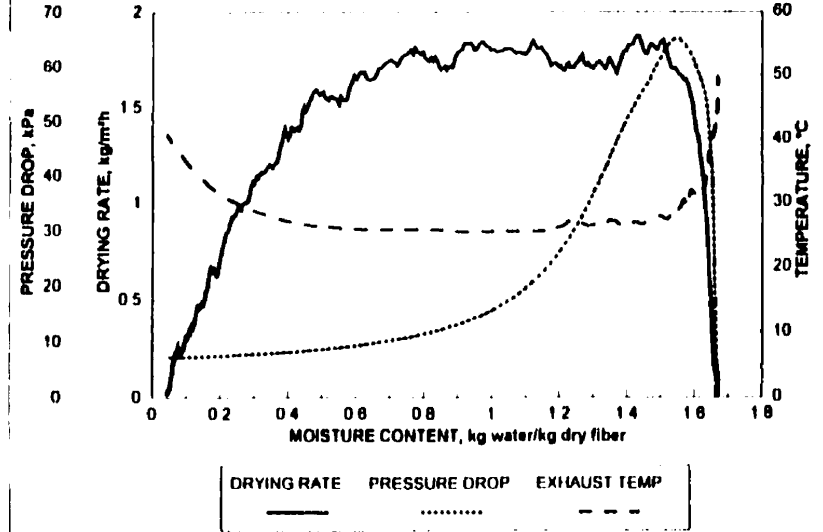
PAPER TYPE #2, B=57.3g/m², Ti=43.4°C, G=0.0195kg/m²s



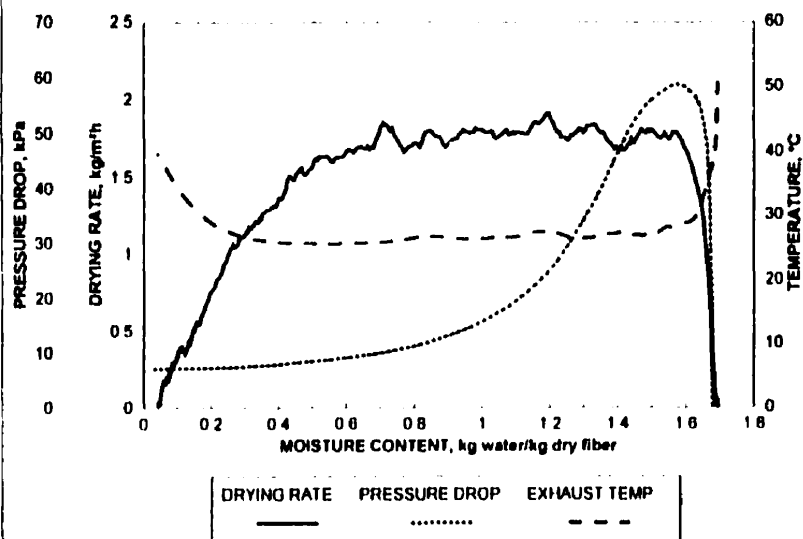
PAPER TYPE #2, B=57.3g/m², Ti=43.3°C, G=0.0195kg/m²s



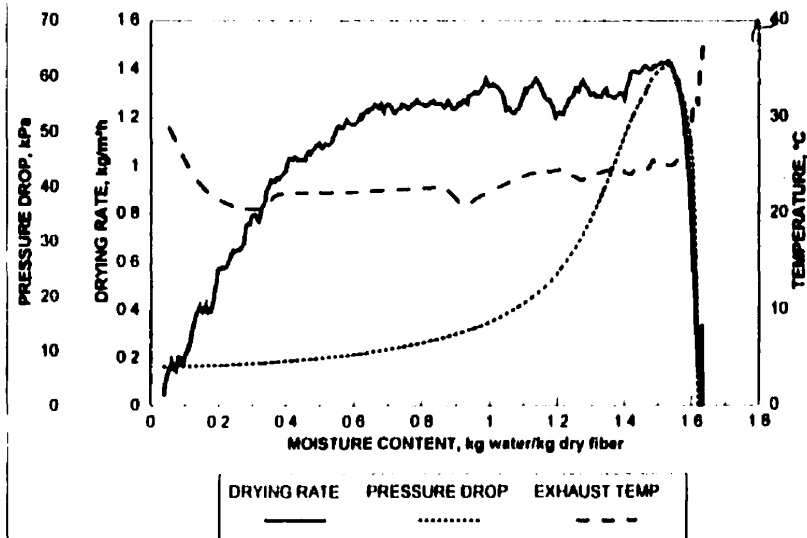
PAPER TYPE #2, B=57.3g/m², Ti=60.8°C, G=0.034kg/m²s



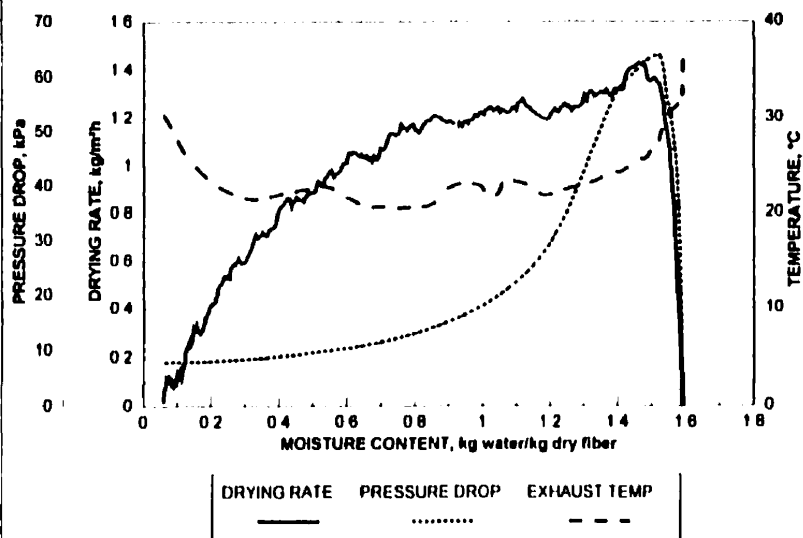
PAPER TYPE #2, B=57.3g/m², Ti=61.1°C, G=0.034kg/m²s



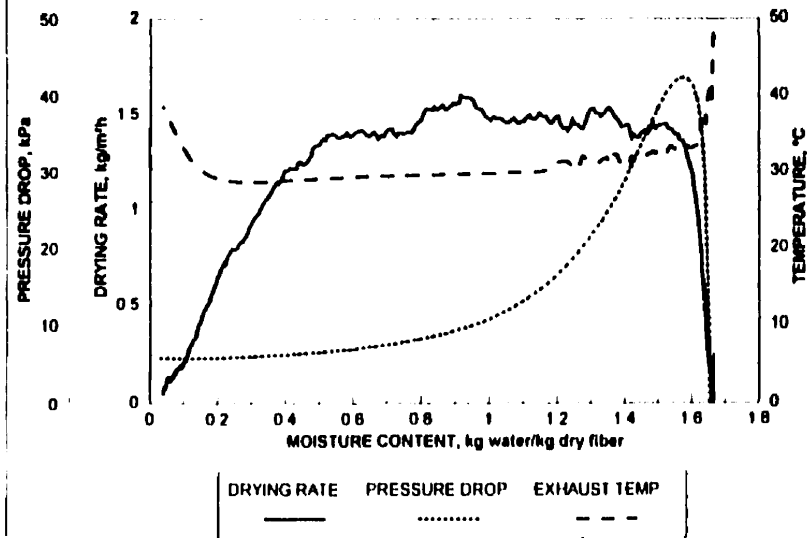
PAPER TYPE #2, B=57.3g/m², Ti=41.5°C, G=0.034kg/m²s



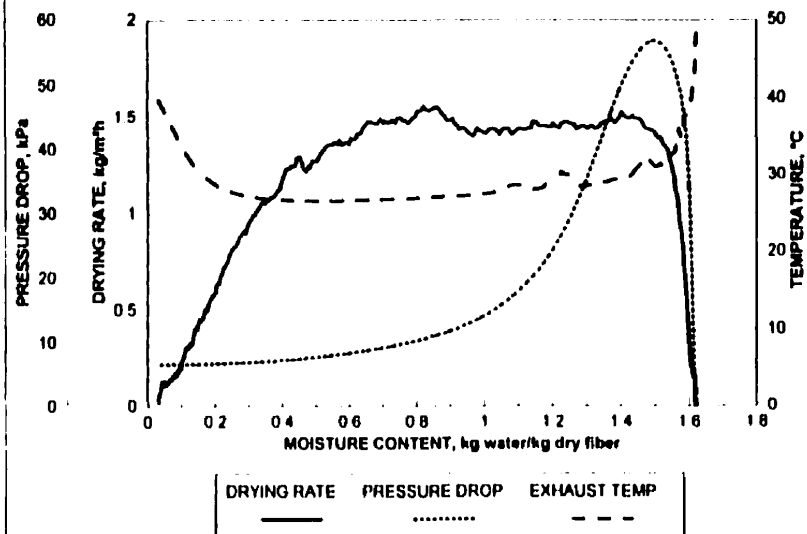
PAPER TYPE #2, B=57.3g/m², Ti=40.9°C, G=0.034kg/m²s



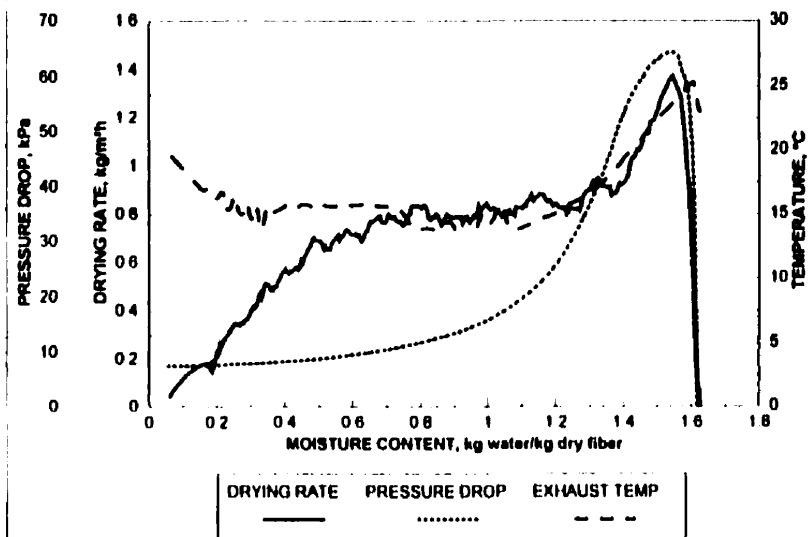
PAPER TYPE #2, B=57.3g/m², Ti=62.2°C, G=0.0265kg/m²s



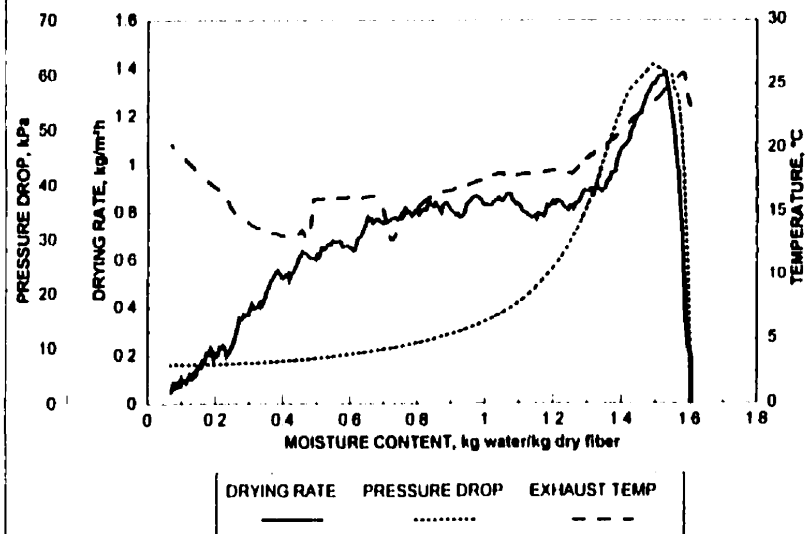
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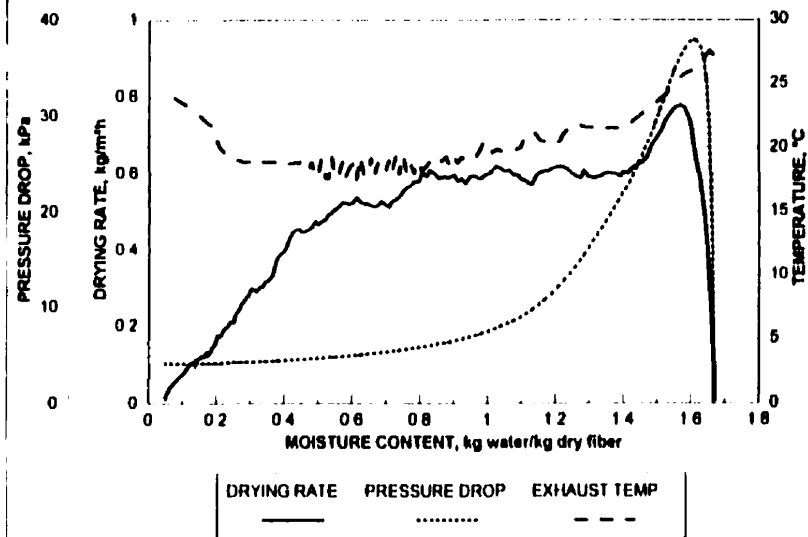
PAPER TYPE #2, B=57.3g/m², Ti=22.5°C, G=0.034kg/m²s



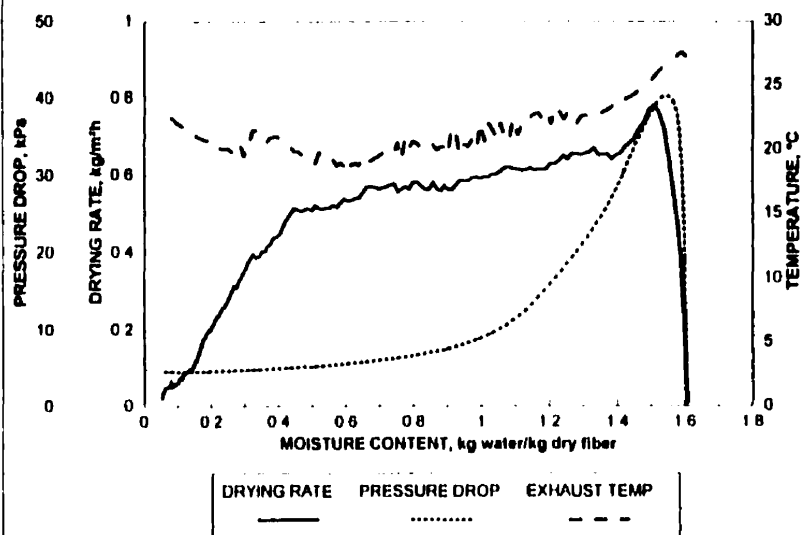
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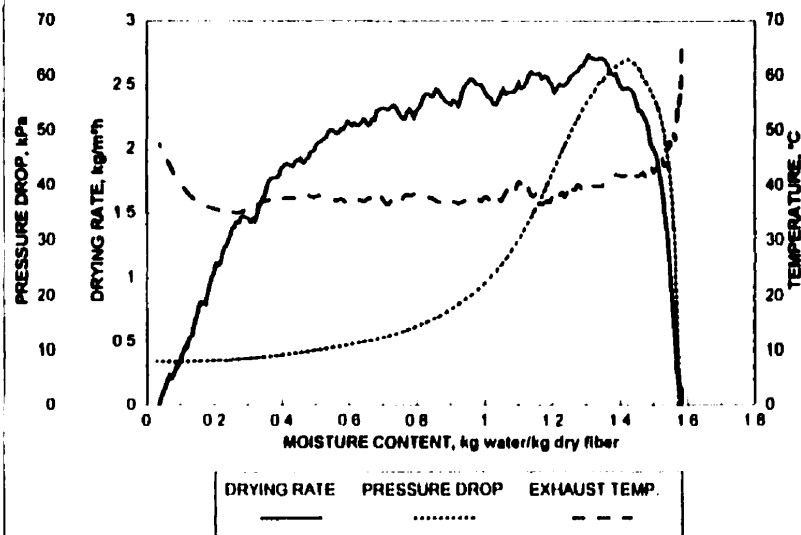
PAPER TYPE #2, B=57.3g/m², Ti=26.9°C, G=0.0195kg/m²s



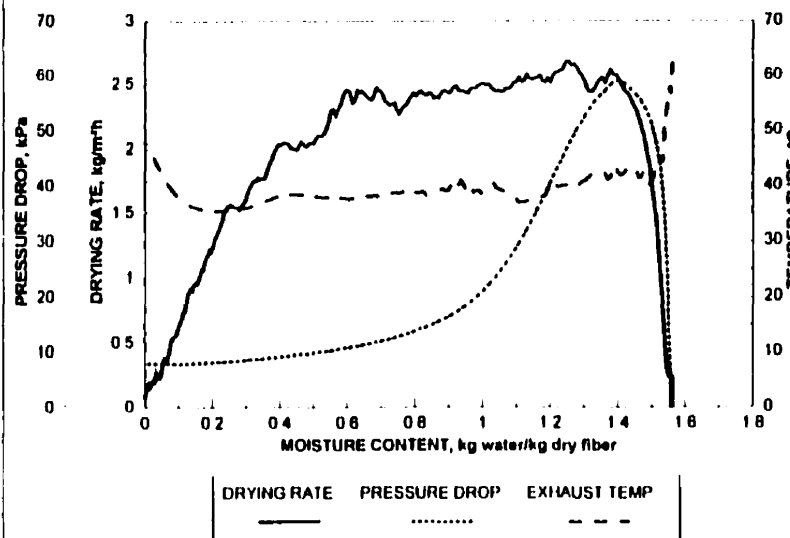
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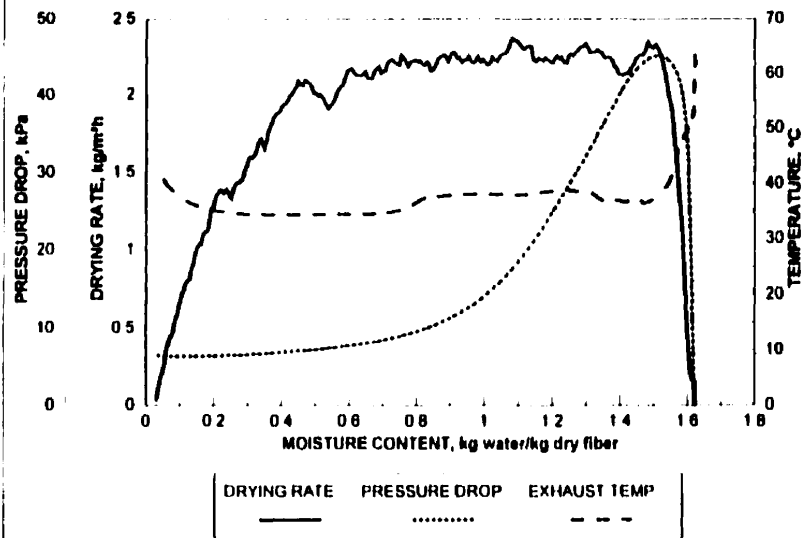
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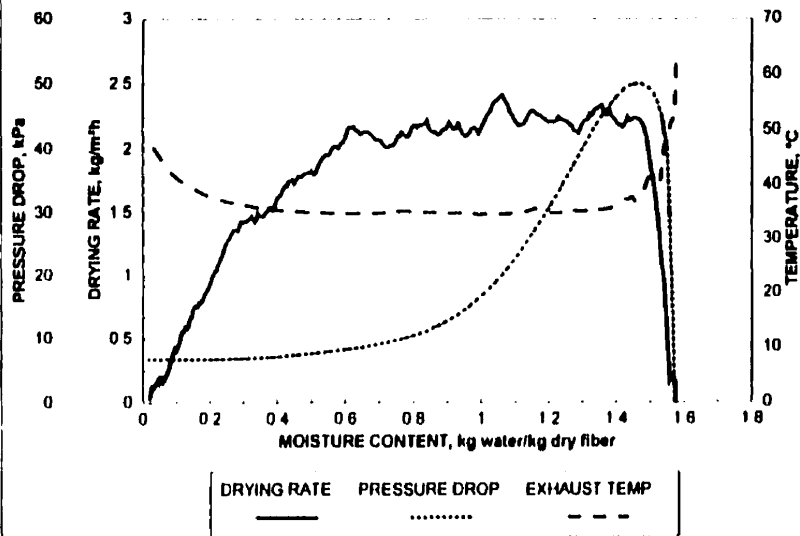
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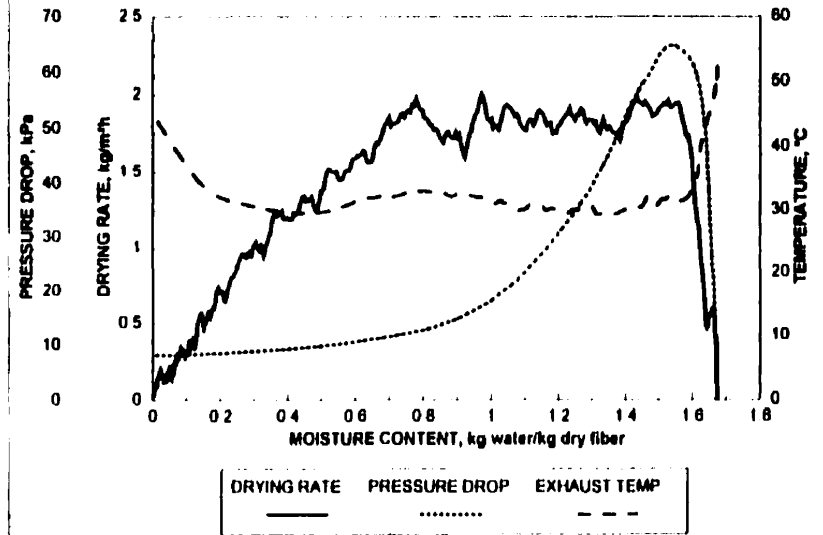
PAPER TYPE #2, B=57.3g/m², Ti=84.5°C, G=0.0265kg/m²s



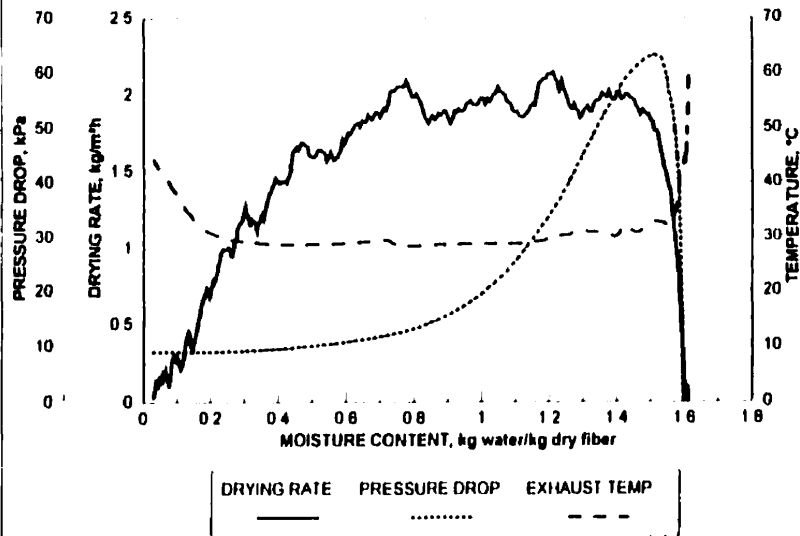
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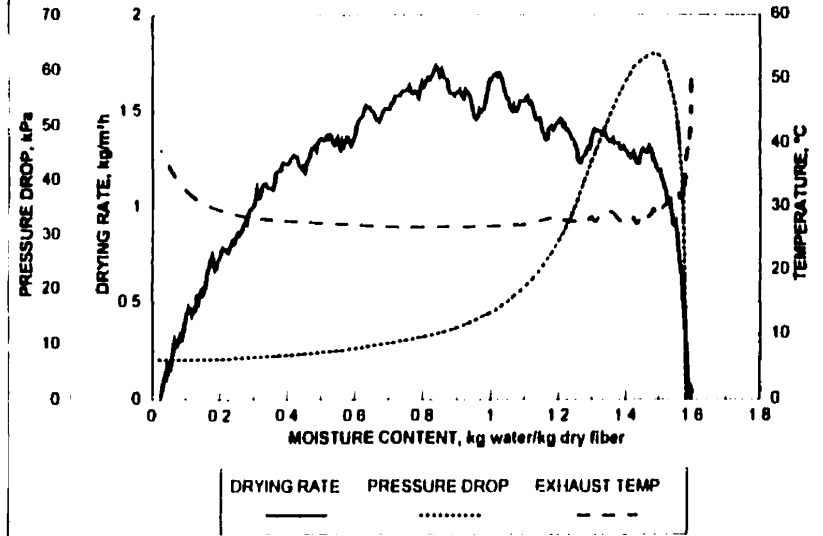
PAPER TYPE #2, B=57.3g/m², Ti=68.7°C, G=0.034kg/m²s



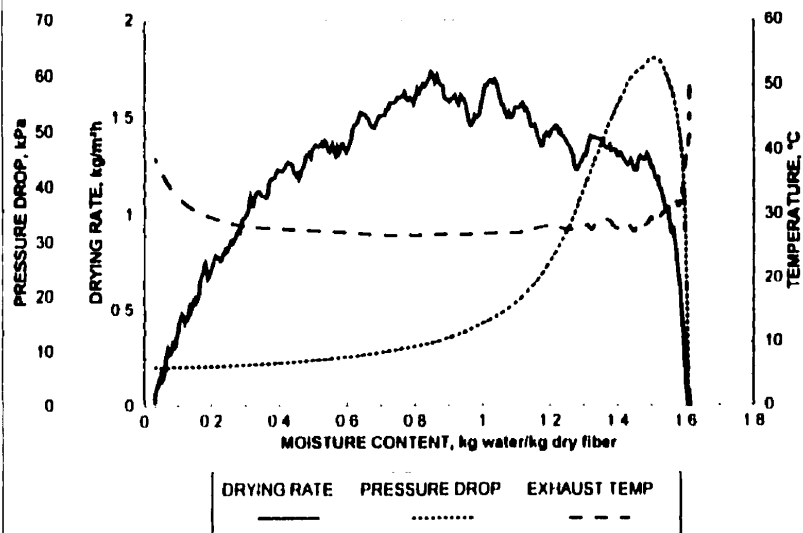
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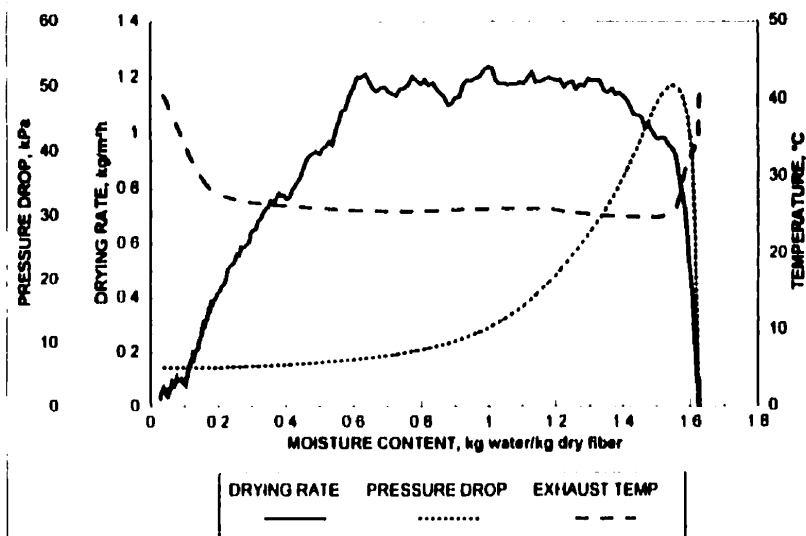
PAPER TYPE #2, B=57.3g/m², Ti=68.7°C, G=0.0265kg/m²s



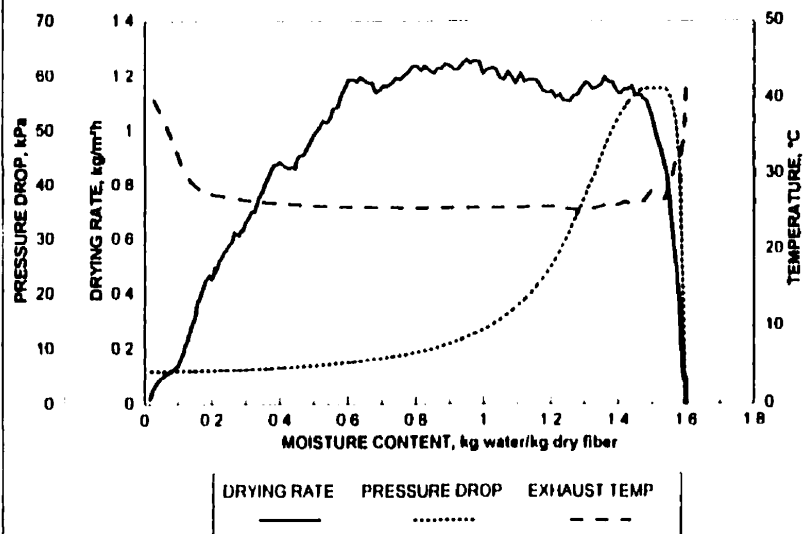
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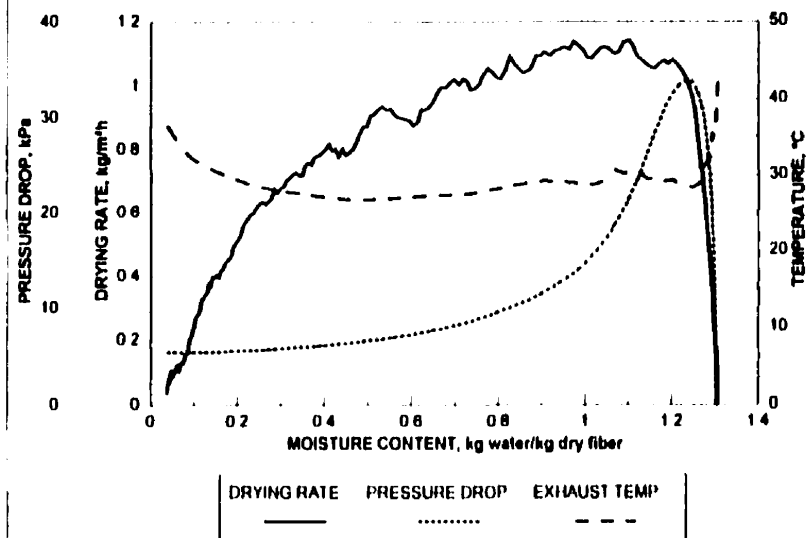
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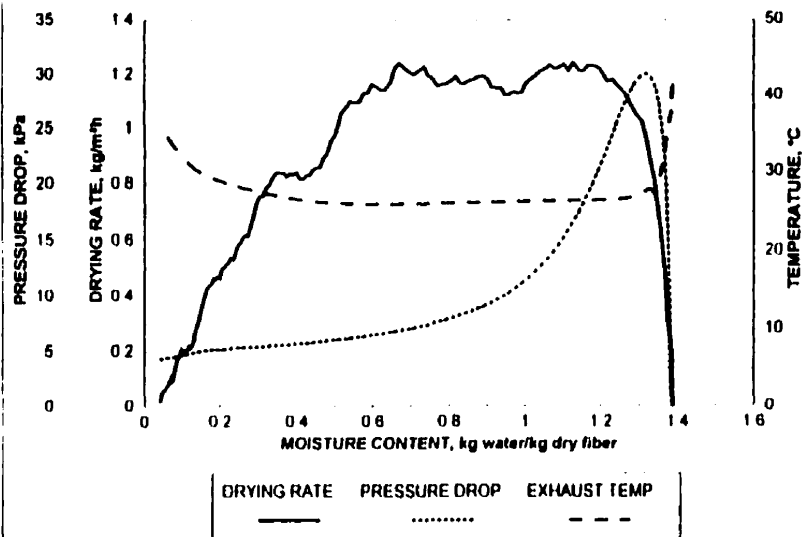
PAPER TYPE #2, B=57.3g/m², Ti=62.1°C, G=0.023kg/m²s



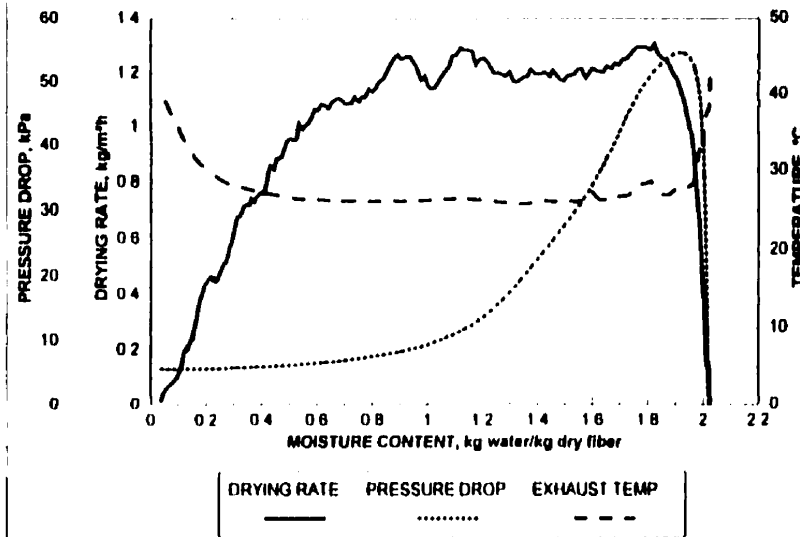
PAPER TYPE #2, B=57.3g/m², Ti=60.8°C, G=0.023kg/m²s



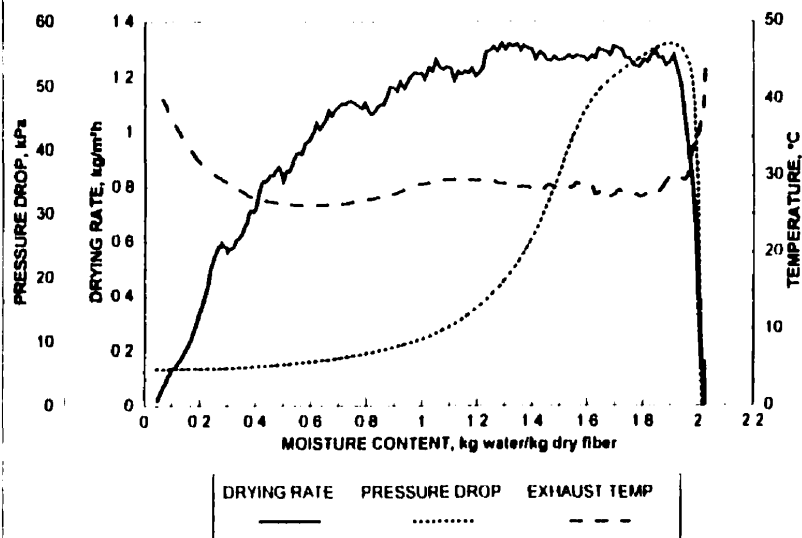
PAPER TYPE #2, B=57.3g/m², Ti=60.6°C, G=0.023kg/m²s



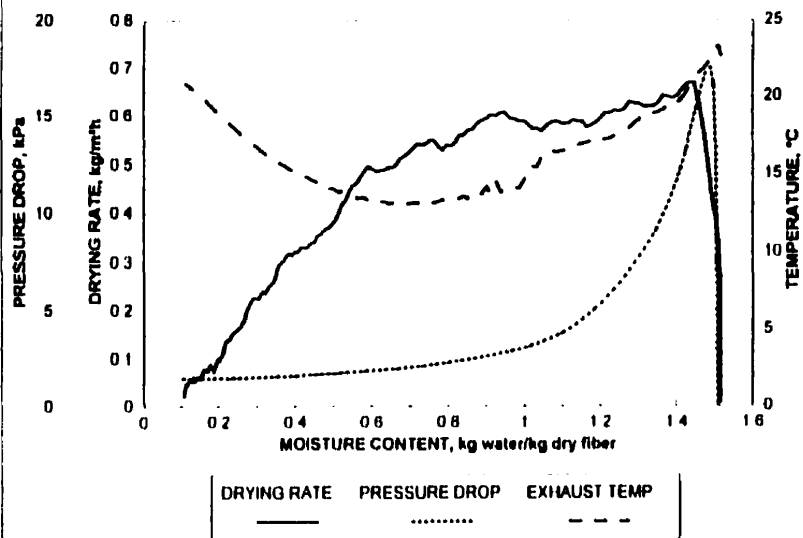
PAPER TYPE #2, B=57.3g/m², Ti=61.4°C, G=0.023kg/m²s



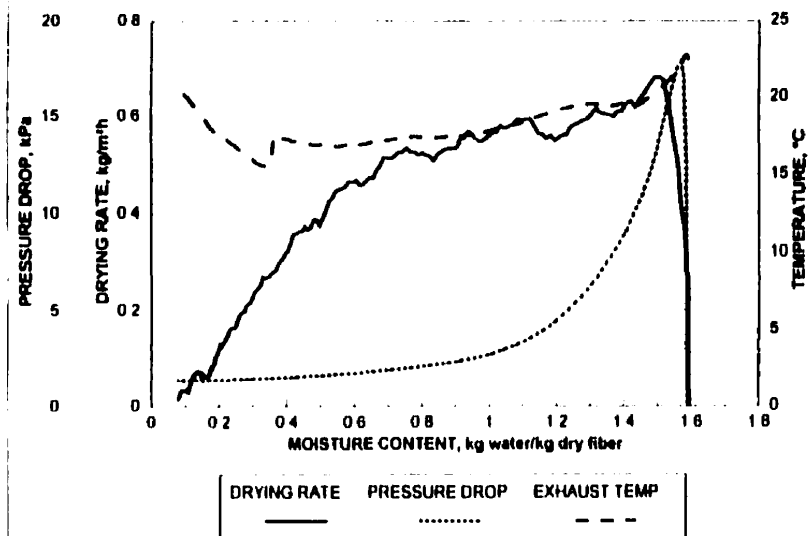
PAPER TYPE #2, B=57.3g/m², Ti=61.0°C, G=0.023kg/m²s



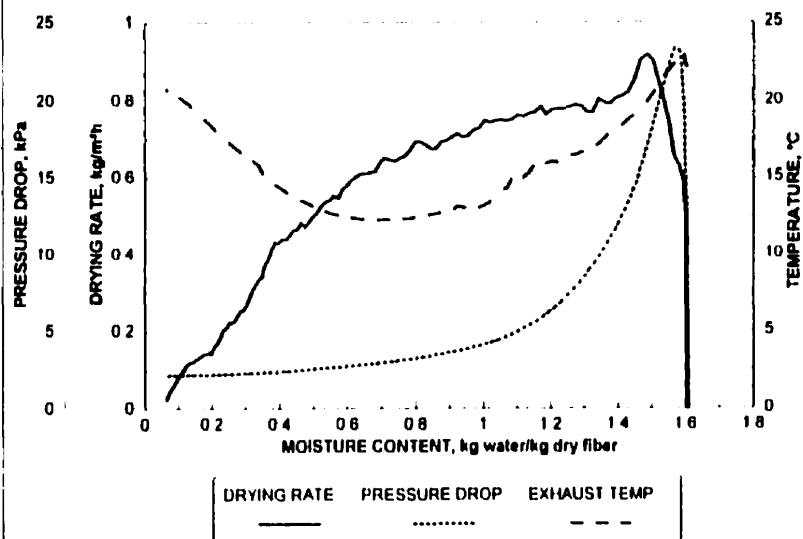
PAPER TYPE #3, B=47.5g/m², Ti=22.2°C, G=0.0246kg/m²s



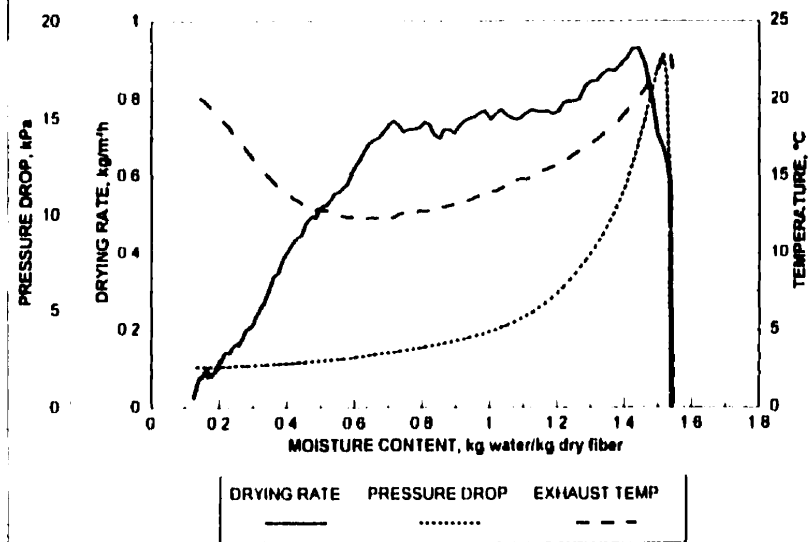
PAPER TYPE #3, B=47.5g/m², Ti=22.1°C, G=0.0246kg/m²s



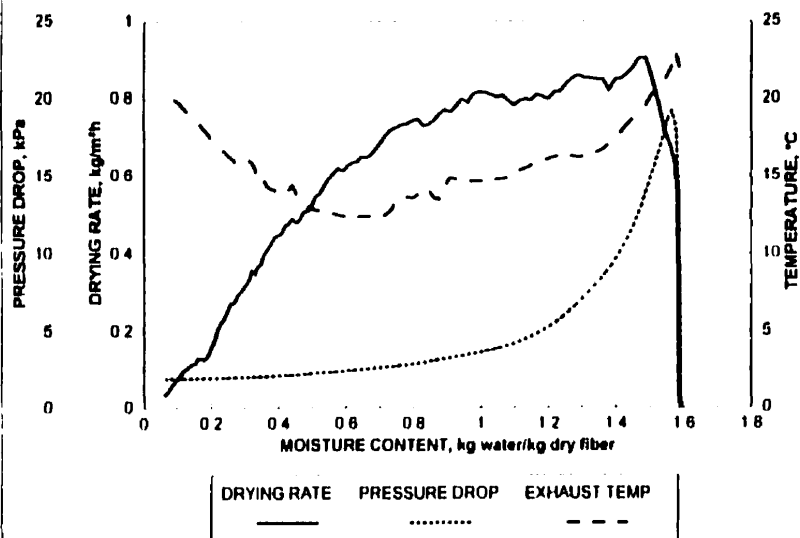
PAPER TYPE #3, B=47.5g/m², Ti=21.7°C, G=0.0362kg/m²s



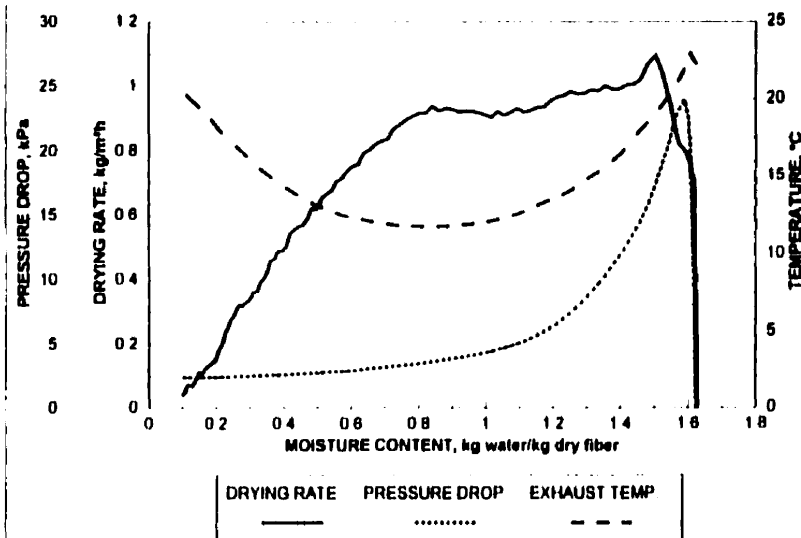
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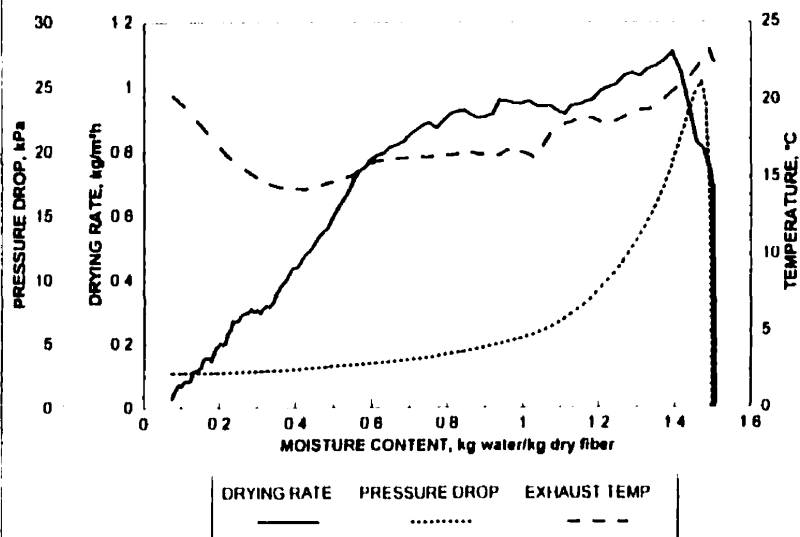
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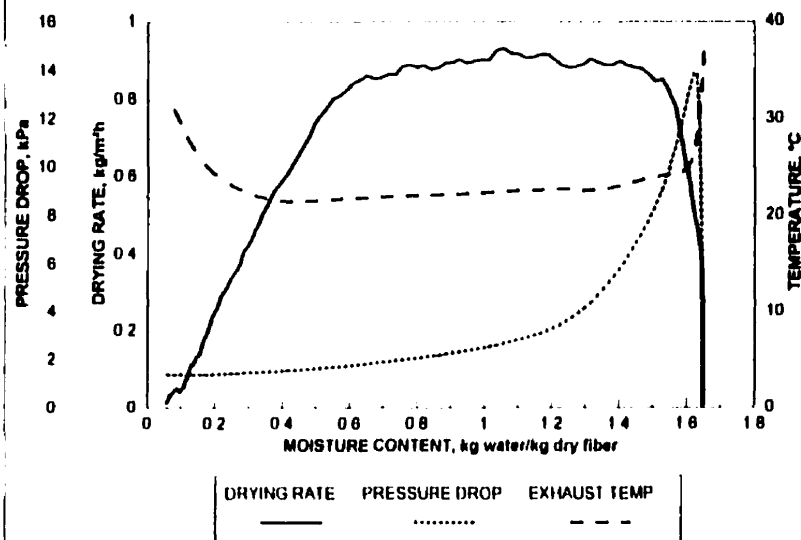
PAPER TYPE #3, B=47.5g/m², Ti=21.9°C, G=0.044kg/m²s



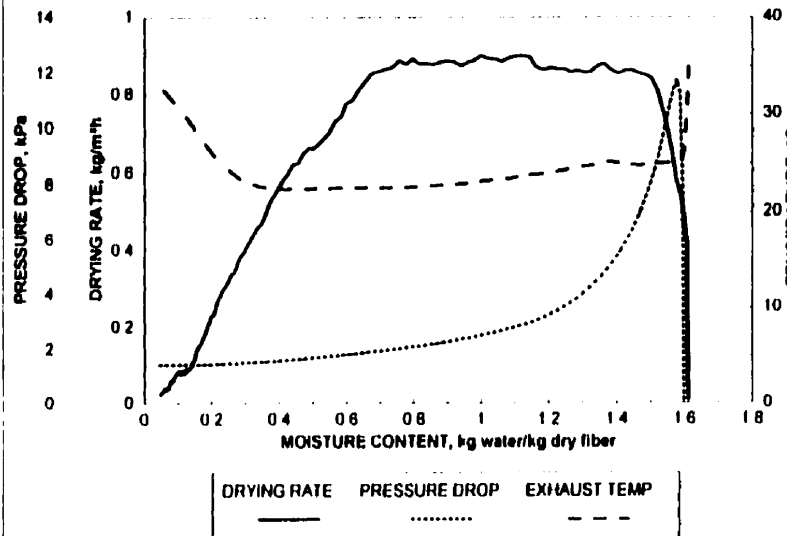
PAPER TYPE #3, B=47.5g/m², Ti=22.0°C, G=0.044kg/m²s



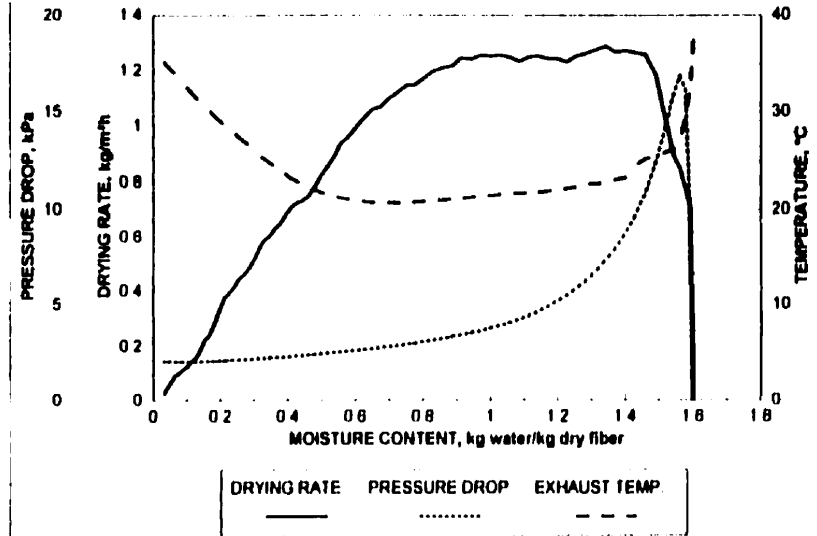
PAPER TYPE #3, B=47.5g/m², Ti=42.2°C, G=0.0246kg/m²s



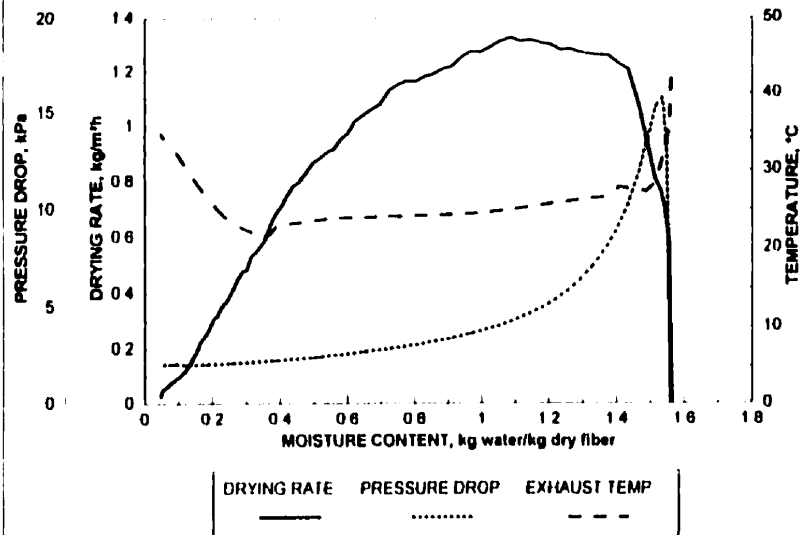
PAPER TYPE #3, B=47.5g/m², Ti=40.7°C, G=0.0246kg/m²s



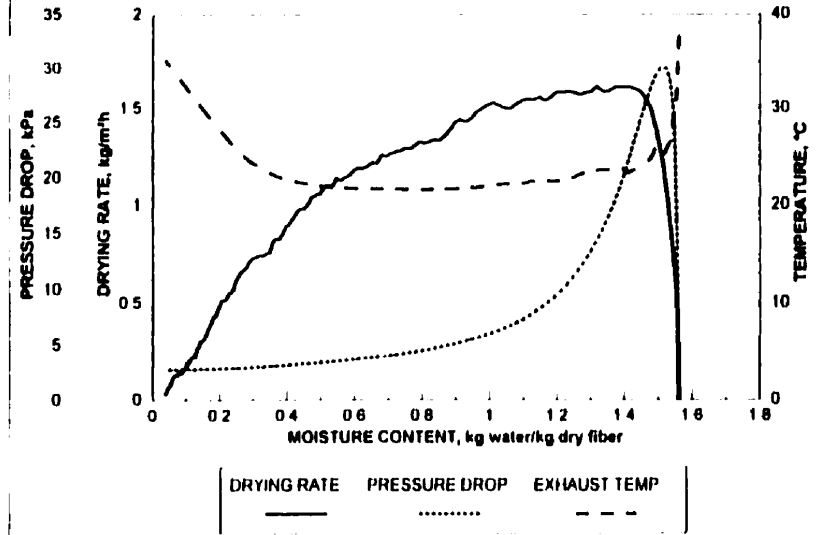
PAPER TYPE #3, B=47.5g/m², Ti=42.9°C, G=0.0362kg/m²s



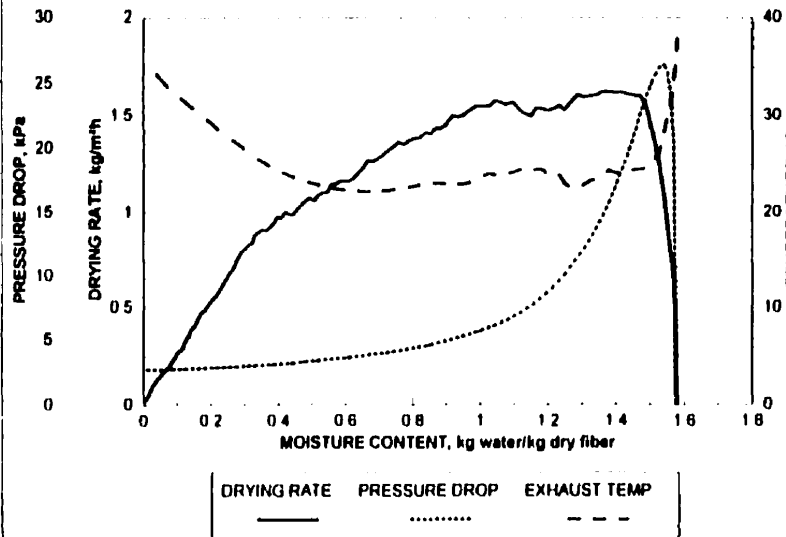
PAPER TYPE #3, B=47.5g/m², Ti=43.8°C, G=0.0362kg/m²s



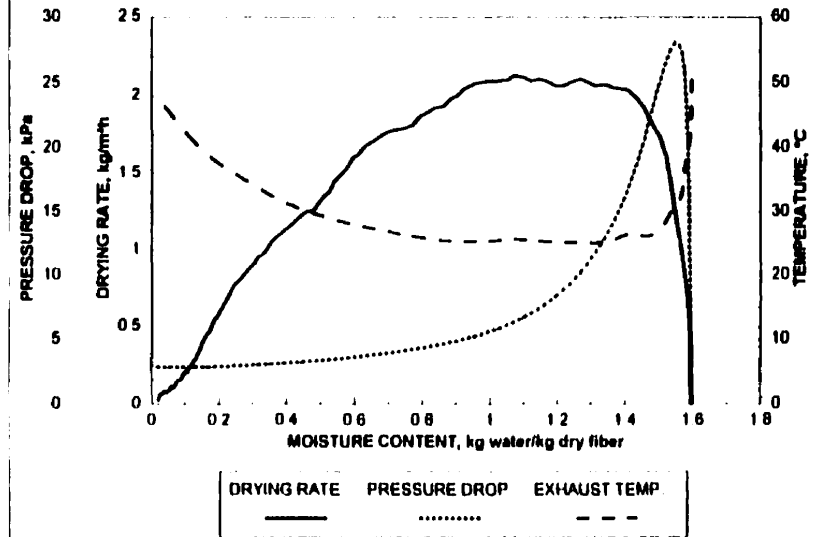
PAPER TYPE #3, B=47.5g/m², Ti=44.7°C, G=0.044kg/m²s



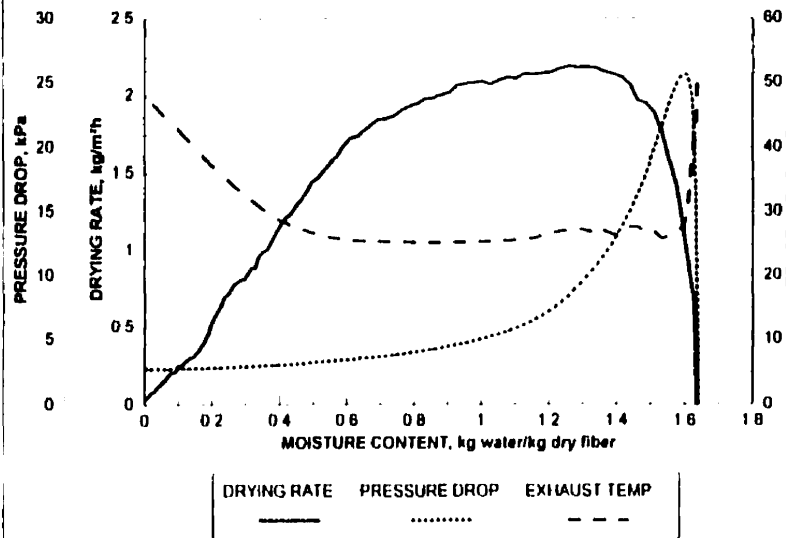
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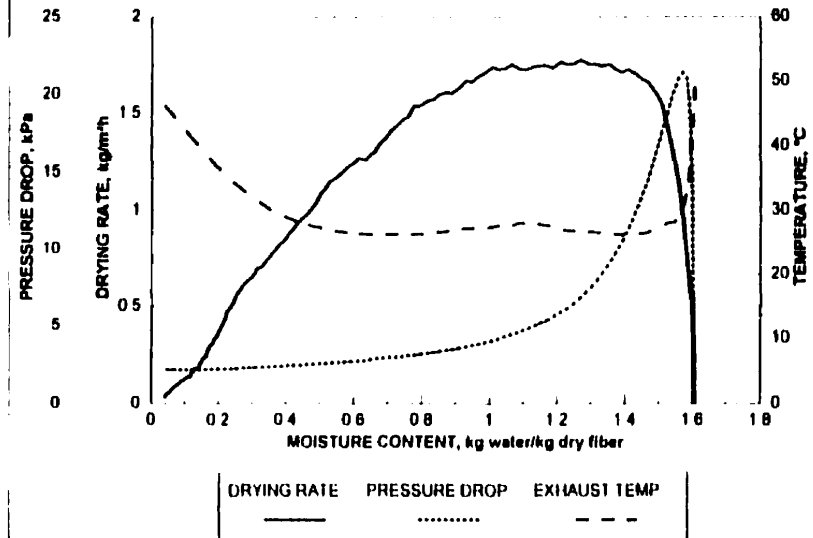
PAPER TYPE #3, B=47.5g/m², Ti=62.3°C, G=0.044kg/m²s



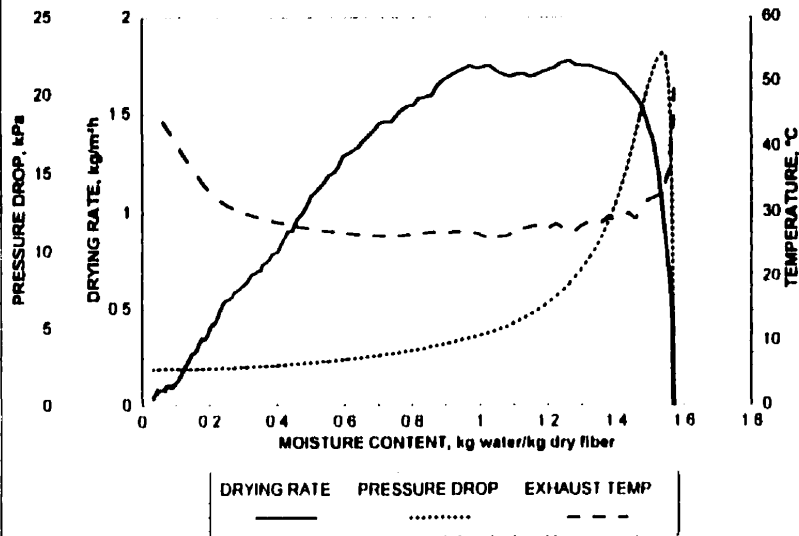
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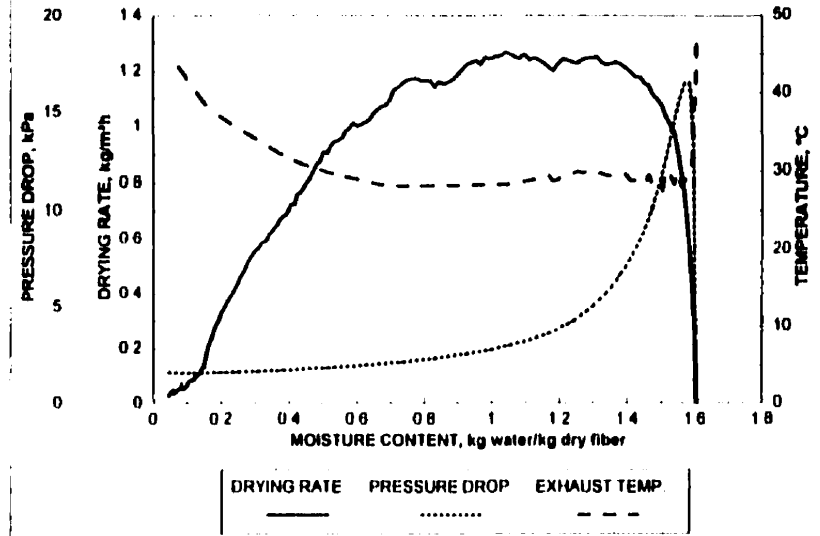
PAPER TYPE #3, B=47.5g/m², Ti=60.8°C, G=0.0362kg/m²s



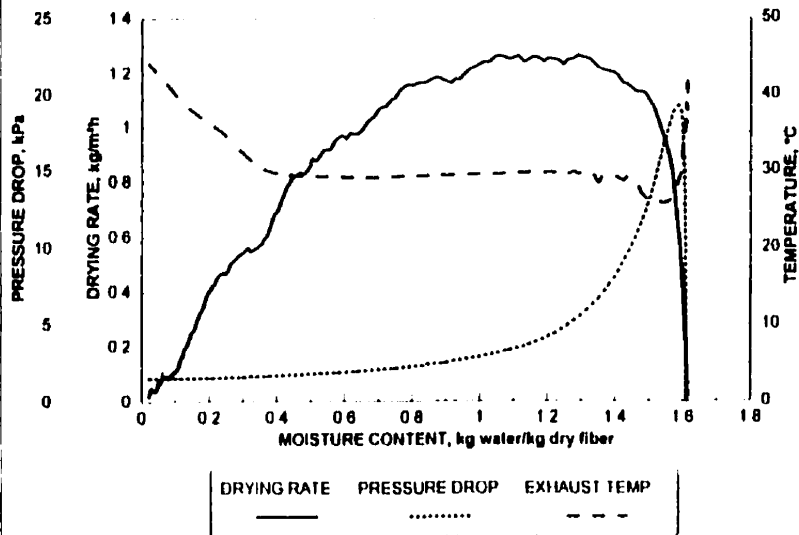
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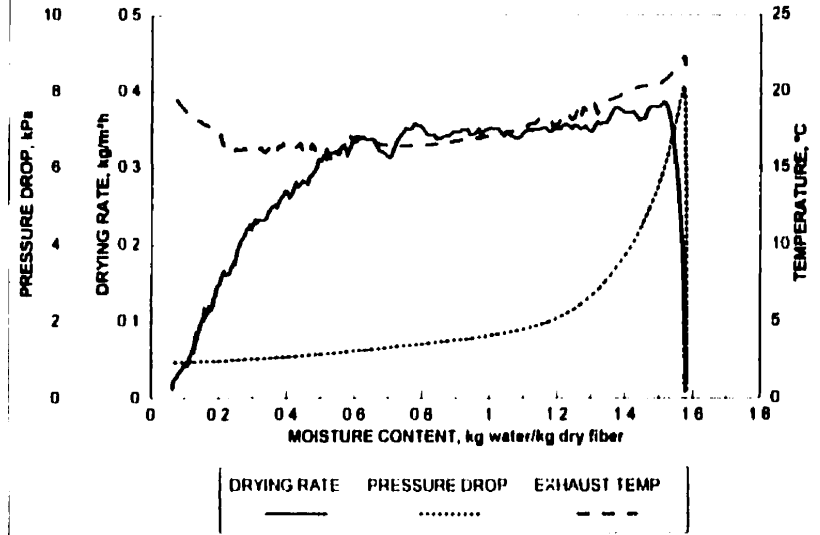
PAPER TYPE #3, B=47.5g/m², Ti=63.1°C, G=0.0246kg/m²s



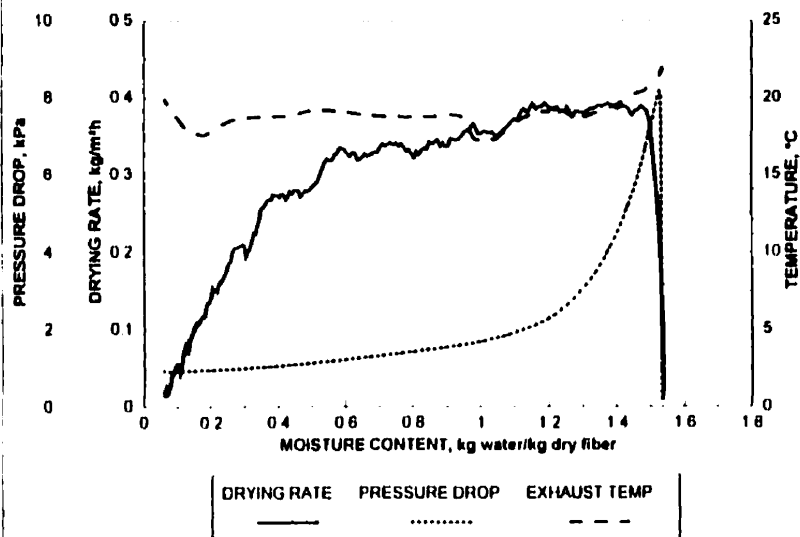
PAPER TYPE #3, B=47.5g/m², Ti=60.5°C, G=0.0246kg/m²s



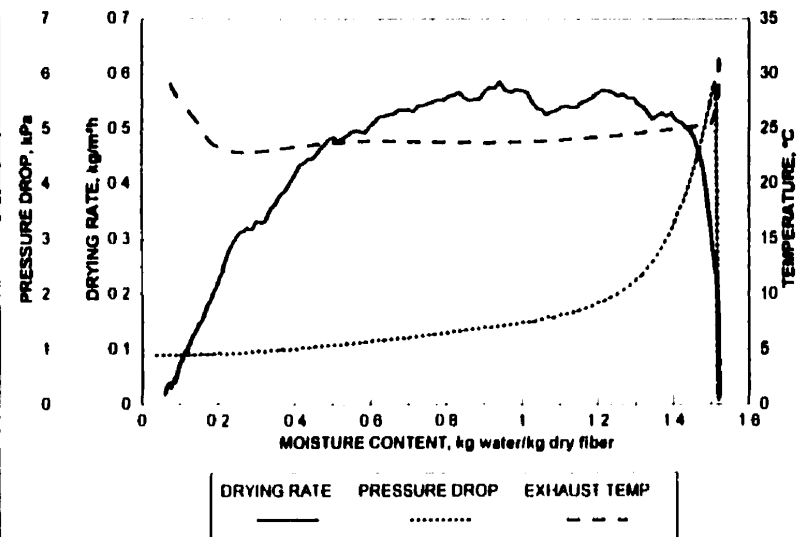
PAPER TYPE #3, B=47.5g/m², Ti=21.2°C, G=0.0127kg/m²s



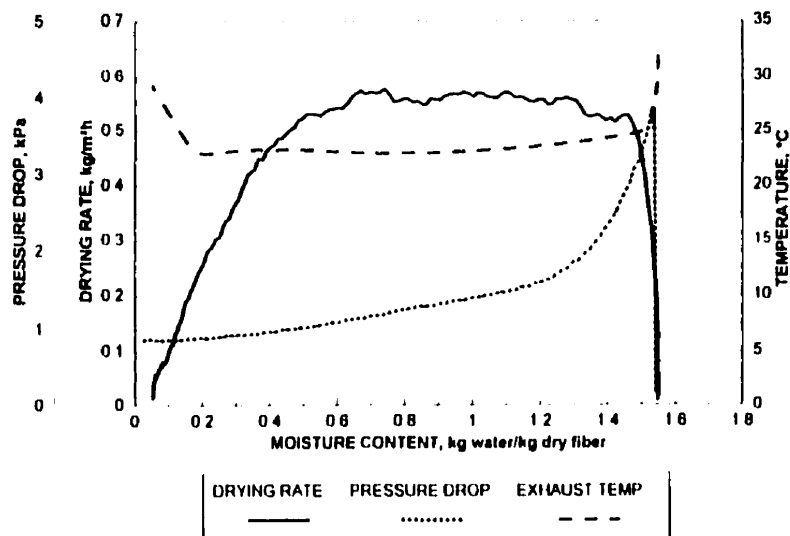
PAPER TYPE #3, B=47.5g/m², Ti=21.3°C, G=0.0127kg/m's



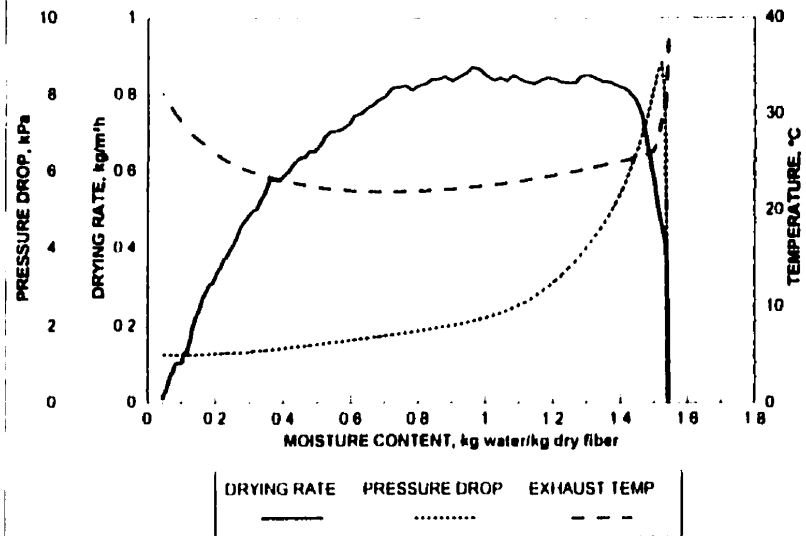
PAPER TYPE #3, B=47.5g/m², Ti=41.7°C, G=0.0127kg/m's



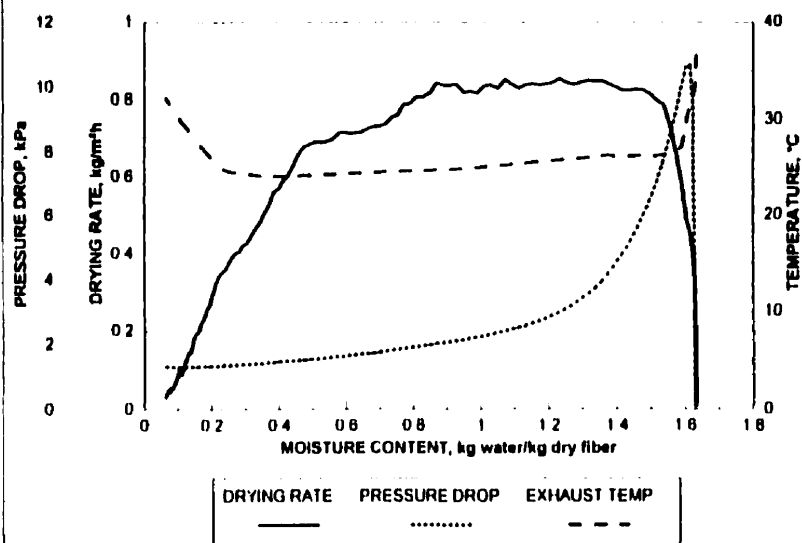
PAPER TYPE #3, B=47.5g/m², Ti=41.7°C, G=0.0127kg/m's



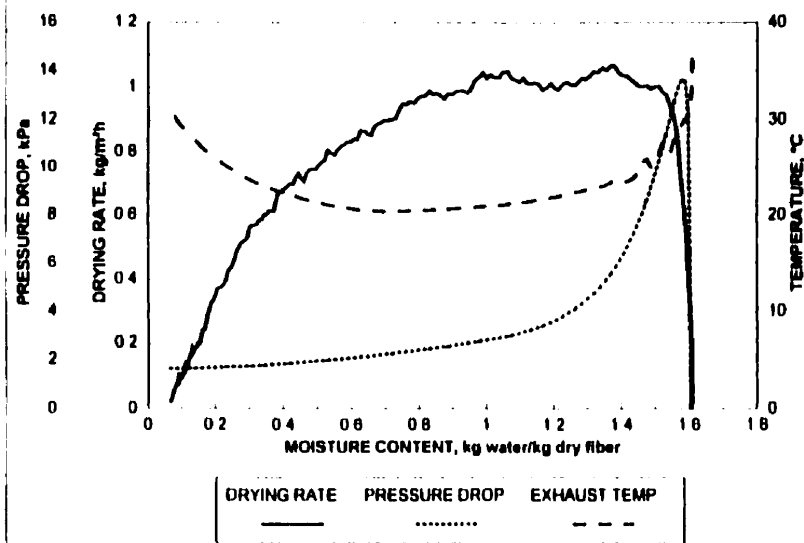
PAPER TYPE #3, B=47.5g/m², Ti=43.5°C, G=0.0195kg/m's



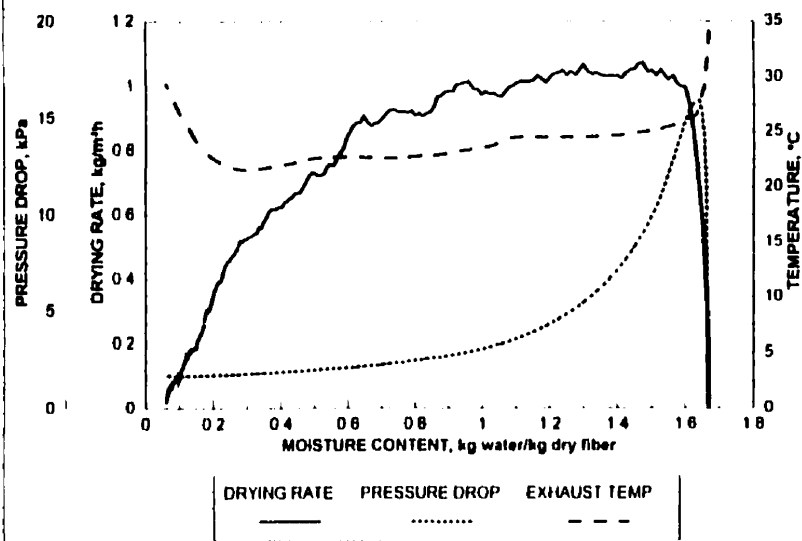
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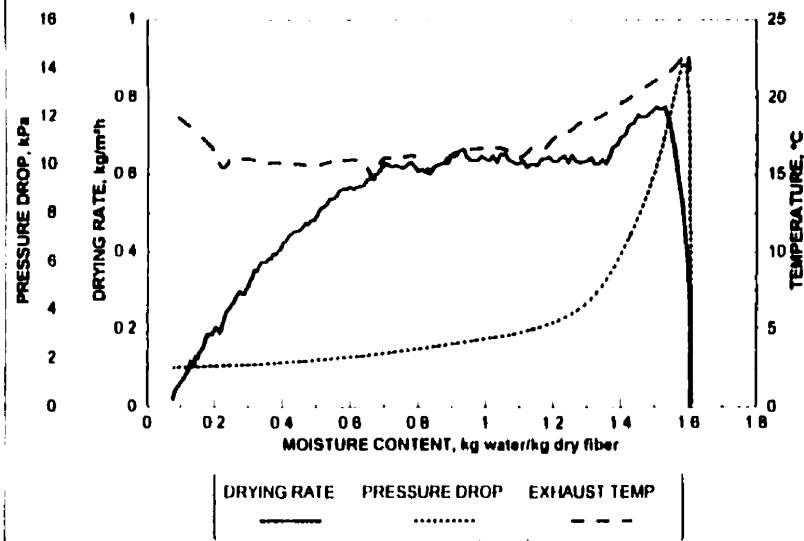
PAPER TYPE #3, B=47.5g/m², Ti=21.4°C, G=0.0265kg/m²s



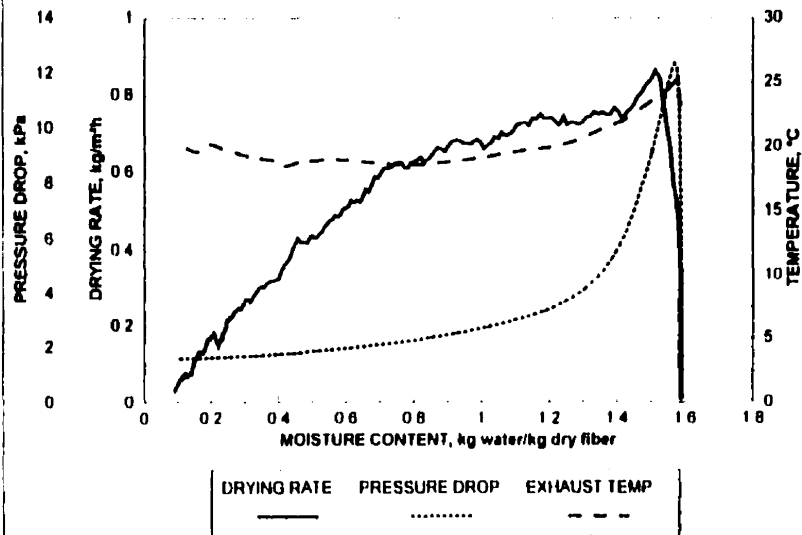
PAPER TYPE #3, B=47.5g/m², Ti=41.4°C, G=0.0265kg/m²s



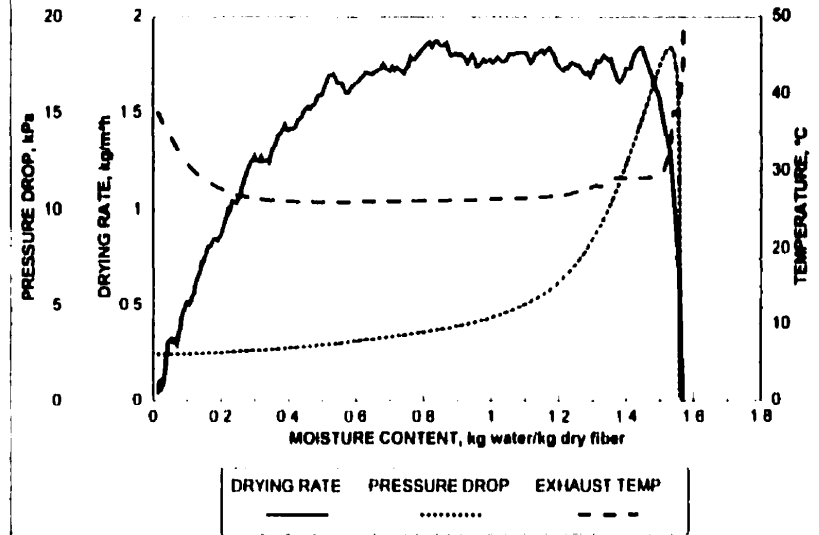
PAPER TYPE #3, B=47.5g/m², Ti=21.4°C, G=0.0265kg/m²s



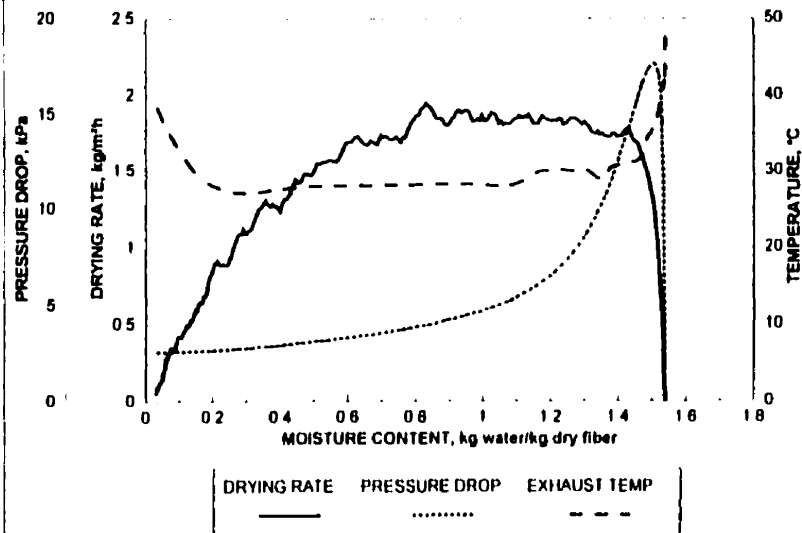
PAPER TYPE #3, B=47.5g/m², Ti=22.8°C, G=0.0265kg/m²s



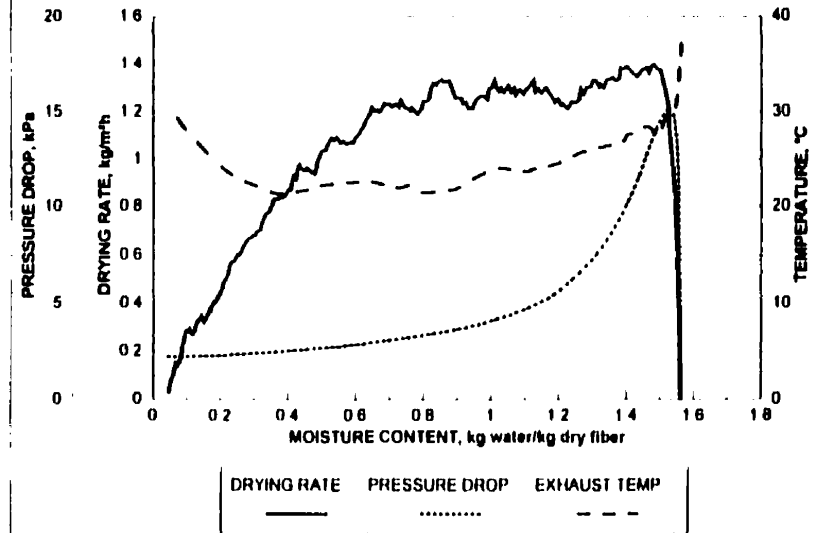
PAPER TYPE #3, B=47.5g/m², Ti=62.0°C, G=0.034kg/m²s



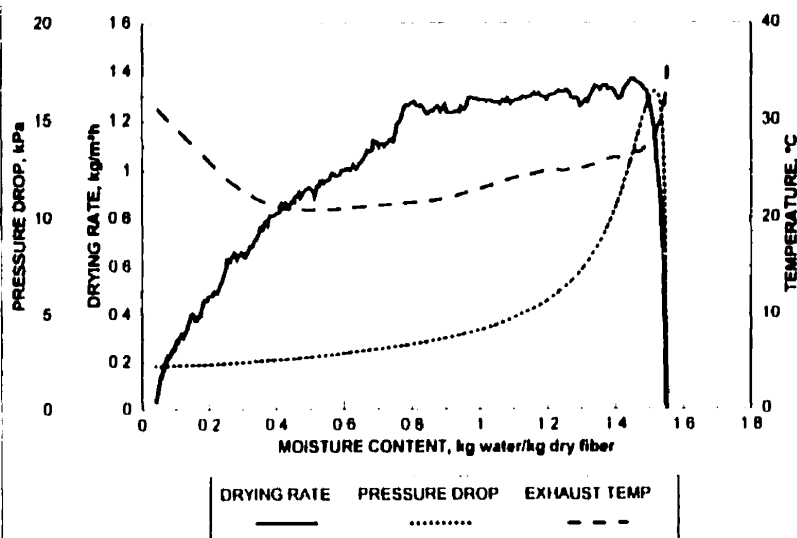
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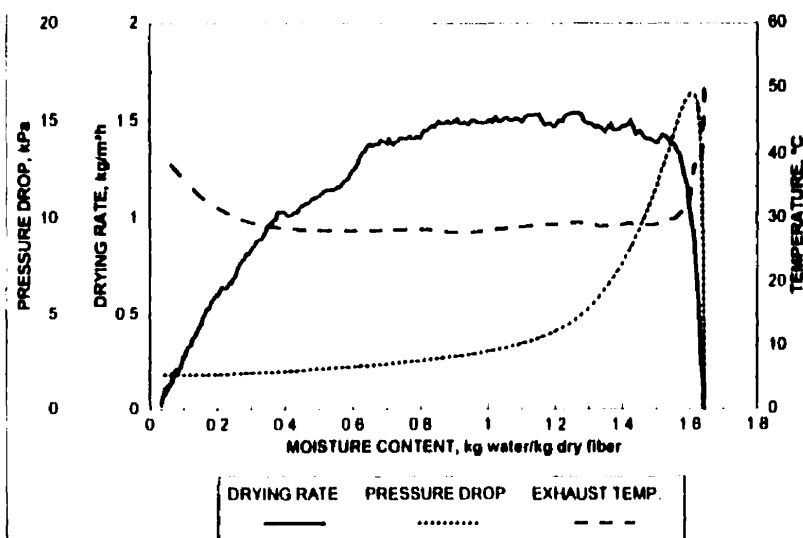
PAPER TYPE #3, B=47.5g/m², Ti=41.2°C, G=0.034kg/m²s



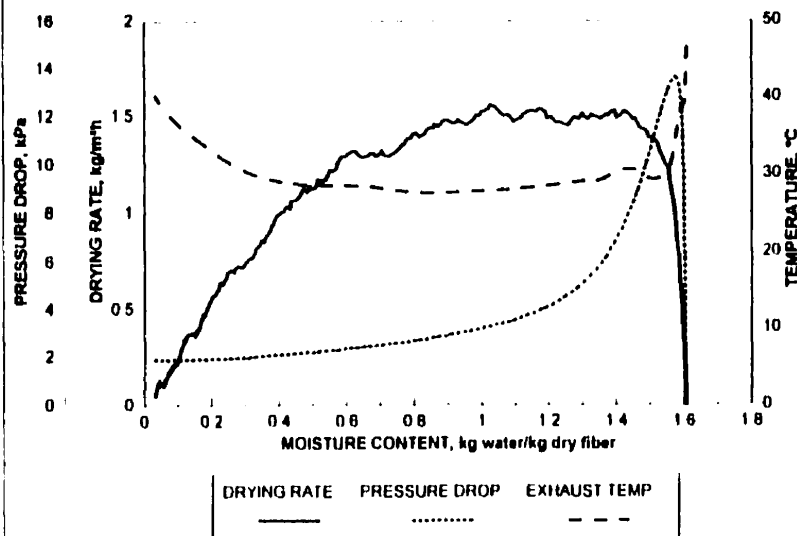
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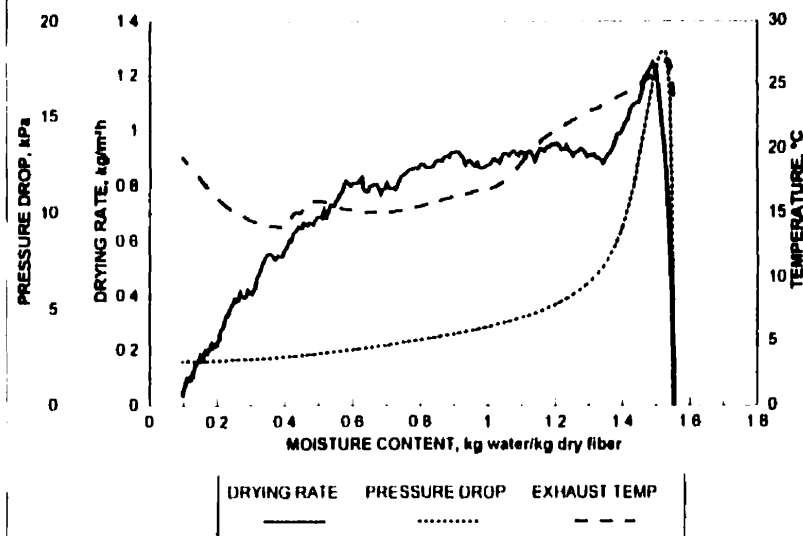
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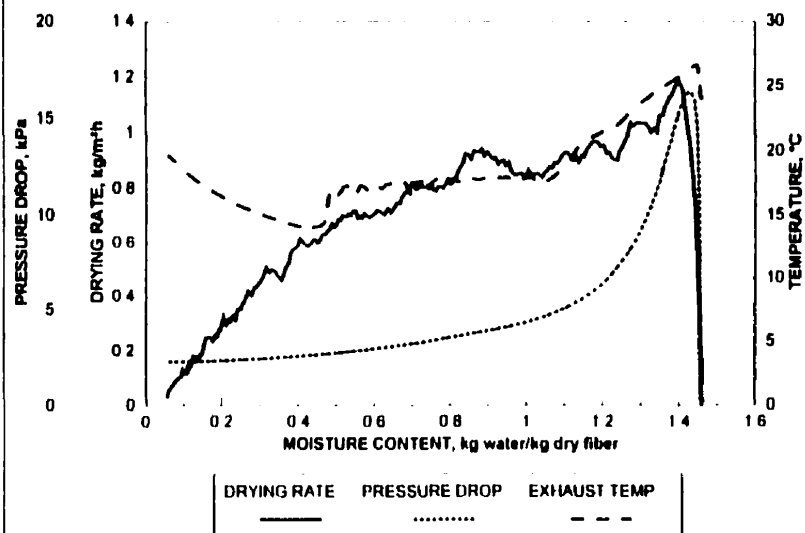
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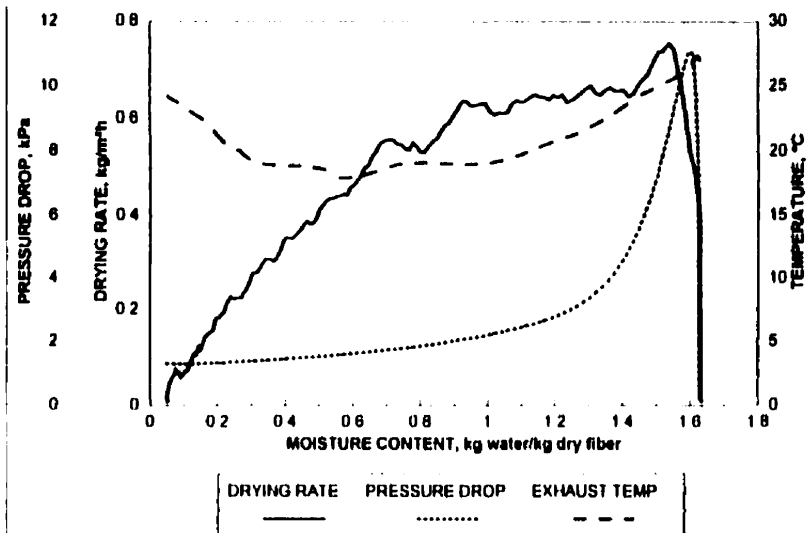
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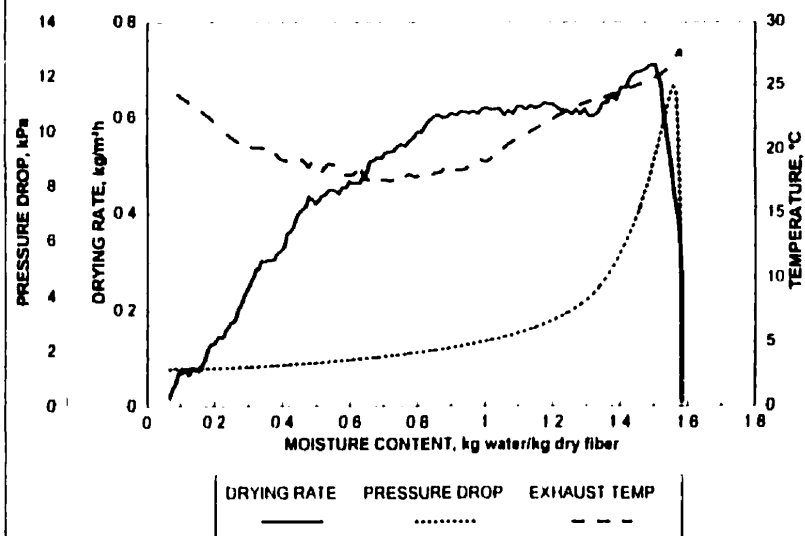
PAPER TYPE #3, B=47.5g/m², Ti=23.5°C, G=0.034kg/m²s



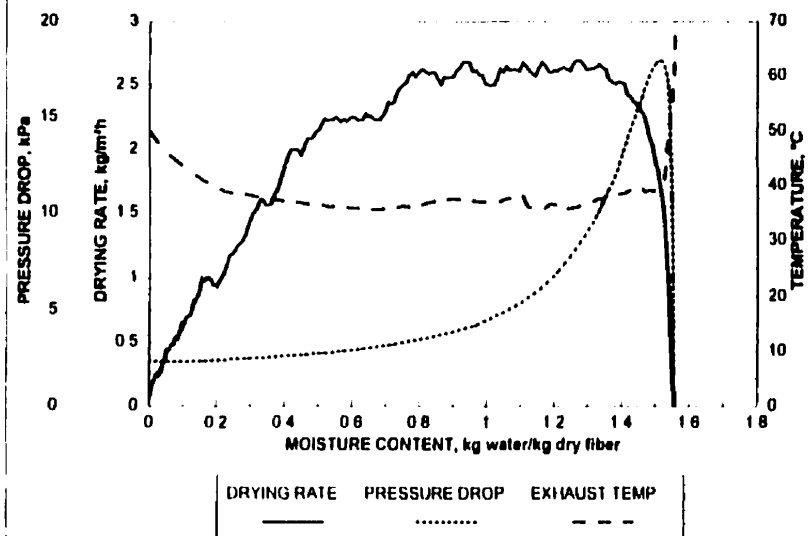
PAPER TYPE #3, B=47.5g/m², Ti=26.9°C, G=0.0195kg/m²s



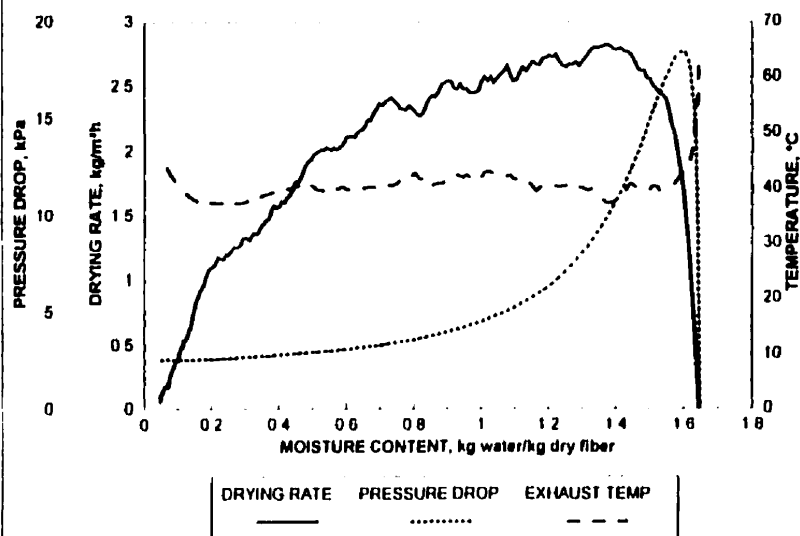
PAPER TYPE #3, B=47.5g/m², Ti=27.0°C, G=0.0195kg/m²s



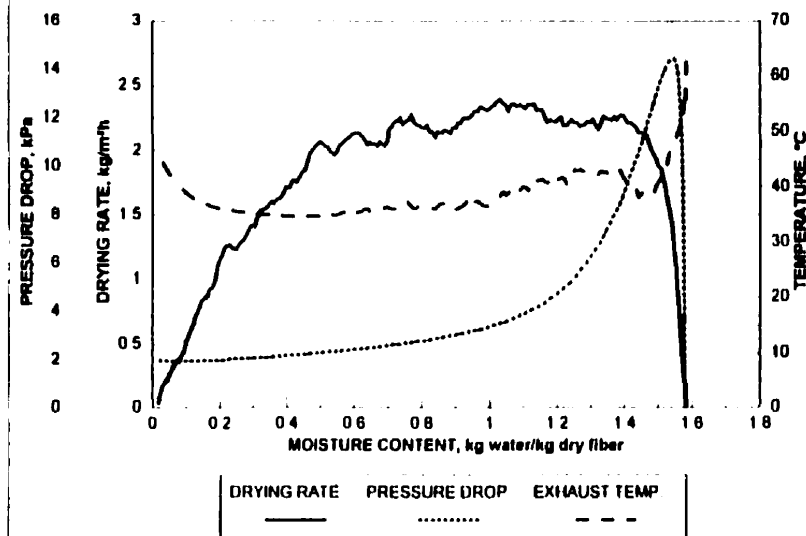
PAPER TYPE #3, B=47.5g/m², Ti=81.9°C, G=0.034kg/m²s



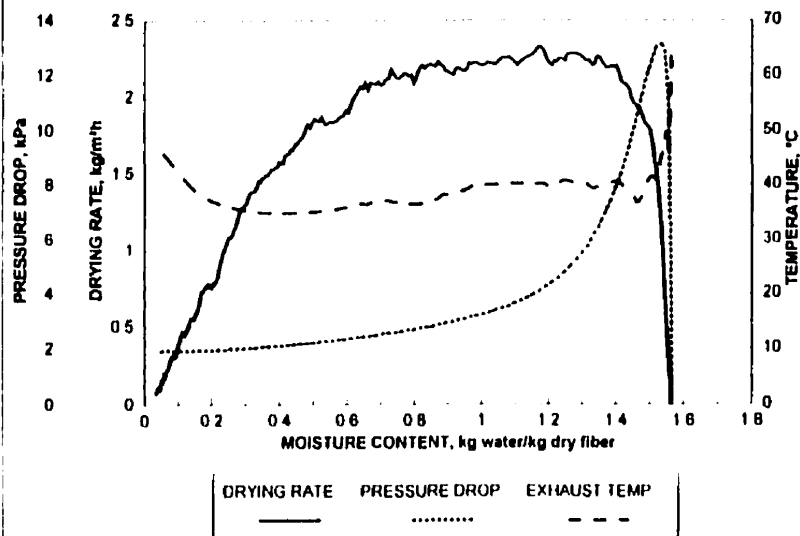
PAPER TYPE #3, B=47.5g/m², Ti=83.2°C, G=0.034kg/m²s



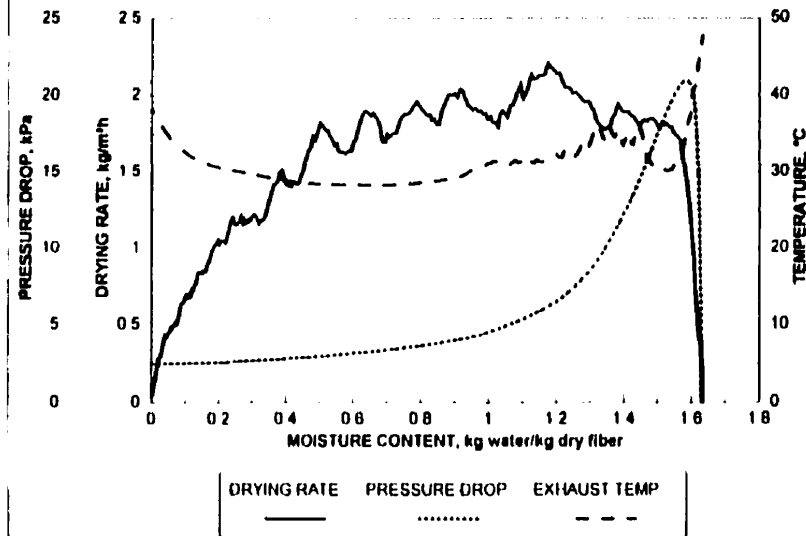
PAPER TYPE #3, B=47.5g/m², Ti=85.0°C, G=0.0265kg/m²s



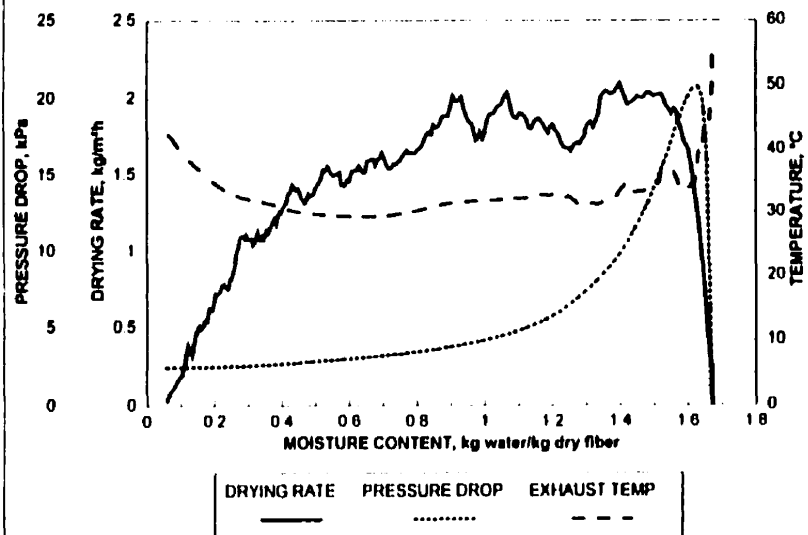
PAPER TYPE #3, B=47.5g/m², Ti=84.5°C, G=0.0265kg/m²s



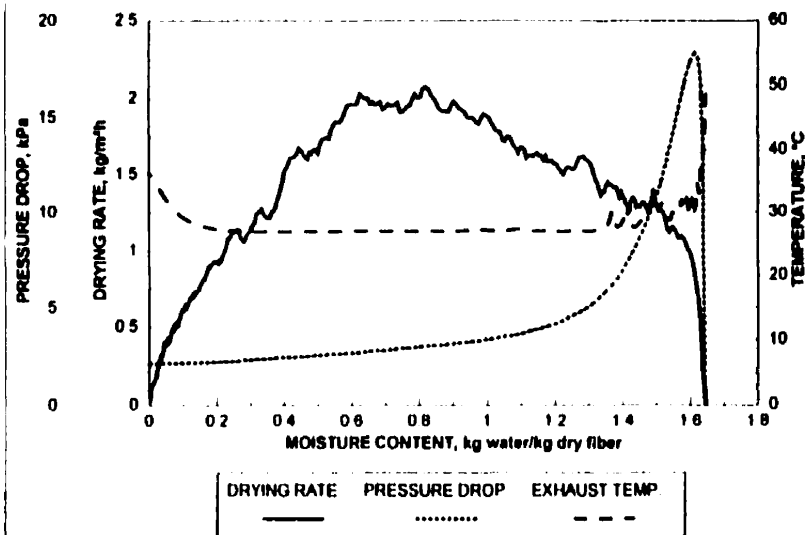
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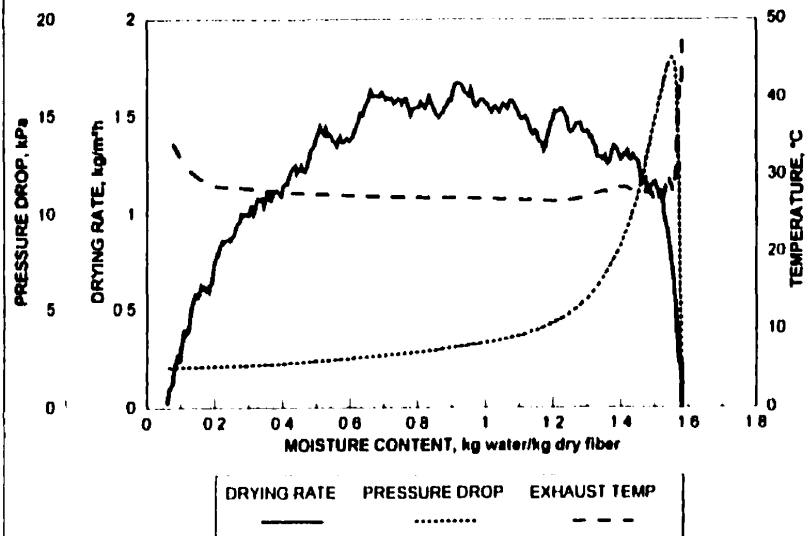
PAPER TYPE #3, B=47.5g/m², Ti=69.1°C, G=0.034kg/m²s



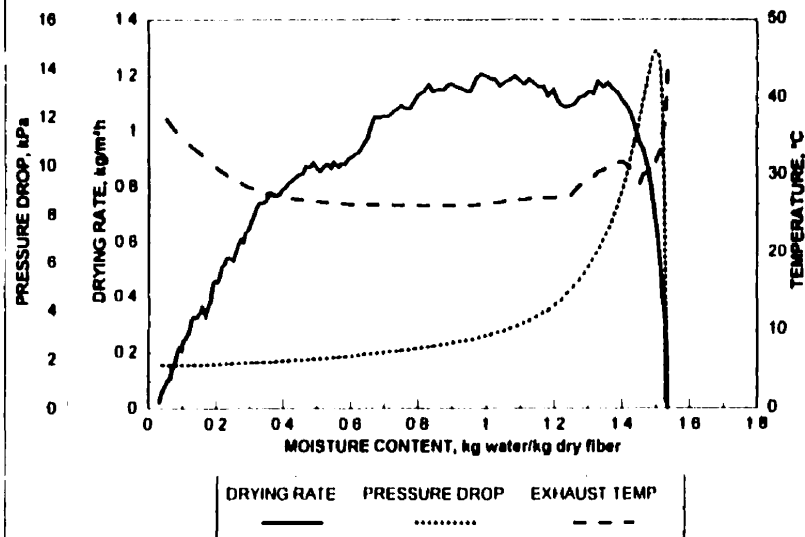
PAPER TYPE #3, B=47.5g/m², Ti=69.9°C, G=0.0265kg/m²s



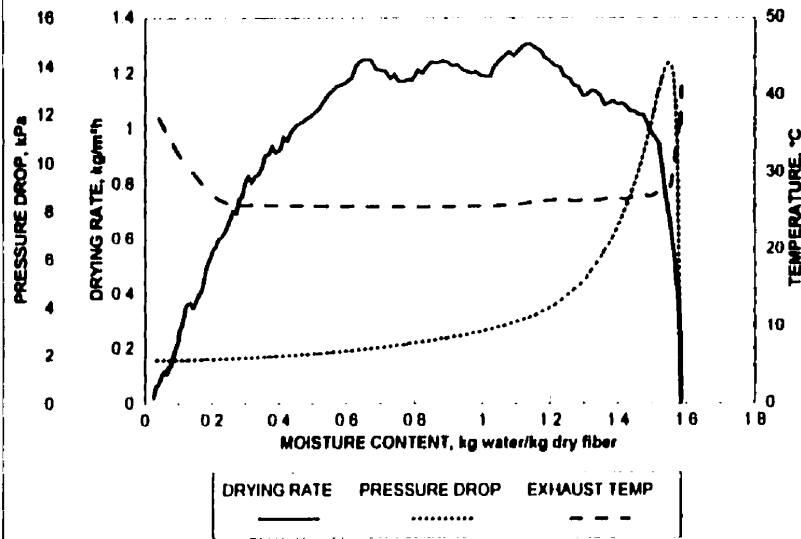
PAPER TYPE #3, B=47.5g/m², Ti=69.9°C, G=0.0265kg/m²s



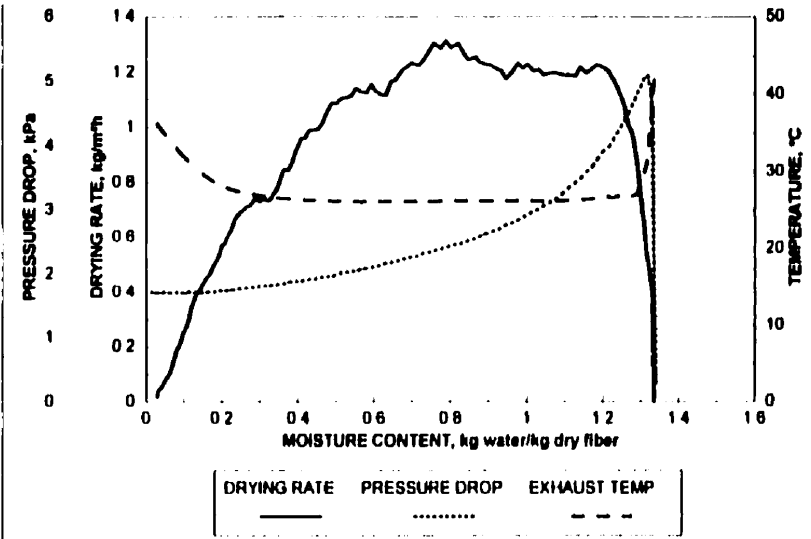
PAPER TYPE #3, B=47.5g/m², Ti=62.5°C, G=0.023kg/m²s



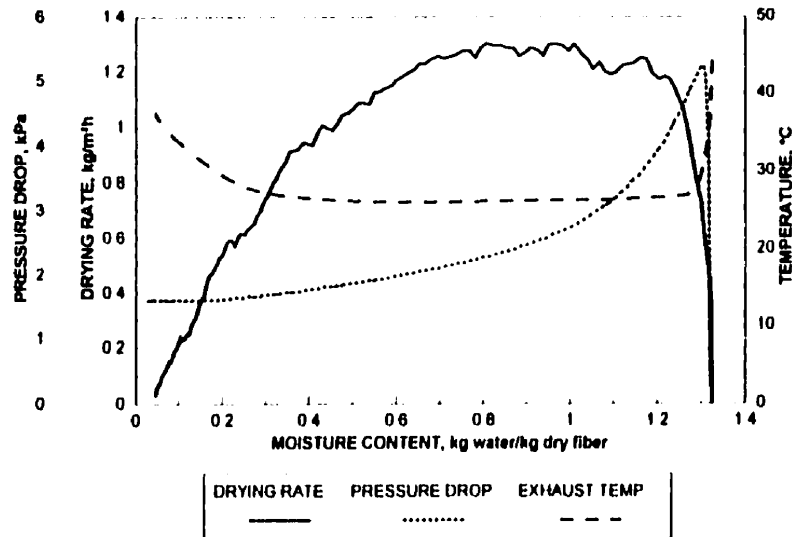
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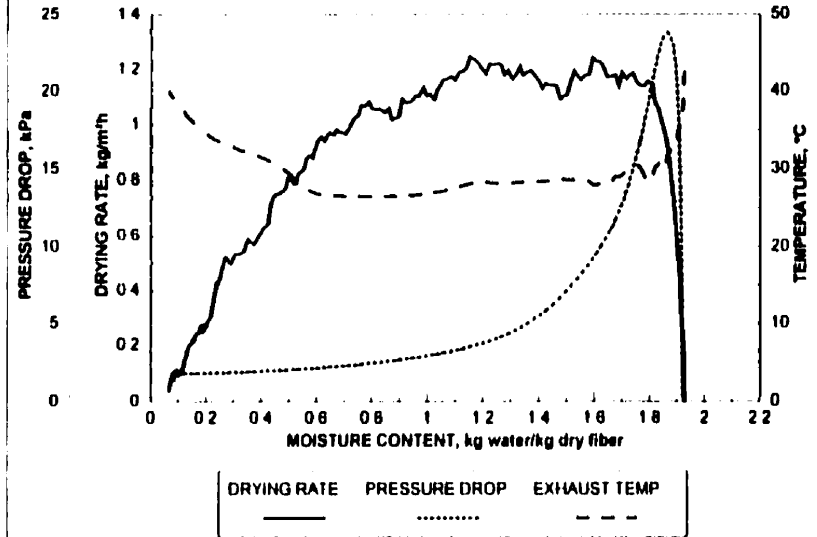
PAPER TYPE #3, B=47.5g/m², Ti=61.3°C, G=0.023kg/m²s



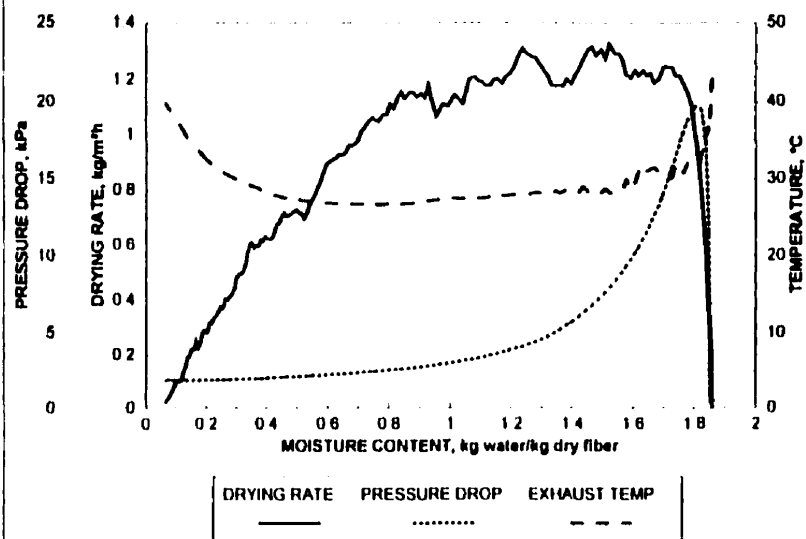
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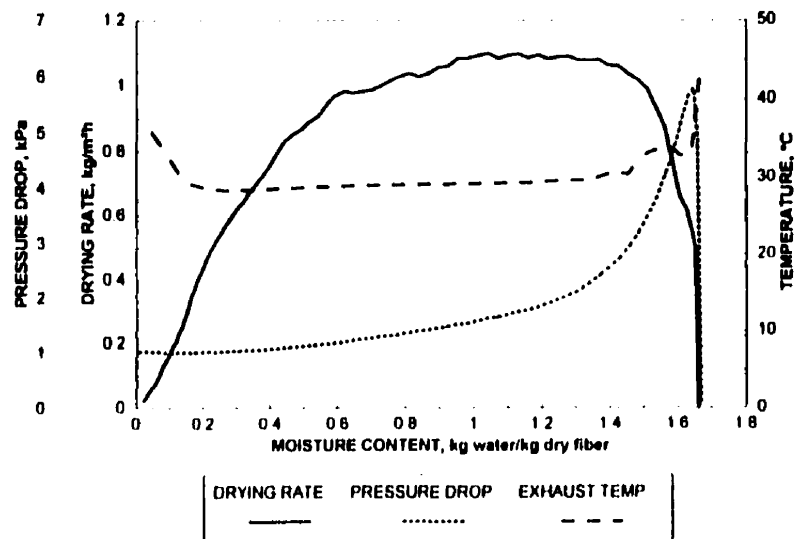
PAPER TYPE #3, B=47.5g/m², Ti=60.1°C, G=0.023kg/m²s



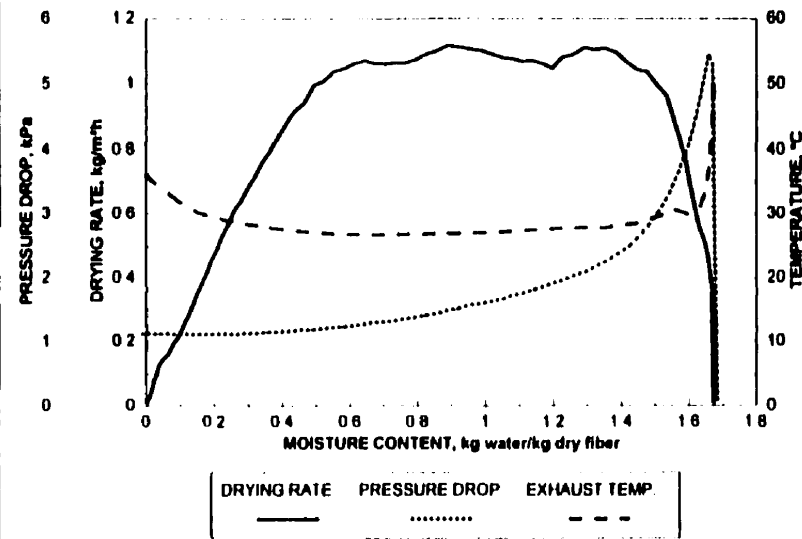
PAPER TYPE #3, B=47.5g/m², Ti=60.3°C, G=0.023kg/m²s



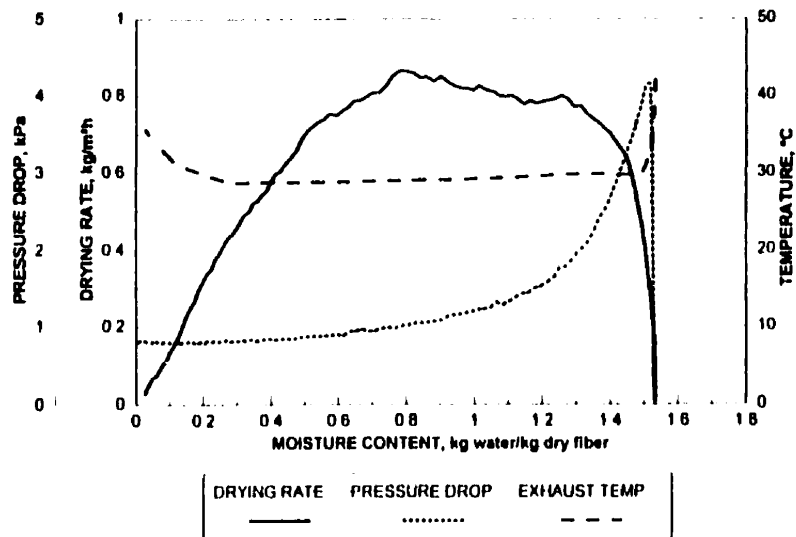
PAPER TYPE #6, B=44.2g/m², Ti=59.9°C, G=0.0195kg/m²s



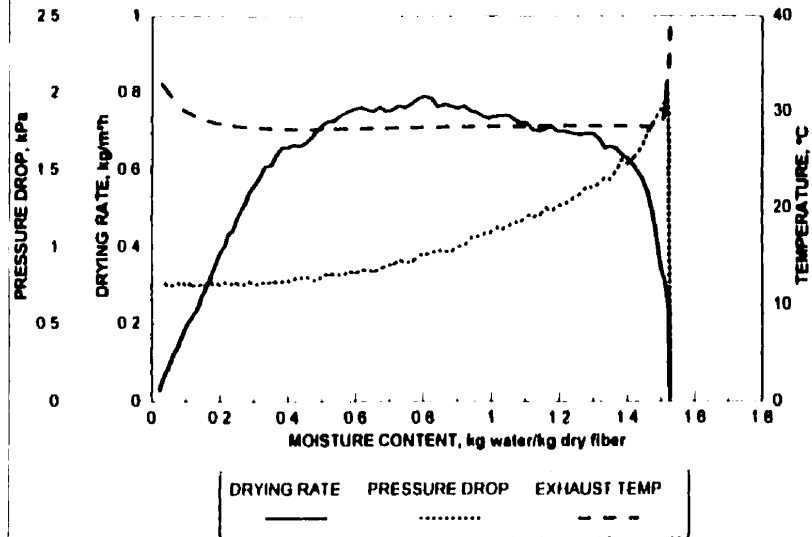
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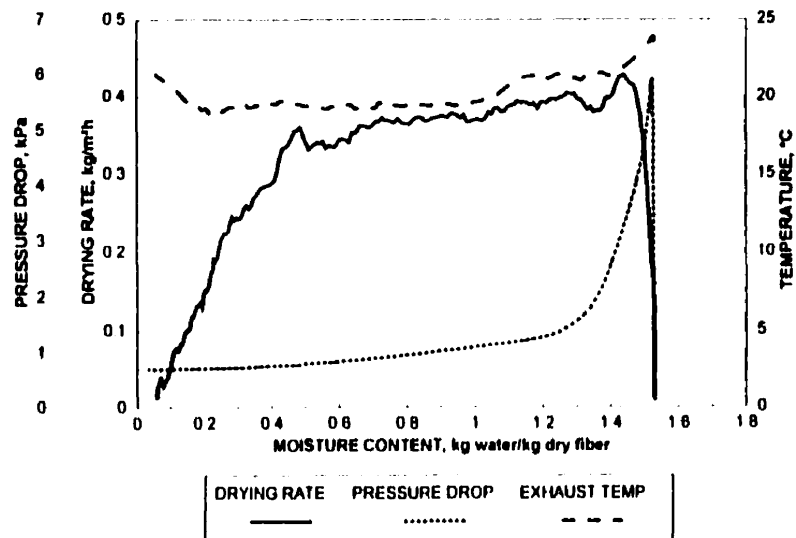
PAPER TYPE #6, B=44.2g/m², Ti=58.9°C, G=0.0127kg/m²s



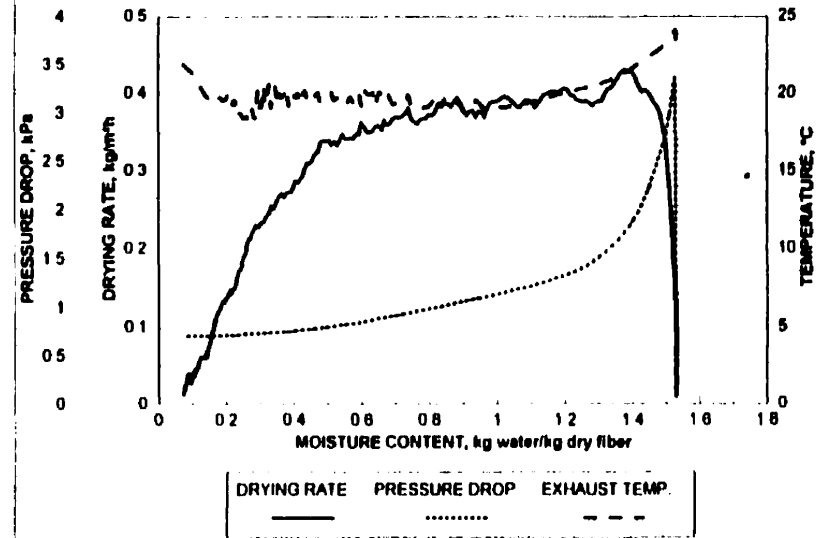
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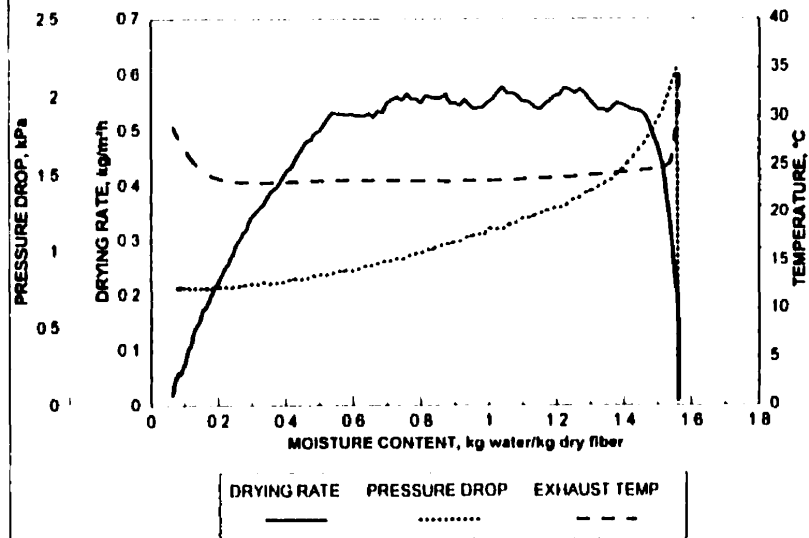
PAPER TYPE #6, B=44.2g/m², Ti=23.2°C, G=0.0127kg/m²s



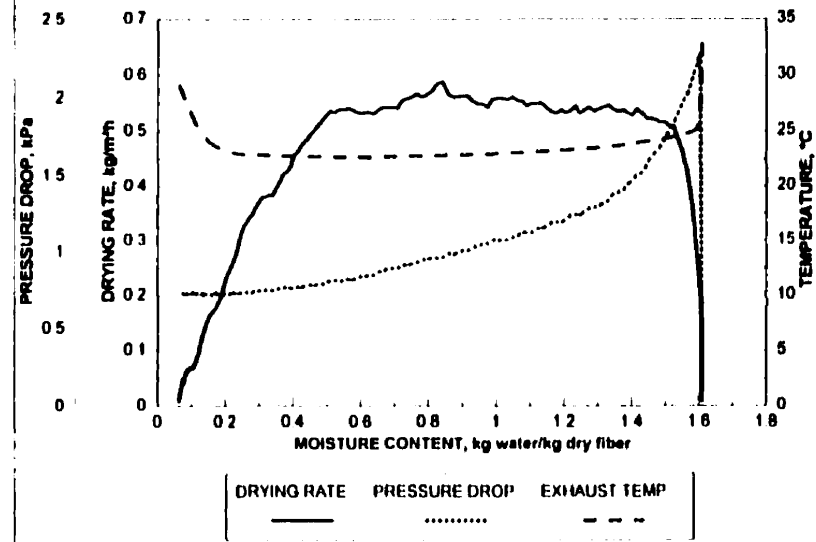
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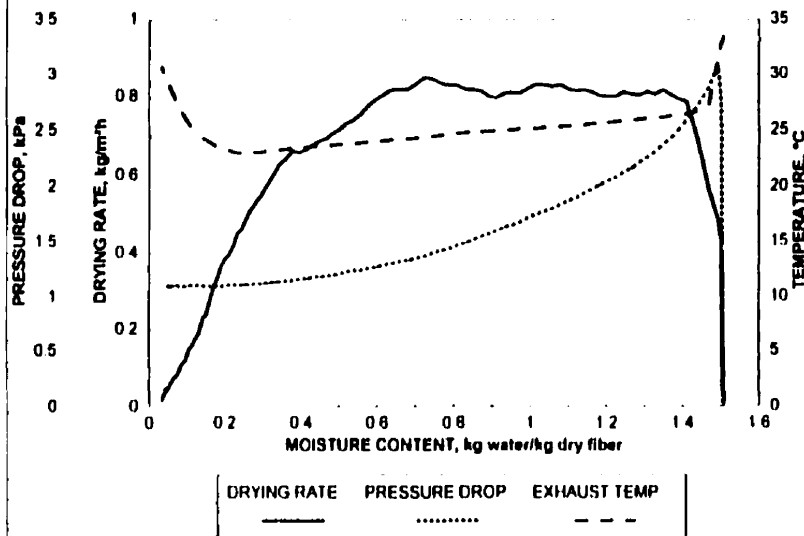
PAPER TYPE #6, B=44.2g/m², Ti=41.9°C, G=0.0127kg/m²s



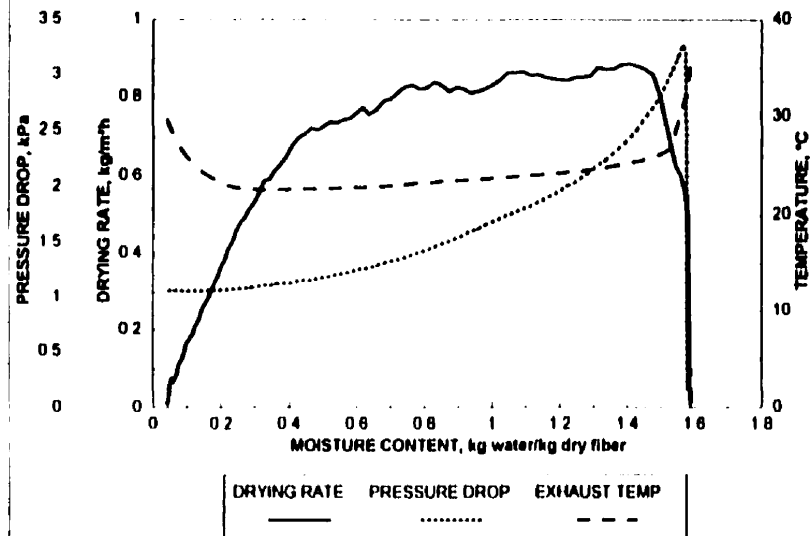
PAPER TYPE #6, B=44.2g/m², Ti=41.8°C, G=0.0127kg/m²s



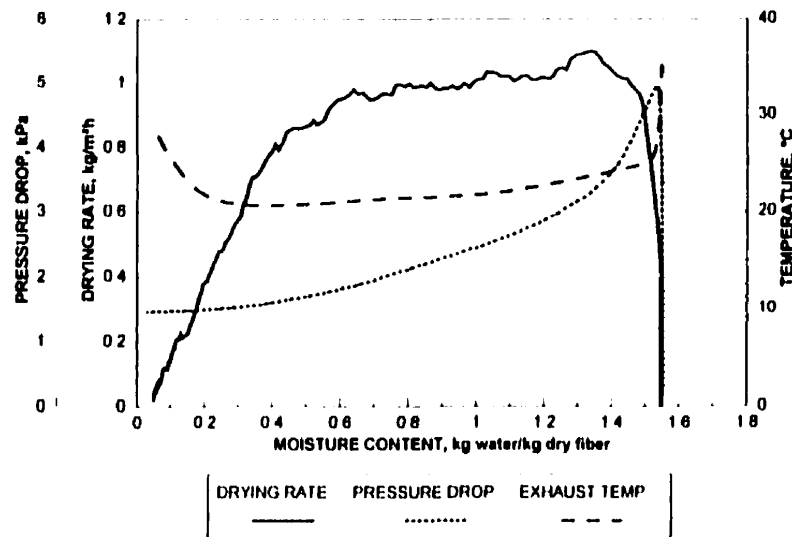
PAPER TYPE #6, $B=44.2\text{g/m}^2$, $T_i=42.7^\circ\text{C}$, $G=0.0195\text{kg/m}^2\text{s}$



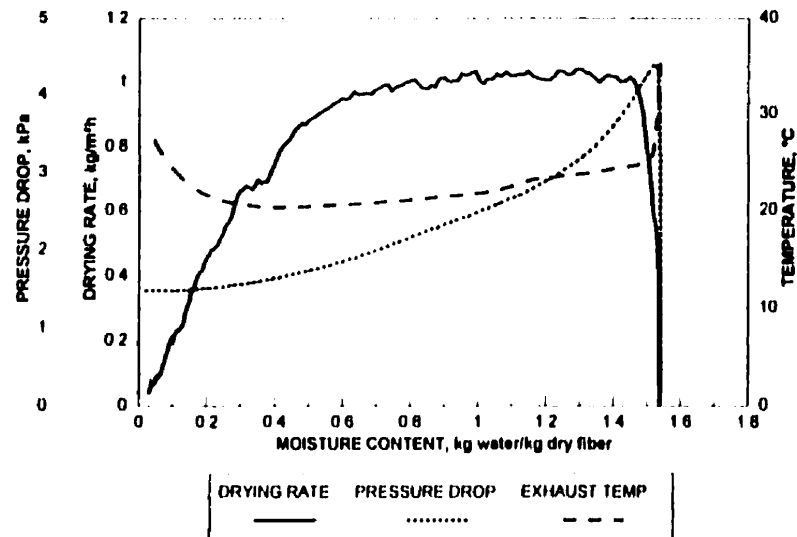
PAPER TYPE #6, $B=44.2\text{g/m}^2$, $T_i=42.9^\circ\text{C}$, $G=0.0195\text{kg/m}^2\text{s}$



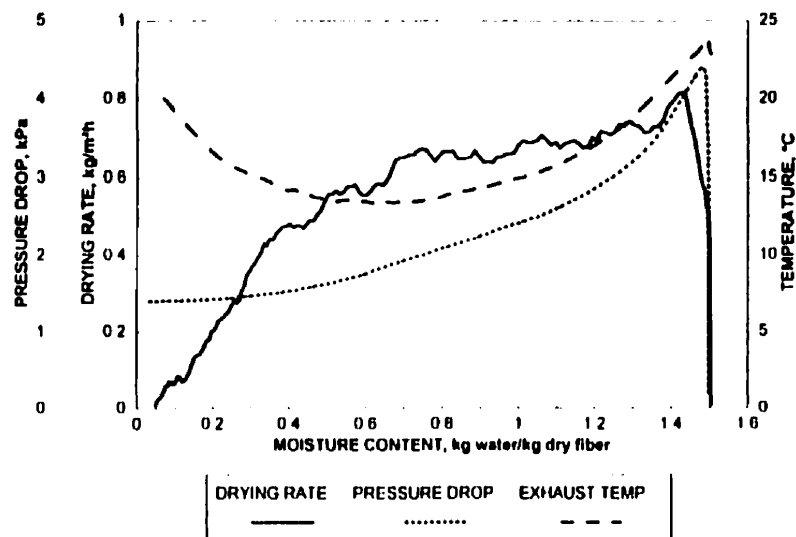
PAPER TYPE #6, $B=44.2\text{g/m}^2$, $T_i=41.0^\circ\text{C}$, $G=0.0265\text{kg/m}^2\text{s}$



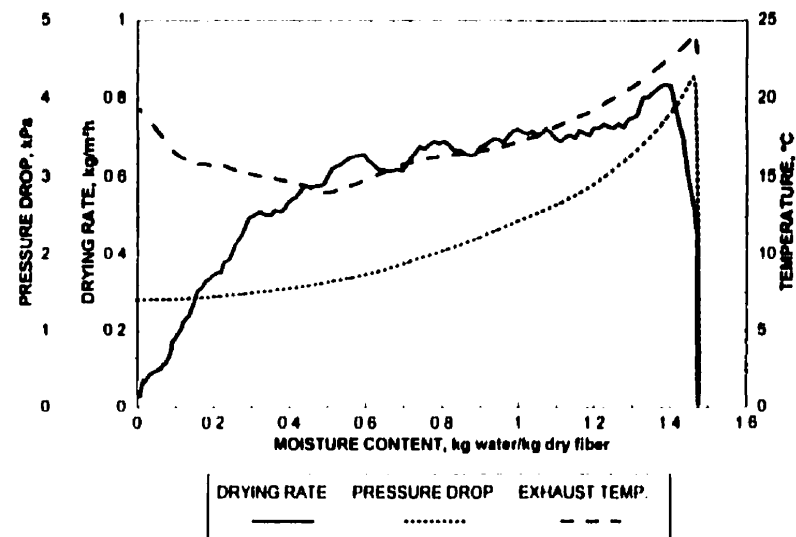
PAPER TYPE #6, $B=44.2\text{g/m}^2$, $T_i=41.2^\circ\text{C}$, $G=0.0265\text{kg/m}^2\text{s}$



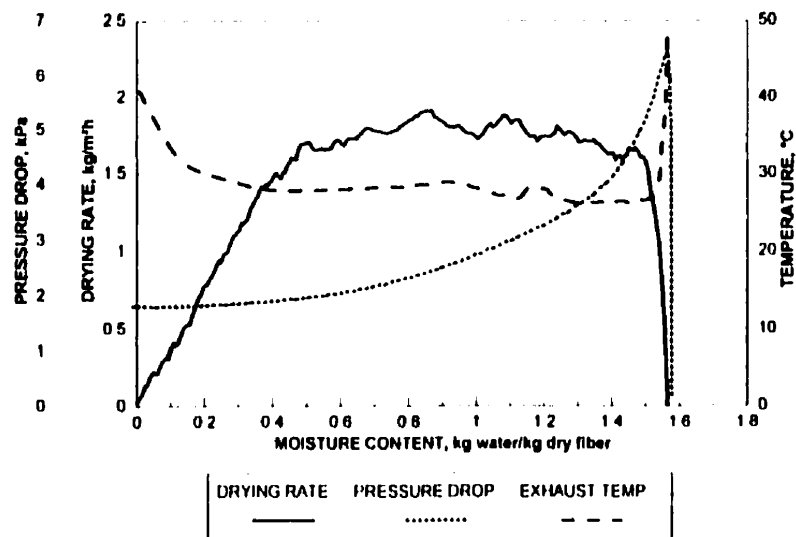
PAPER TYPE #6, B=44.2g/m², Ti=22.4°C, G=0.0265kg/m²s



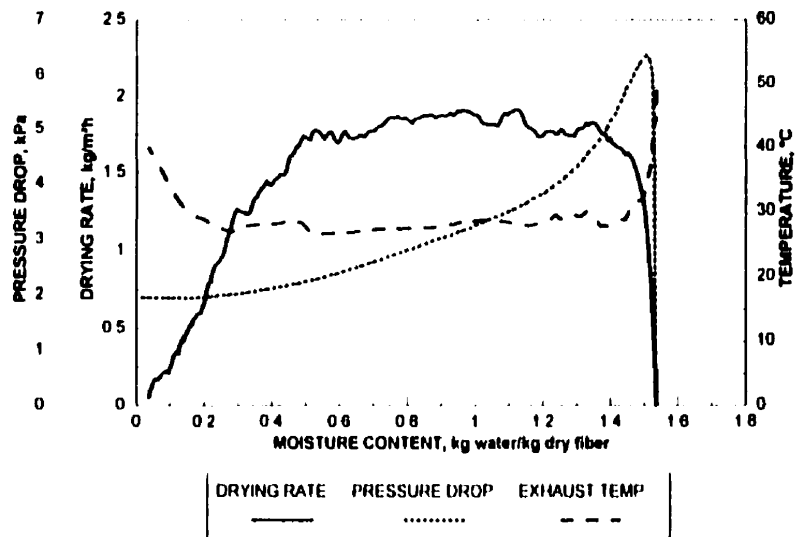
PAPER TYPE #6, B=44.2g/m², Ti=22.5°C, G=0.0265kg/m²s



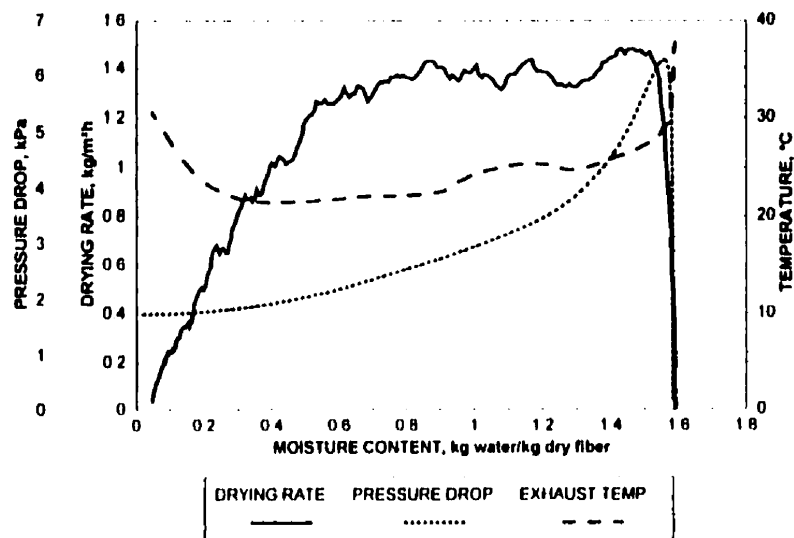
PAPER TYPE #6, B=44.2g/m², Ti=61.7°C, G=0.034kg/m²s



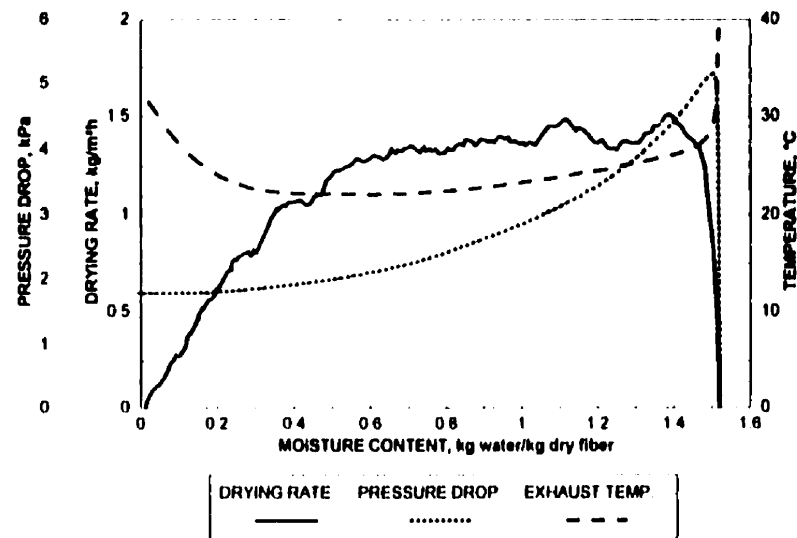
PAPER TYPE #6, B=44.2g/m², Ti=61.8°C, G=0.034kg/m²s



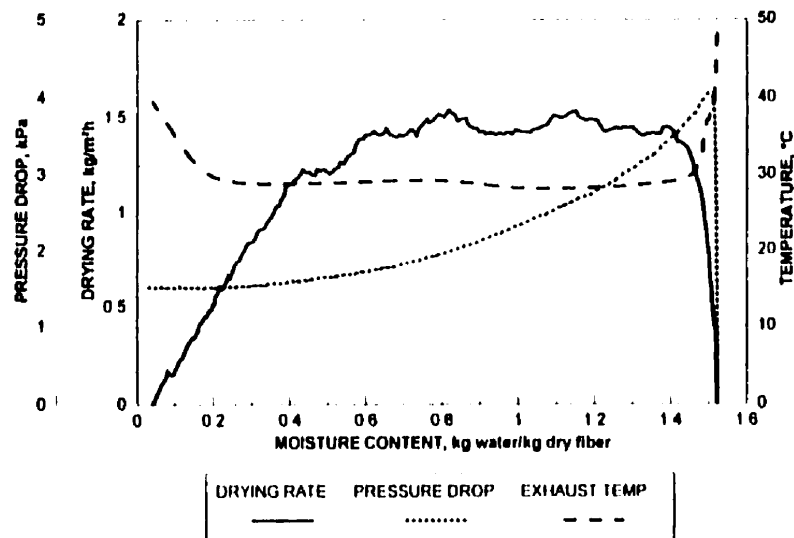
PAPER TYPE #6, B=44.2g/m², Ti=43.6°C, G=0.034kg/m²s



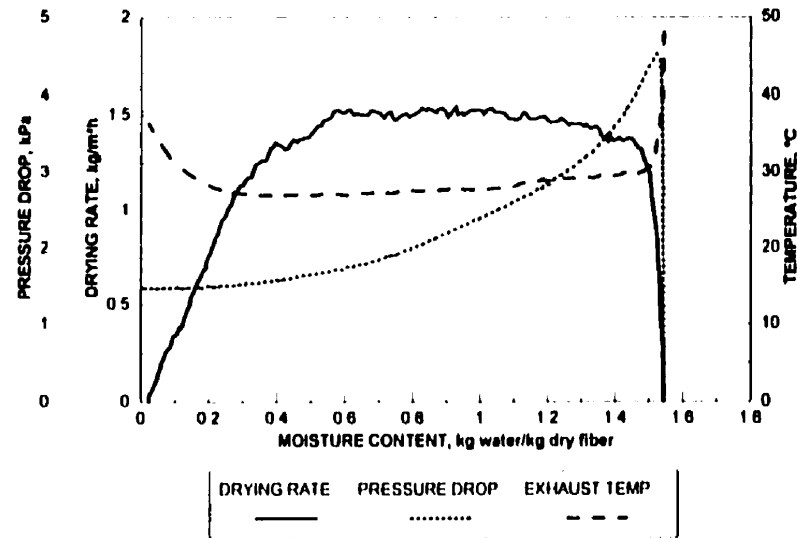
PAPER TYPE #6, B=44.2g/m², Ti=44.0°C, G=0.034kg/m²s



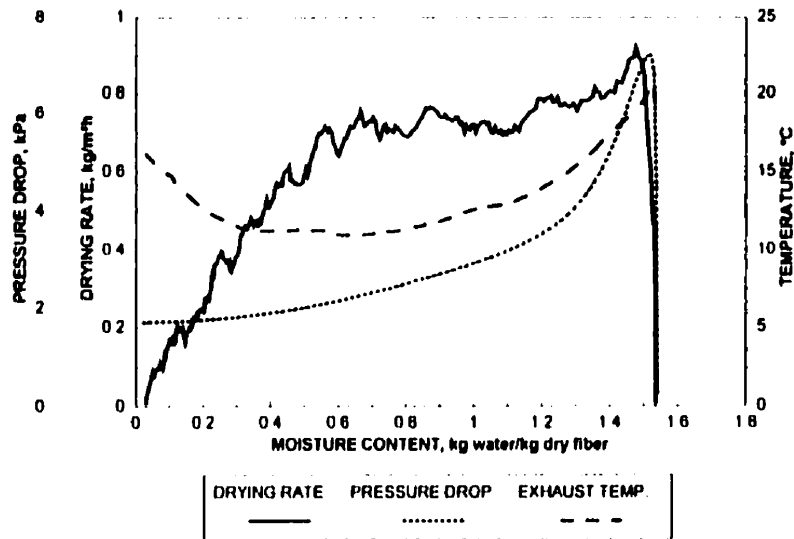
PAPER TYPE #6, B=44.2g/m², Ti=61.7°C, G=0.0265kg/m²s



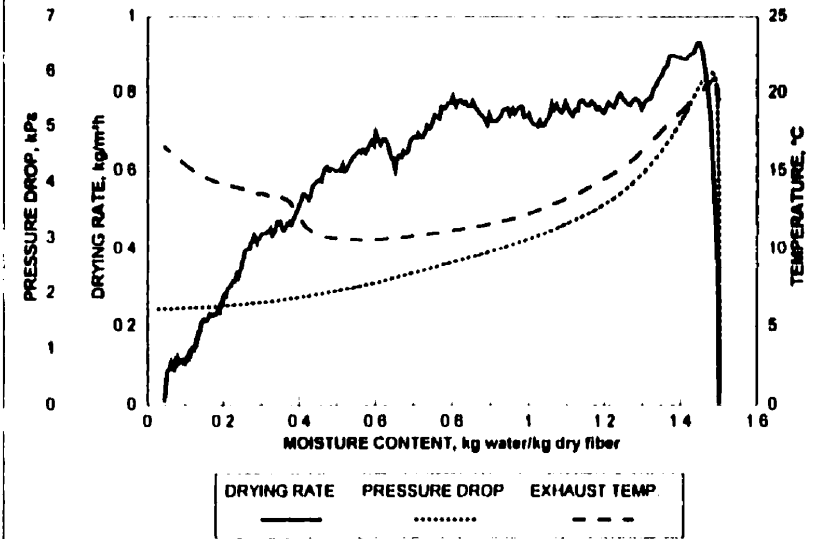
PAPER TYPE #6, B=44.2g/m², Ti=62.4°C, G=0.0265kg/m²s



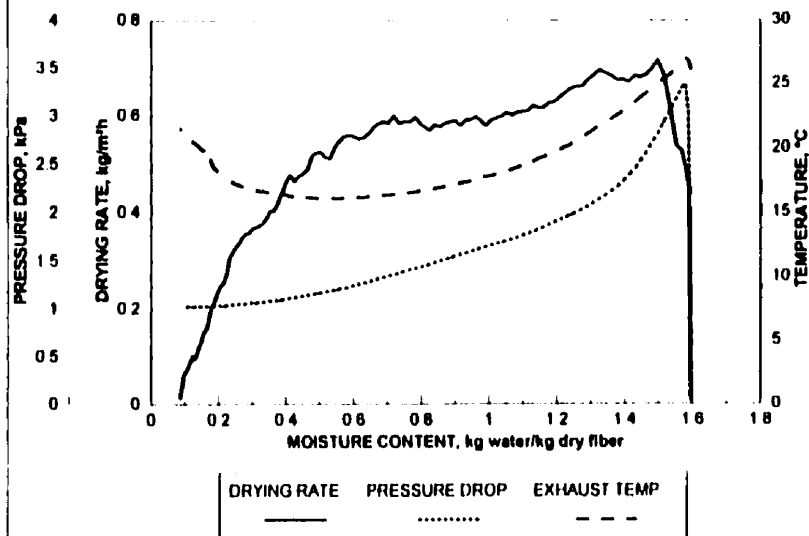
PAPER TYPE #6, B=44.2g/m², Ti=19.2°C, G=0.034kg/m²s



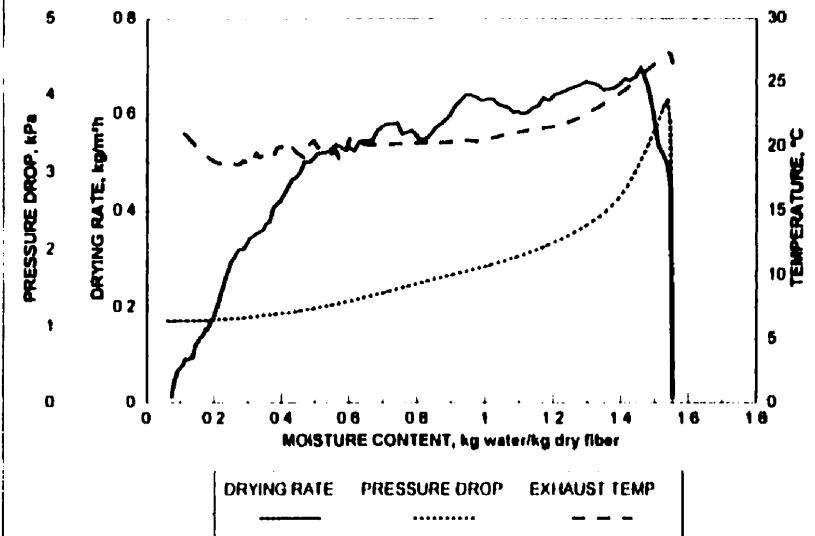
PAPER TYPE #6, B=44.2g/m², Ti=19.3°C, G=0.034kg/m²s



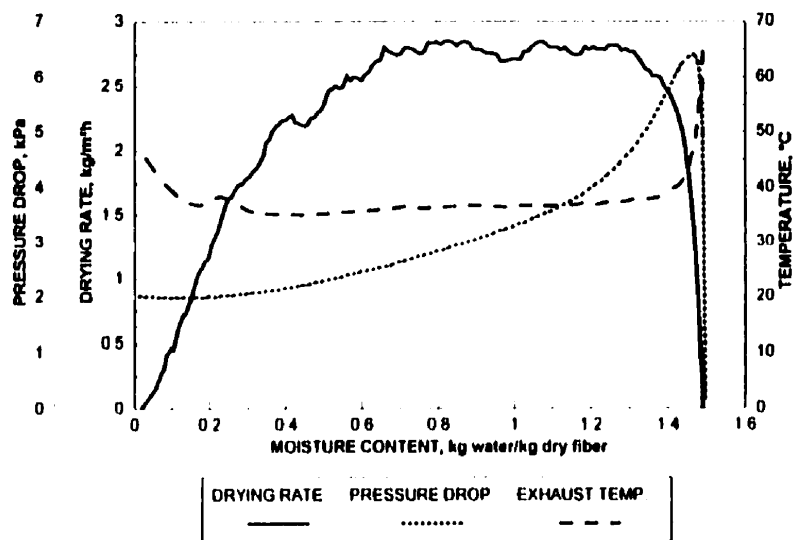
PAPER TYPE #6, B=44.2g/m², Ti=25.9°C, G=0.0195kg/m²s



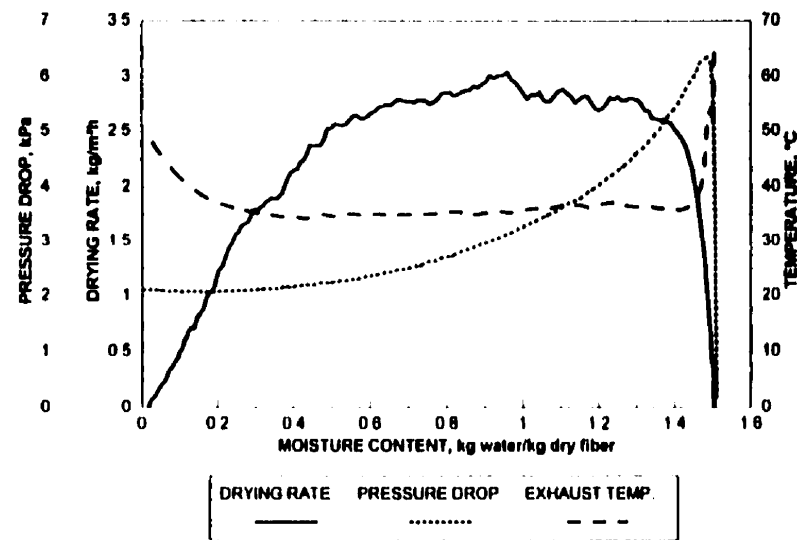
PAPER TYPE #6, B=44.2g/m², Ti=26.2°C, G=0.0195kg/m²s



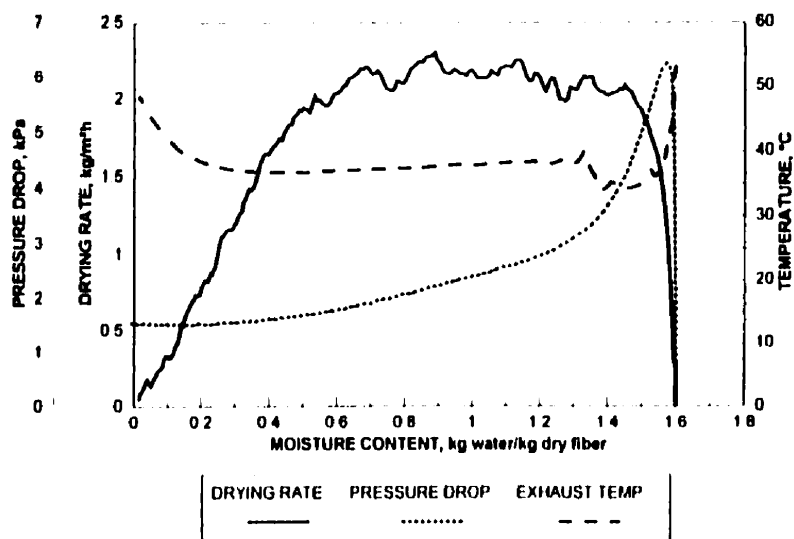
PAPER TYPE #6, B=44.2g/m², Ti=82.8°C, G=0.034kg/m²s



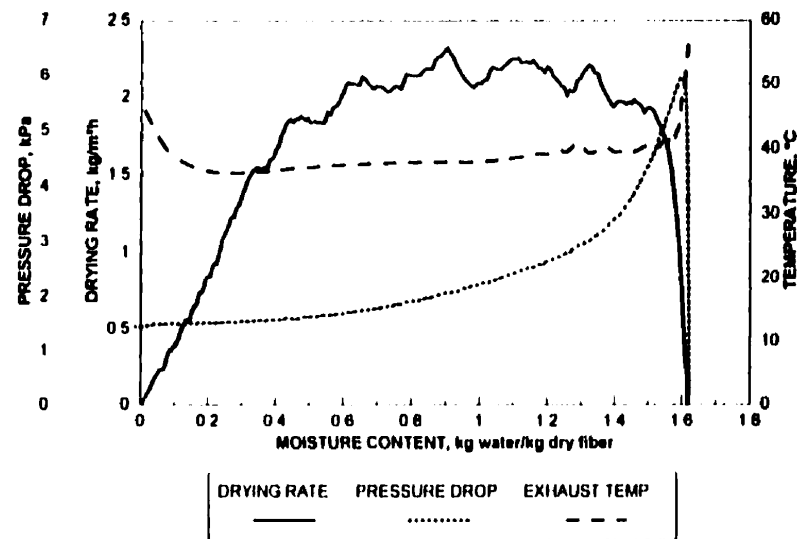
PAPER TYPE #6, B=44.2g/m², Ti=83.0°C, G=0.034kg/m²s



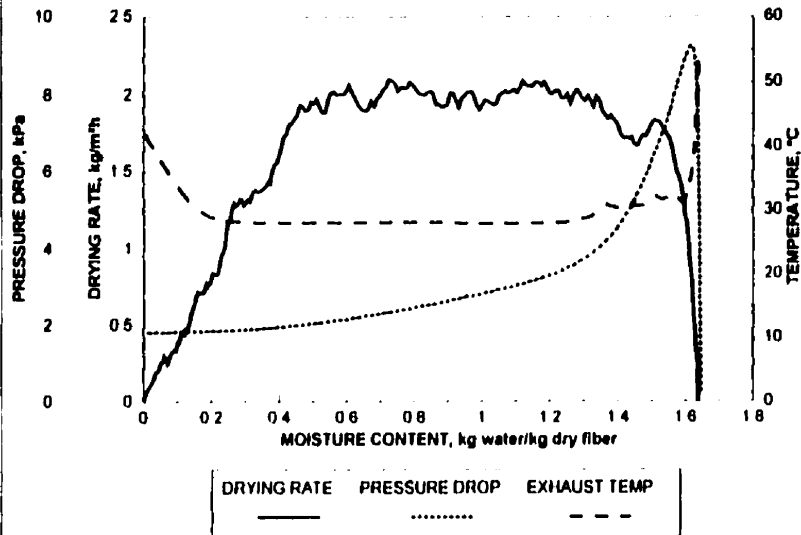
PAPER TYPE #6, B=44.2g/m², Ti=81.4°C, G=0.0265kg/m²s



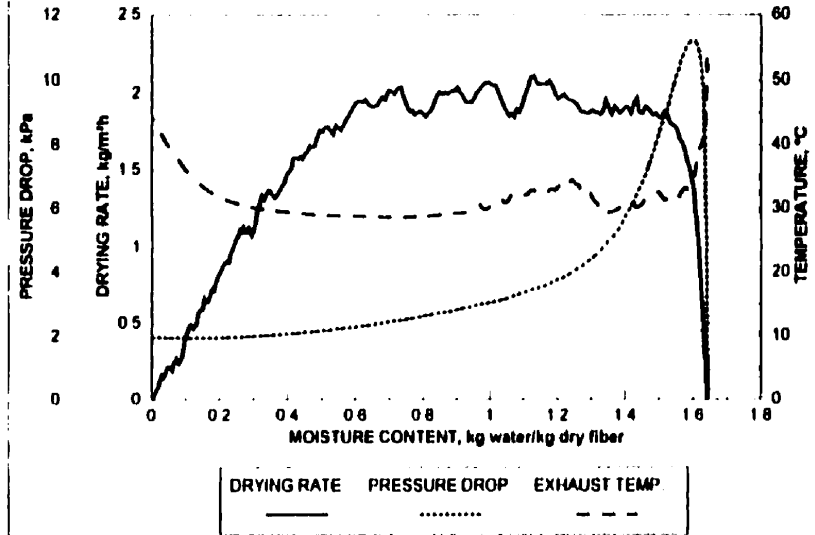
PAPER TYPE #6, B=44.2g/m², Ti=81.0°C, G=0.0265kg/m²s



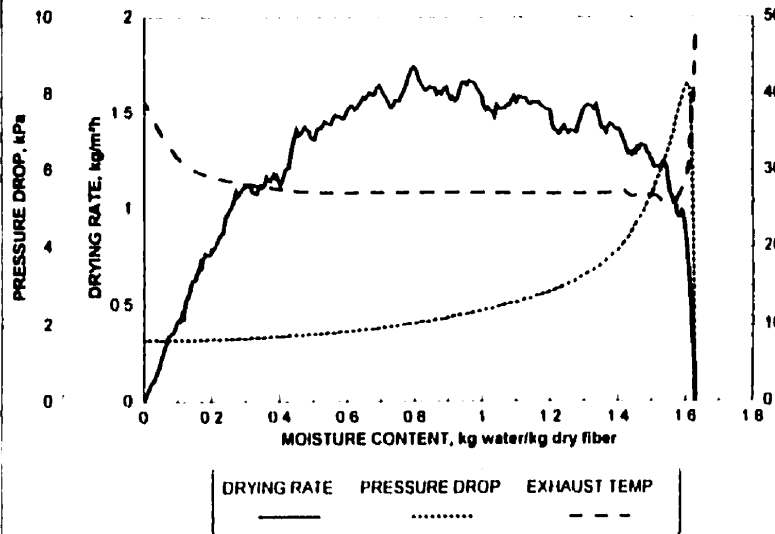
PAPER TYPE #6, B=44.2g/m², Ti=70.5°C, G=0.034kg/m²s



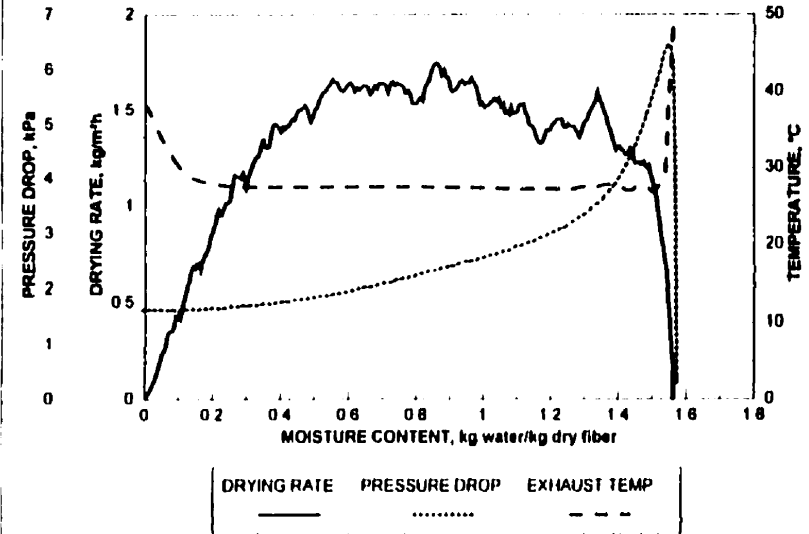
PAPER TYPE #6, B=44.2g/m², Ti=70.3°C, G=0.034kg/m²s



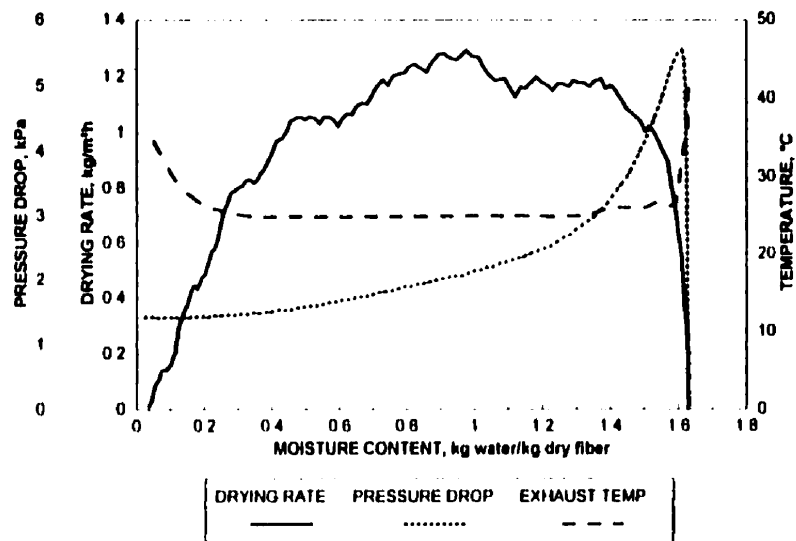
PAPER TYPE #6, B=44.2g/m², Ti=70.1°C, G=0.0265kg/m²s



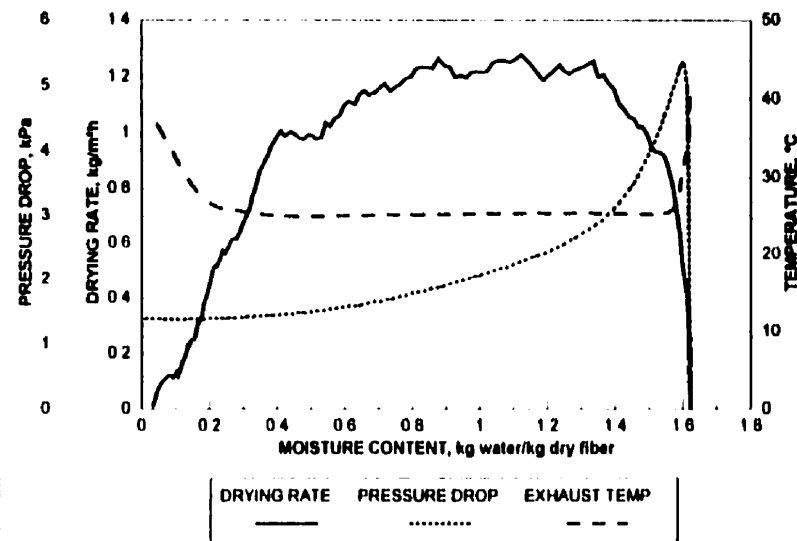
PAPER TYPE #6, B=44.2g/m², Ti=70.6°C, G=0.0265kg/m²s



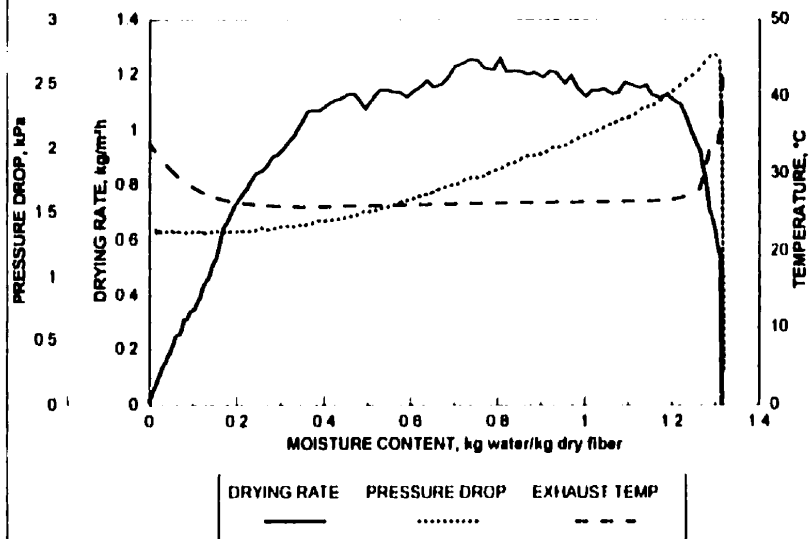
PAPER TYPE #6, B=44.2g/m², Ti=61.6°C, G=0.023kg/m²s



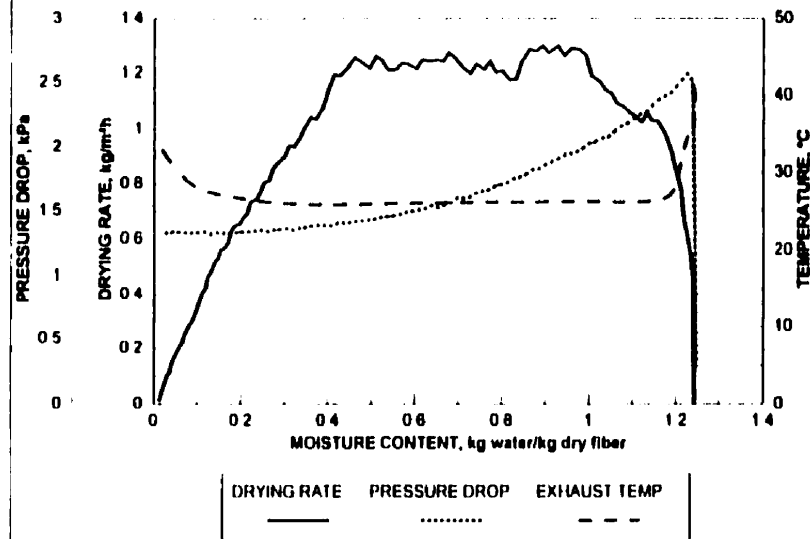
PAPER TYPE #6, B=44.2g/m², Ti=61.6°C, G=0.023kg/m²s



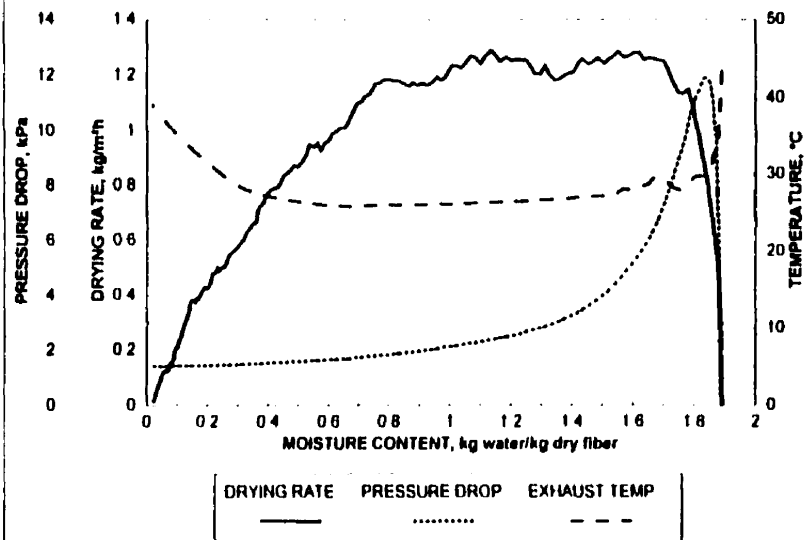
PAPER TYPE #6, B=44.2g/m², Ti=61.5°C, G=0.023kg/m²s



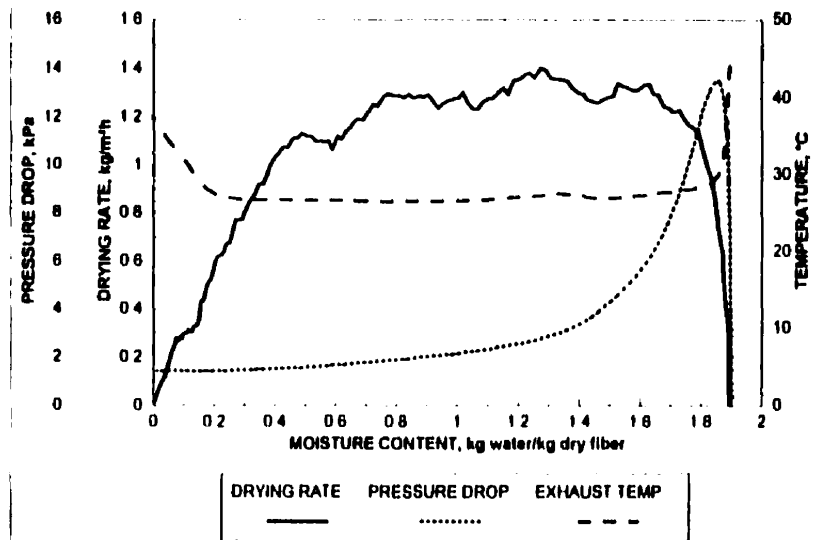
PAPER TYPE #6, B=44.2g/m², Ti=61.7°C, G=0.023kg/m²s



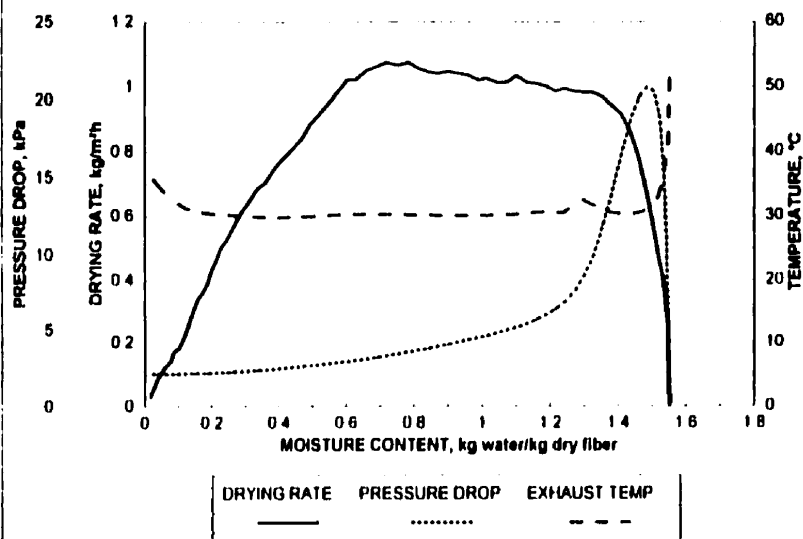
PAPER TYPE #6, B=44.2g/m², Ti=61.5°C, G=0.023kg/m's



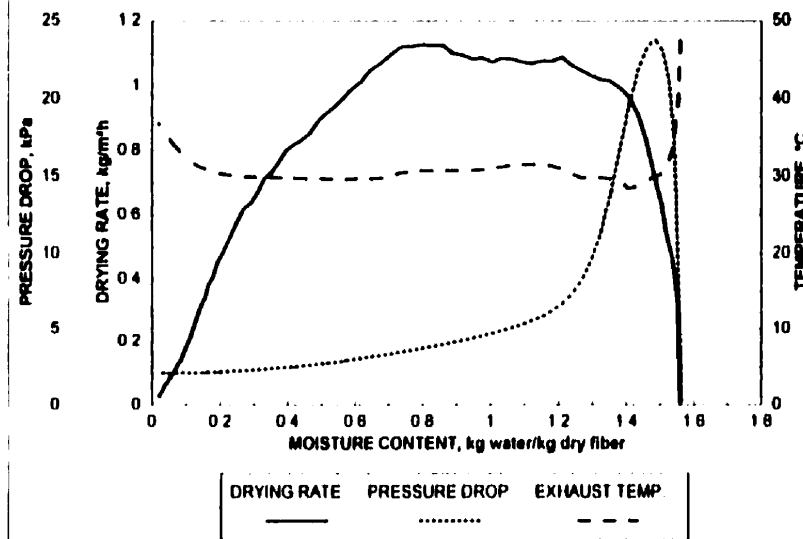
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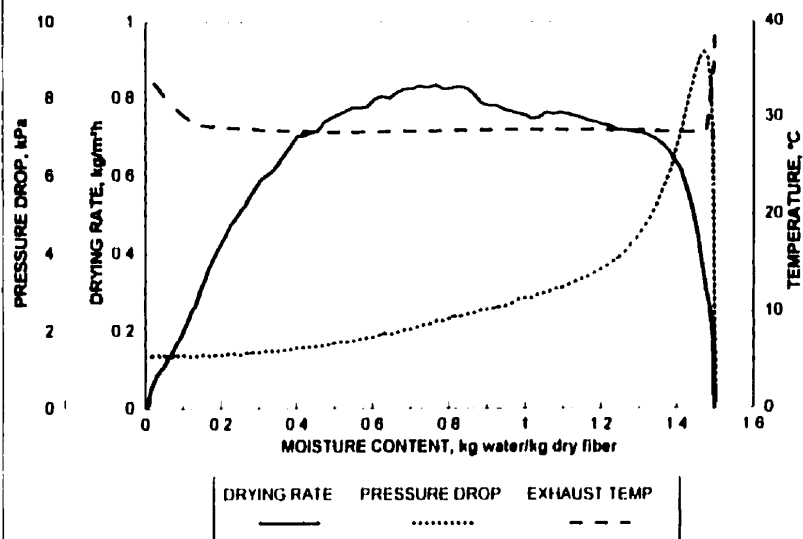
PAPER TYPE #7, B=44.5g/m², Ti=60.9°C, G=0.0195kg/m²s



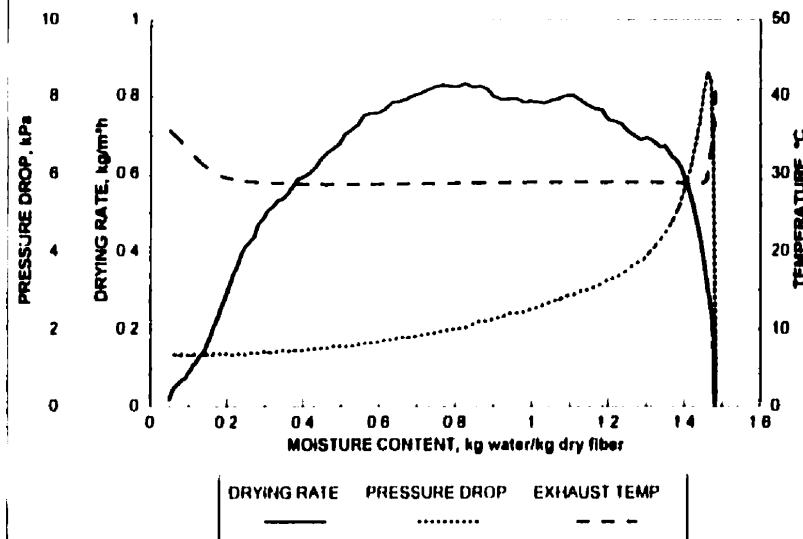
PAPER TYPE #7, B=44.5g/m², Ti=60.0°C, G=0.0195kg/m²s



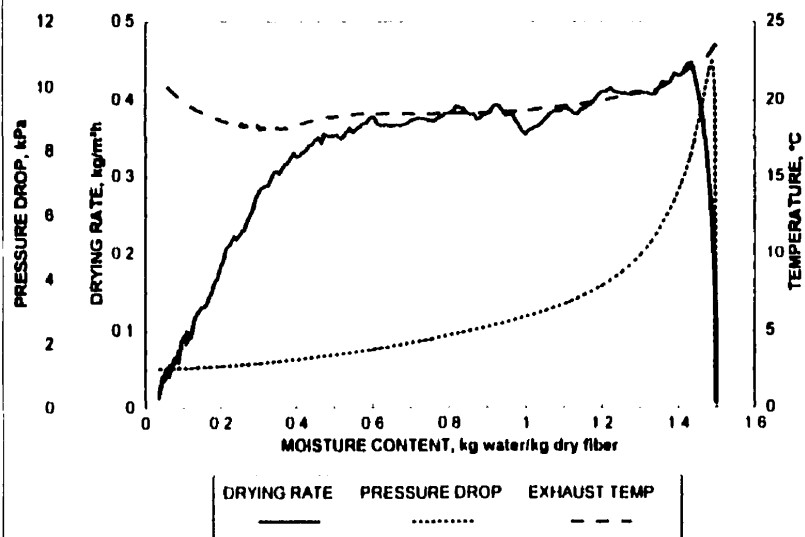
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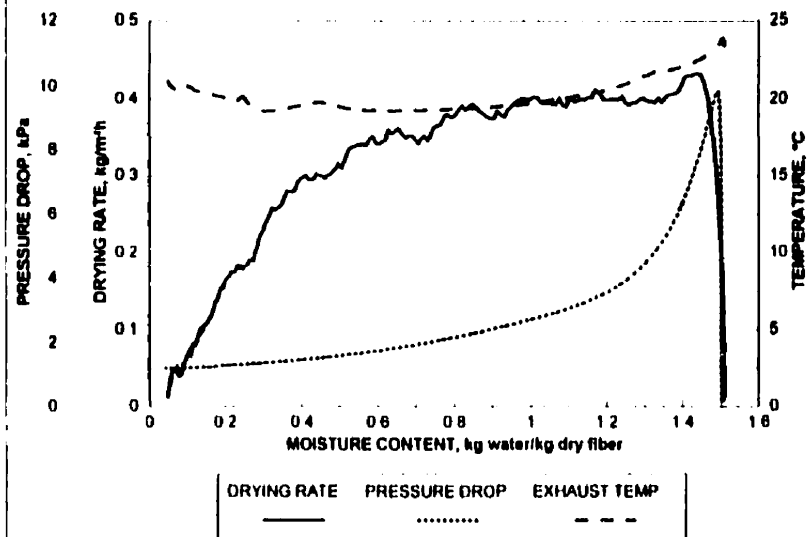
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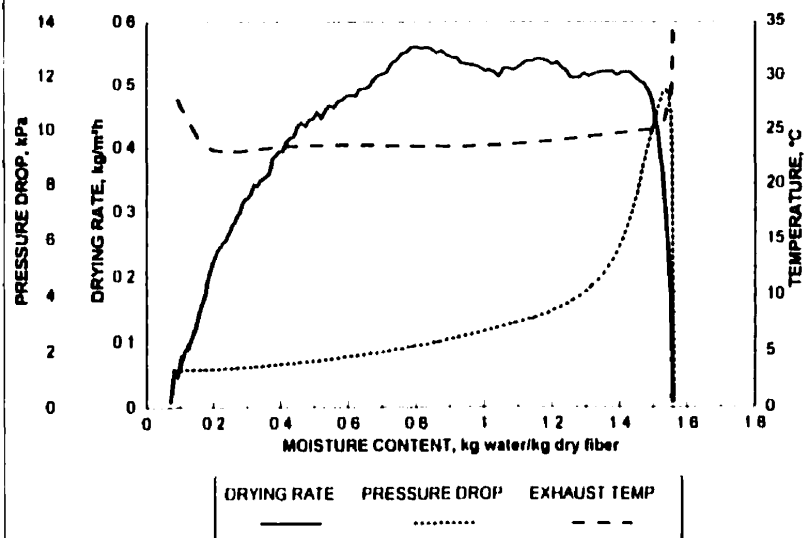
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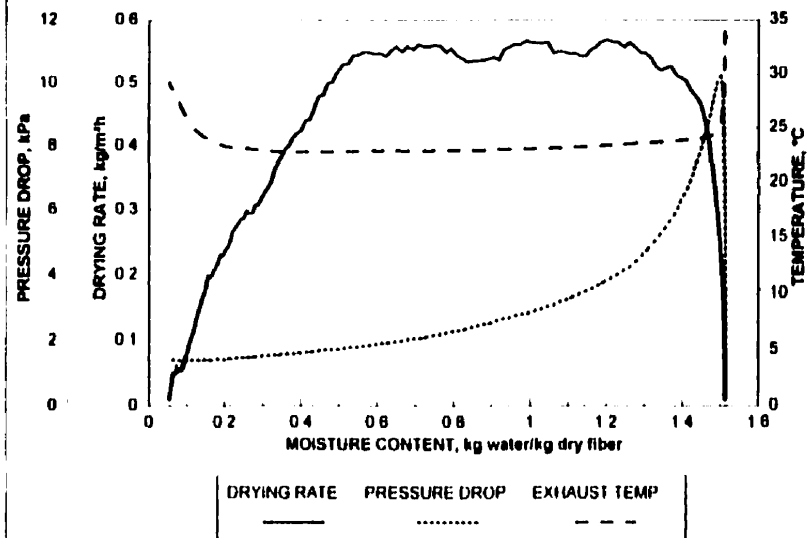
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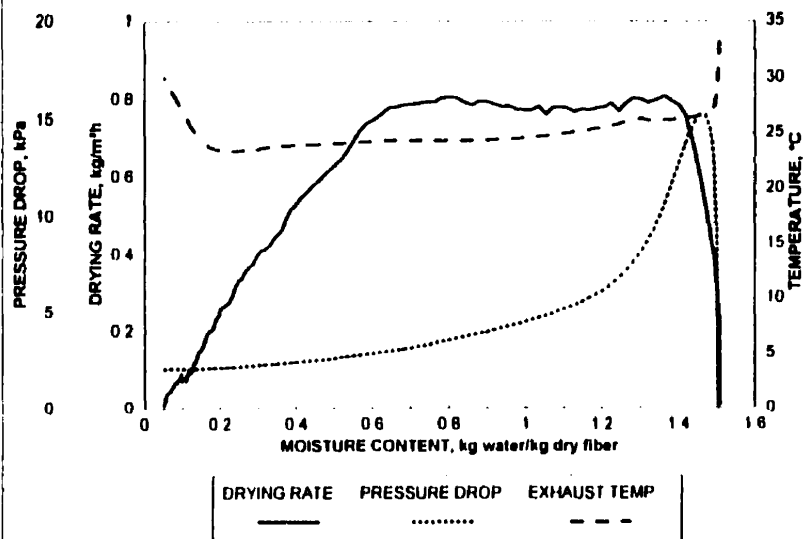
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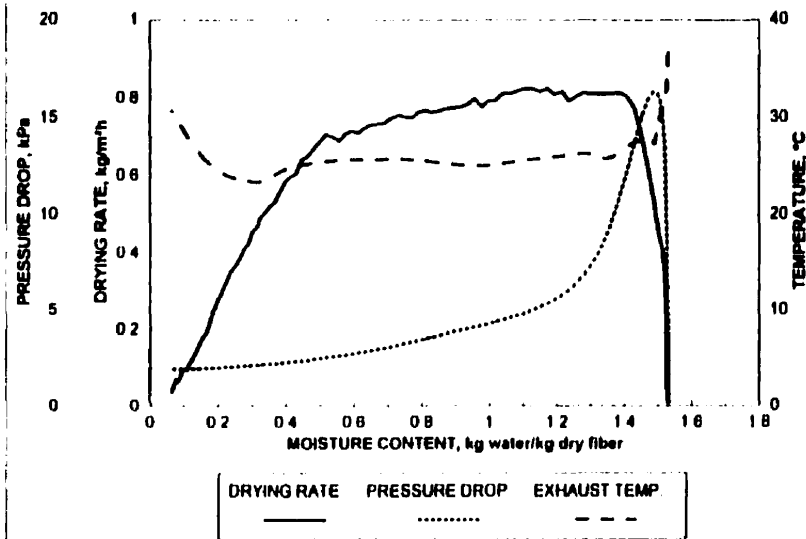
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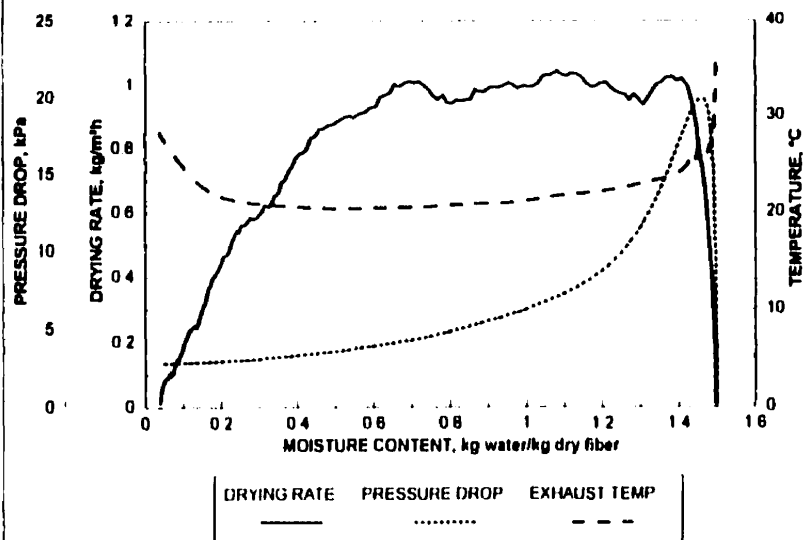
PAPER TYPE #7, $B=44.5\text{g/m}^2$, $T_i=41.7^\circ\text{C}$, $G=0.0127\text{kg/m}^2\text{s}$



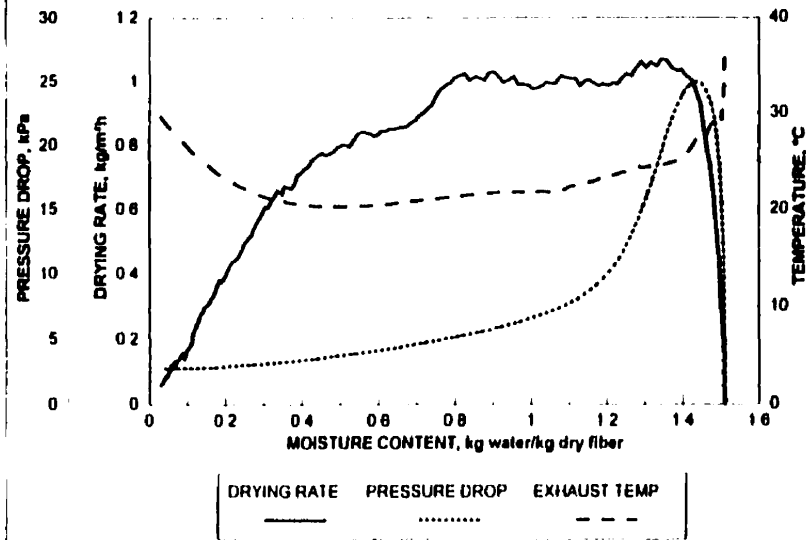
PAPER TYPE #7, $B=44.5\text{g/m}^2$, $T_i=42.2^\circ\text{C}$, $G=0.0195\text{kg/m}^2\text{s}$



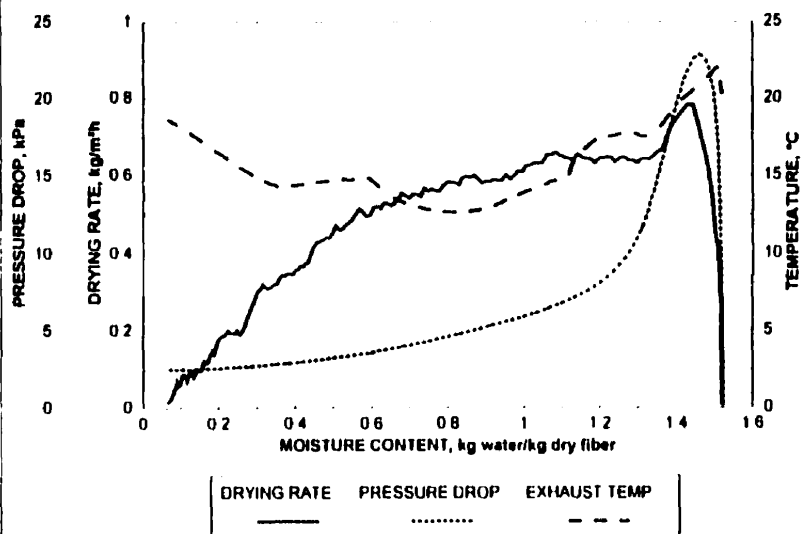
PAPER TYPE #7, $B=44.5\text{g/m}^2$, $T_i=40.7^\circ\text{C}$, $G=0.0265\text{kg/m}^2\text{s}$



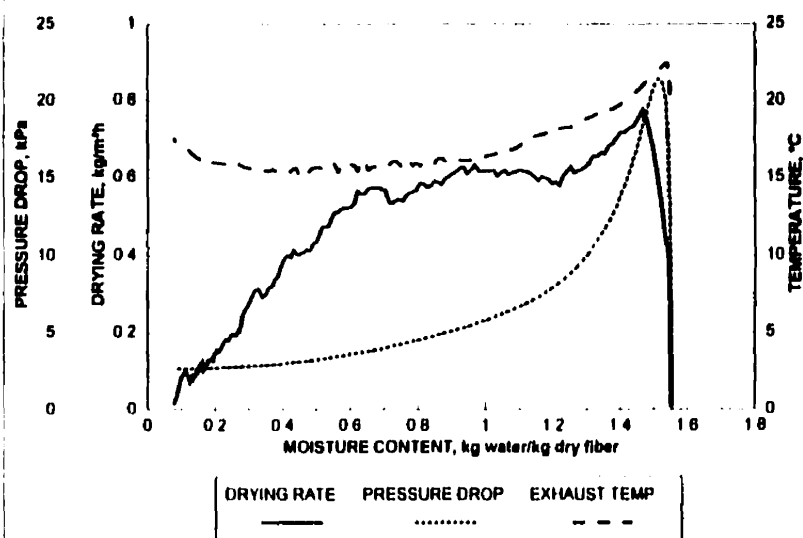
PAPER TYPE #7, $B=44.5\text{g/m}^2$, $T_i=40.5^\circ\text{C}$, $G=0.0265\text{kg/m}^2\text{s}$



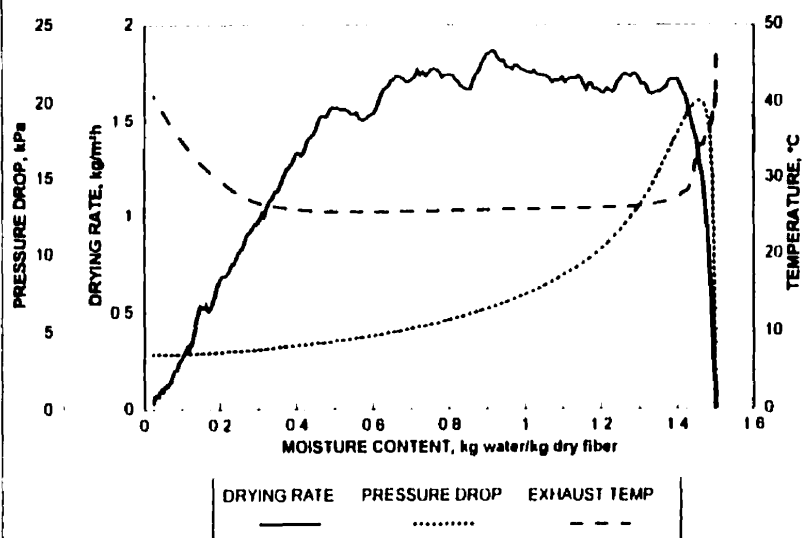
PAPER TYPE #7, B=44.5g/m², Ti=20.3°C, G=0.0265kg/m²s



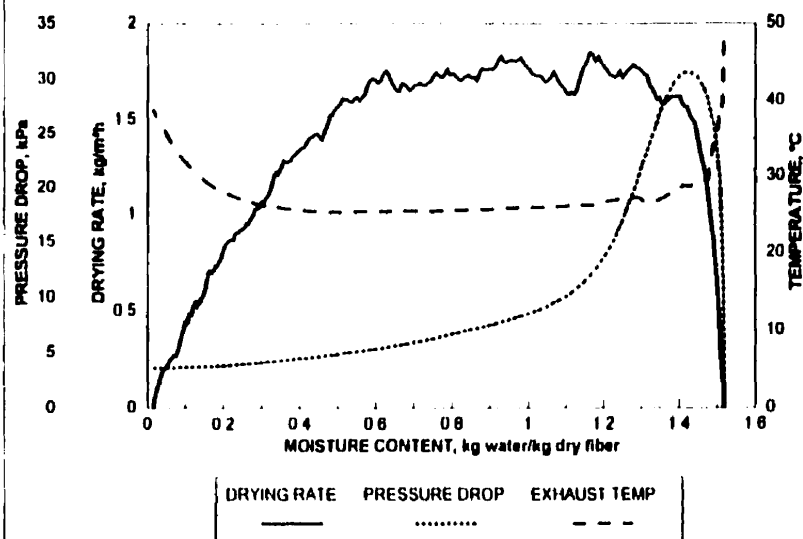
PAPER TYPE #7, B=44.5g/m², Ti=20.5°C, G=0.0265kg/m²s



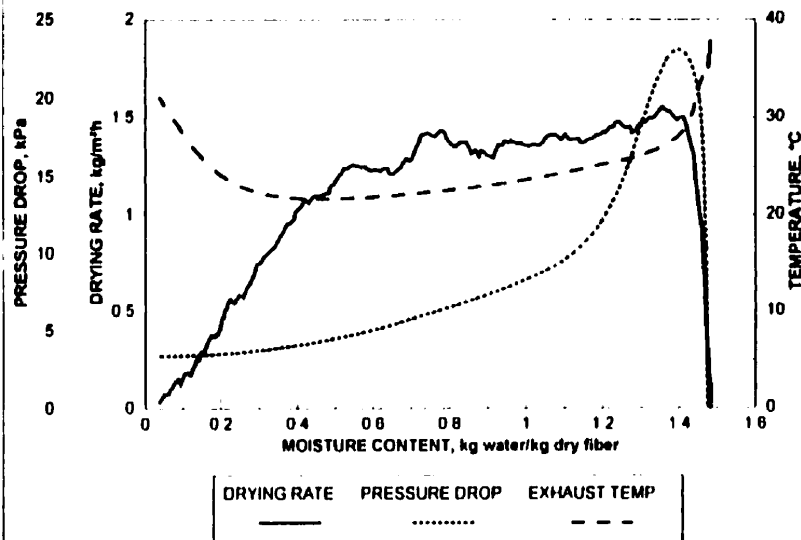
PAPER TYPE #7, B=44.5g/m², Ti=60.1°C, G=0.034kg/m²s



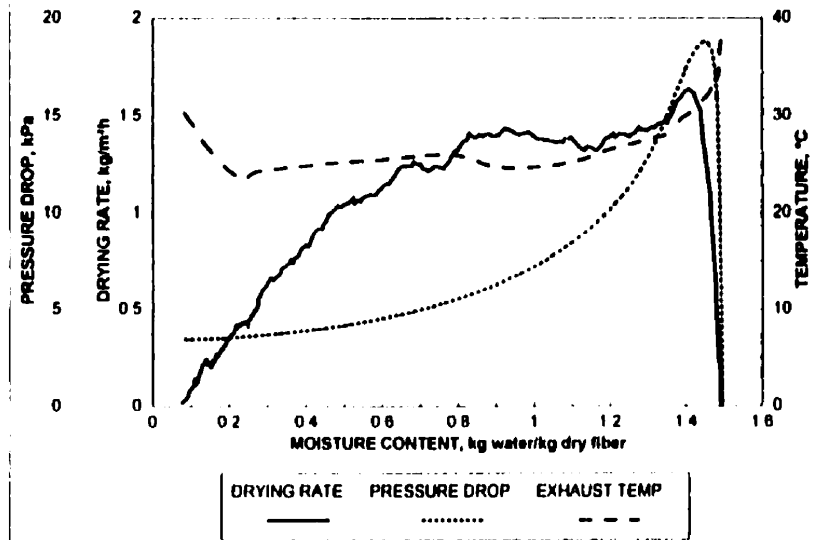
PAPER TYPE #7, B=44.5g/m², Ti=59.9°C, G=0.034kg/m²s



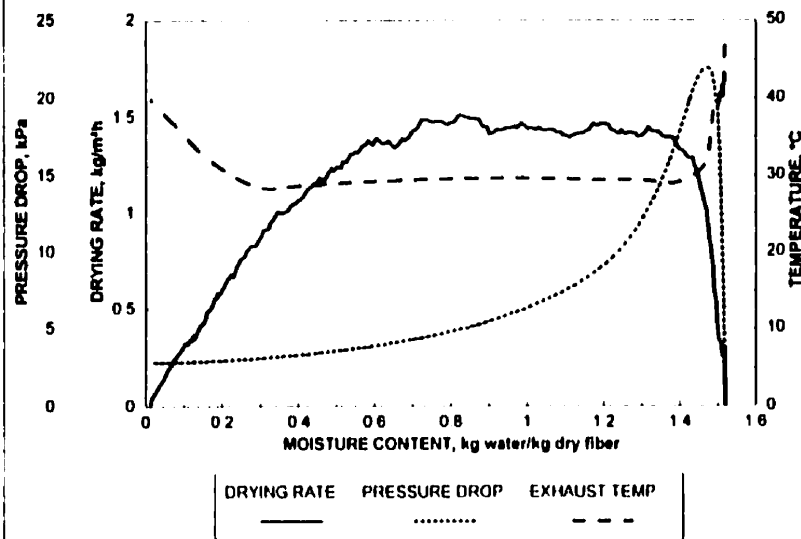
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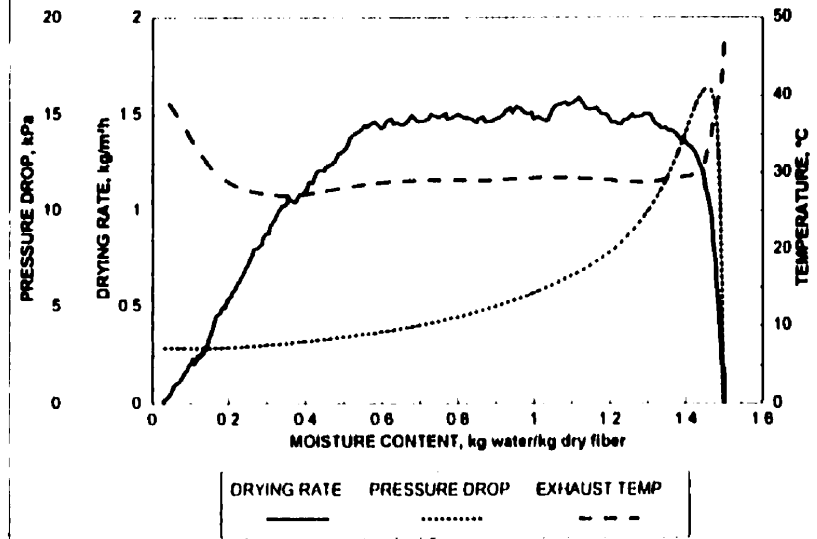
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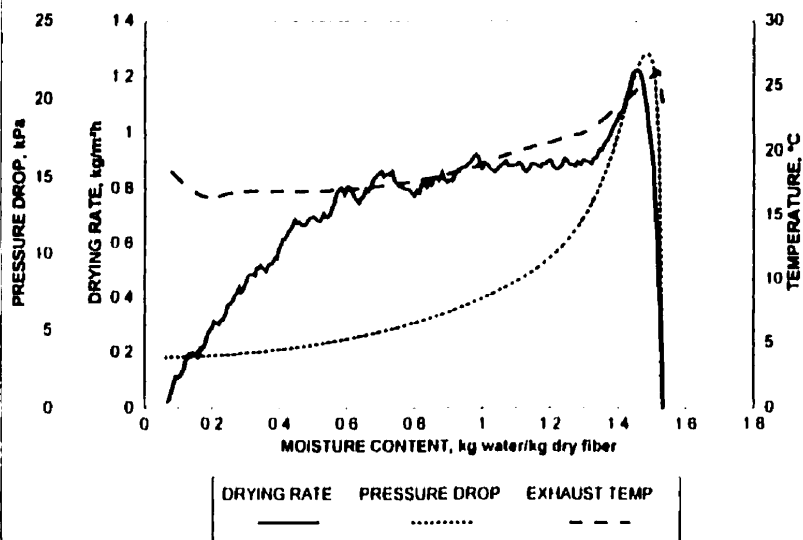
PAPER TYPE #7, B=44.5g/m², Ti=61.3°C, G=0.0265kg/m²s



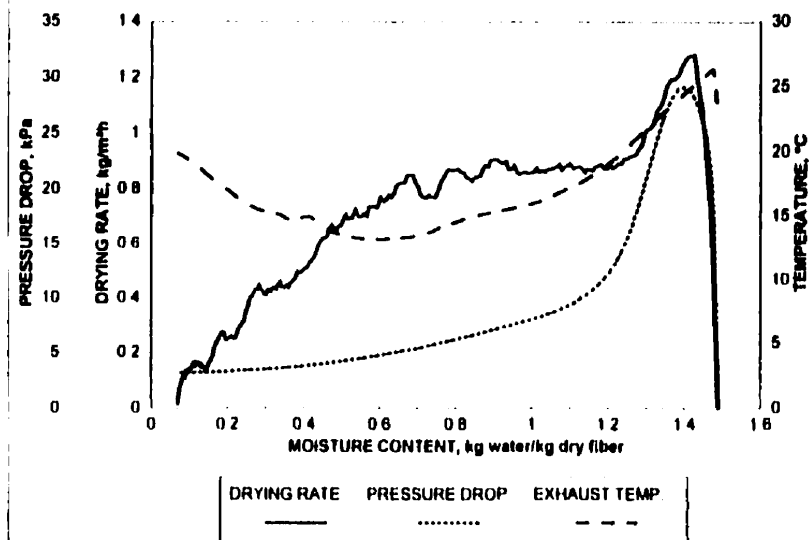
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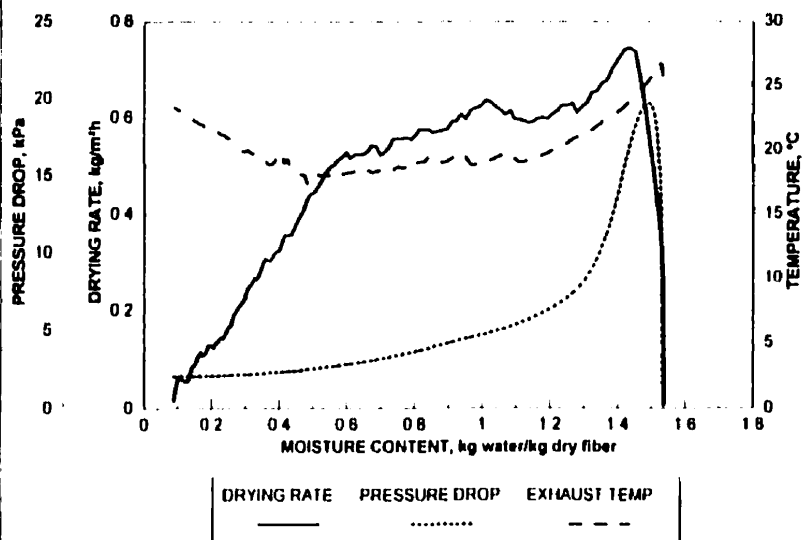
PAPER TYPE #7, B=44.5g/m², Ti=23.2°C, G=0.034kg/m²s



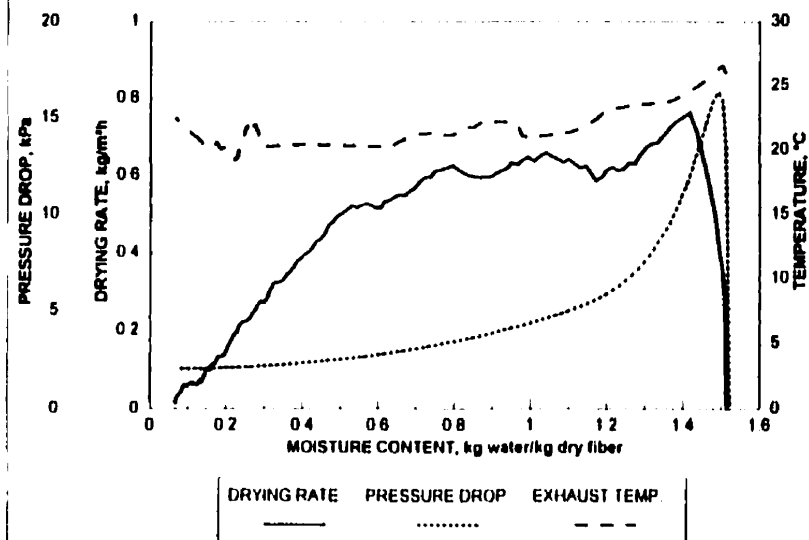
PAPER TYPE #7, B=44.5g/m², Ti=23.2°C, G=0.034kg/m²s



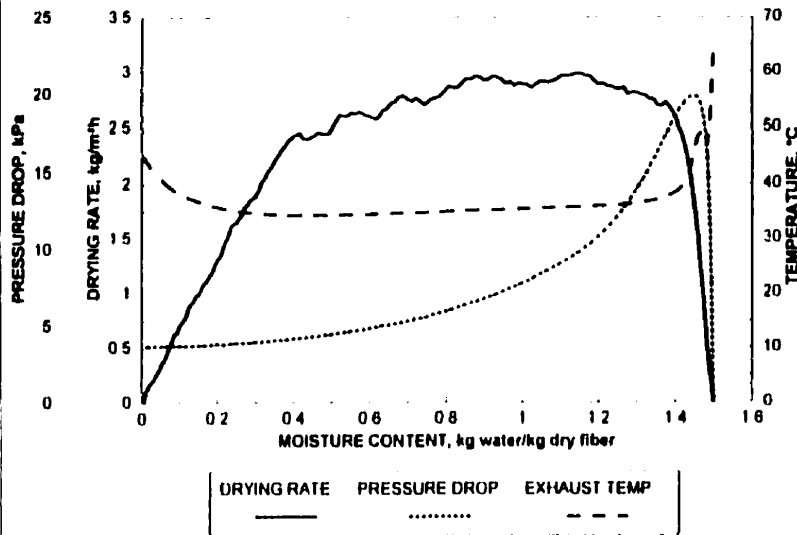
PAPER TYPE #7, B=44.5g/m², Ti=25.5°C, G=0.0195kg/m²s



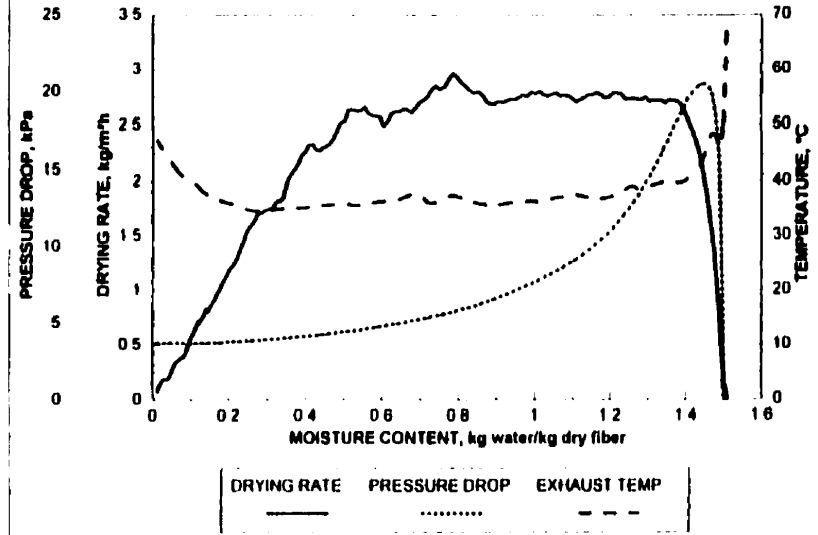
PAPER TYPE #7, B=44.5g/m², Ti=25.7°C, G=0.0195kg/m²s



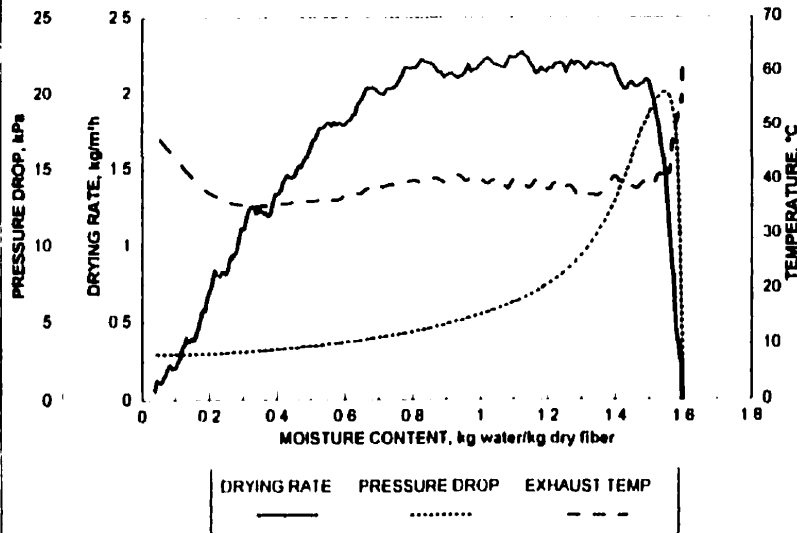
PAPER TYPE #7, B=44.5g/m², Ti=82.6°C, G=0.034kg/m²s



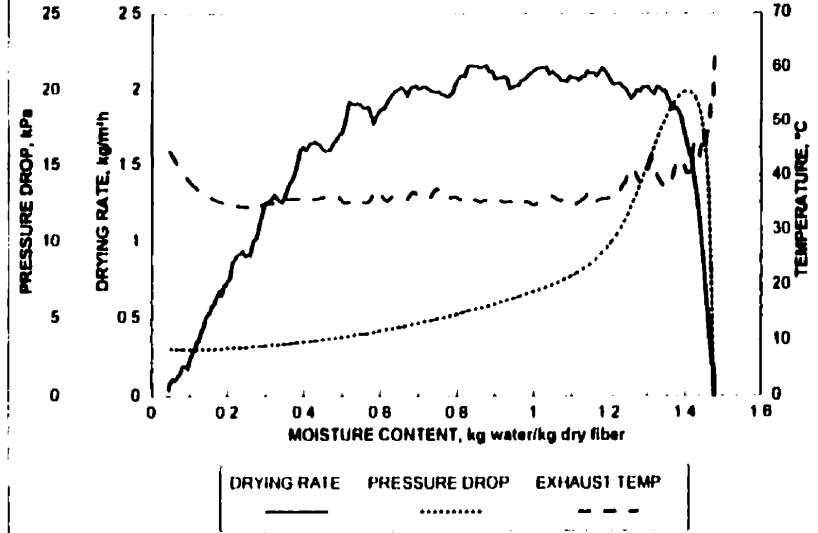
PAPER TYPE #7, B=44.5g/m², Ti=82.4°C, G=0.034kg/m²s



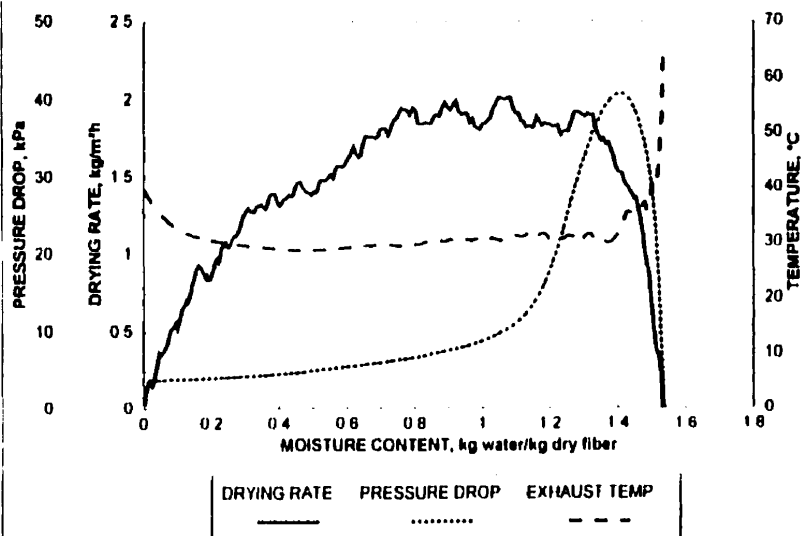
PAPER TYPE #7, B=44.5g/m², Ti=80.4°C, G=0.0265kg/m²s



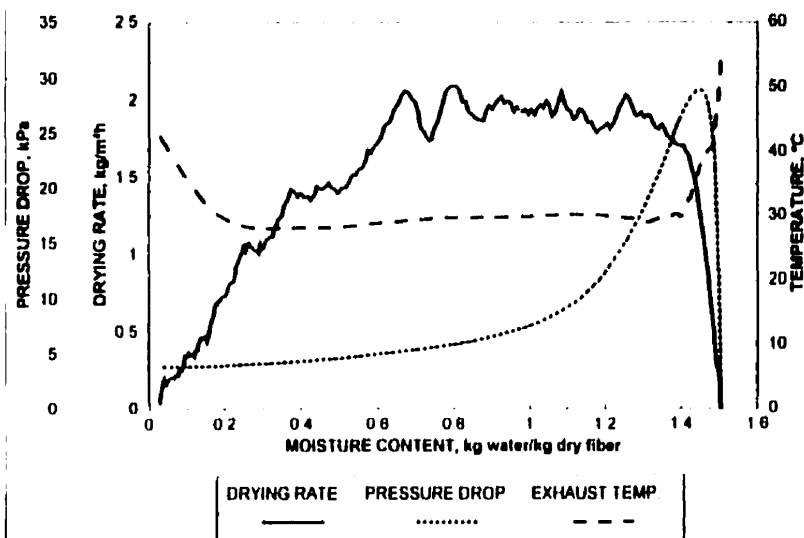
PAPER TYPE #7, B=44.5g/m², Ti=80.7°C, G=0.0265kg/m²s



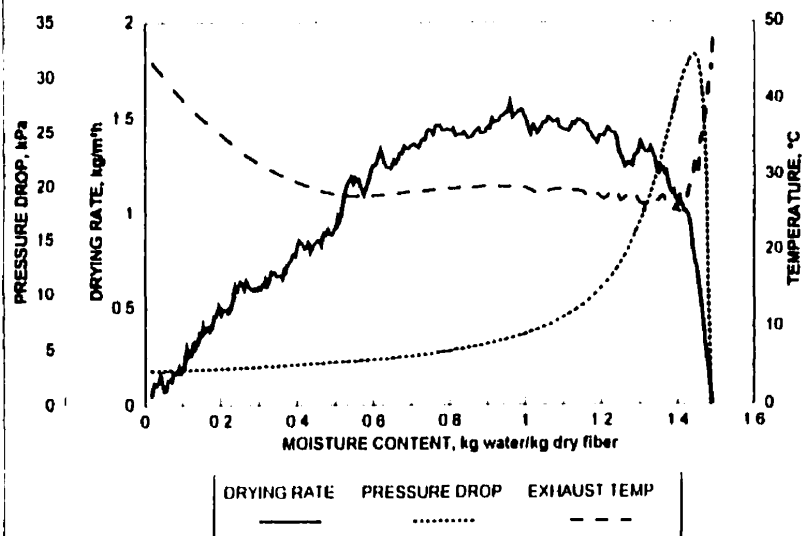
PAPER TYPE #7, B=44.5g/m², Ti=70.3°C, G=0.034kg/m²s



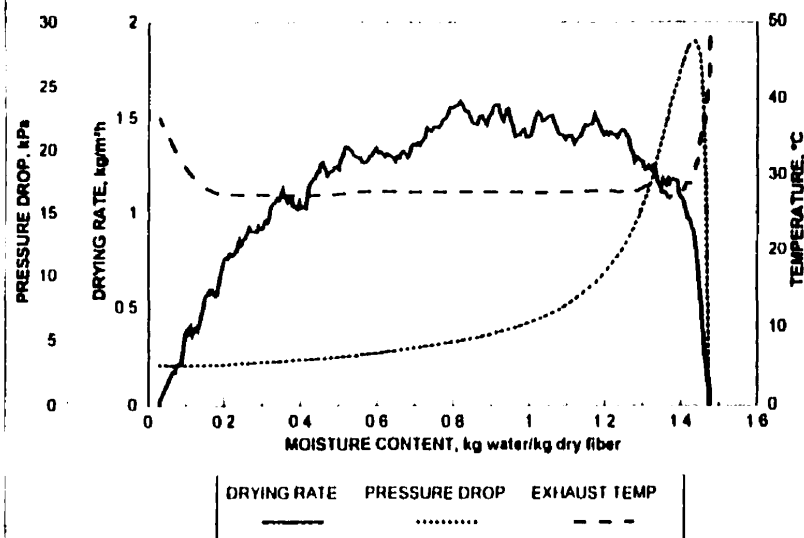
PAPER TYPE #7, B=44.5g/m², Ti=70.2°C, G=0.034kg/m²s



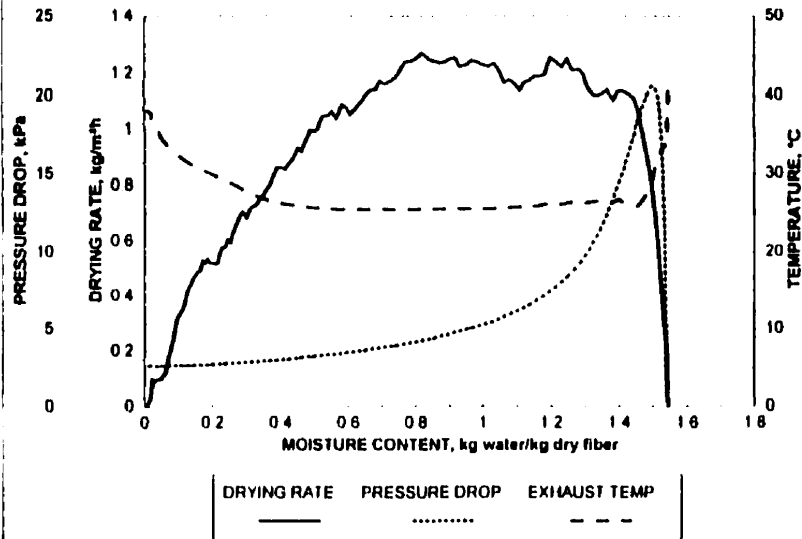
PAPER TYPE #7, B=44.5g/m², Ti=69.5°C, G=0.0265kg/m²s



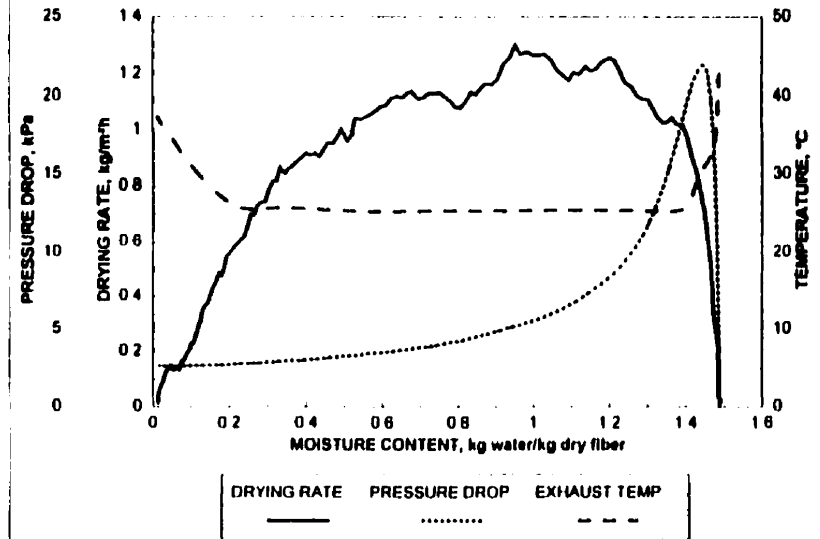
PAPER TYPE #7, B=44.5g/m², Ti=69.4°C, G=0.0265kg/m²s



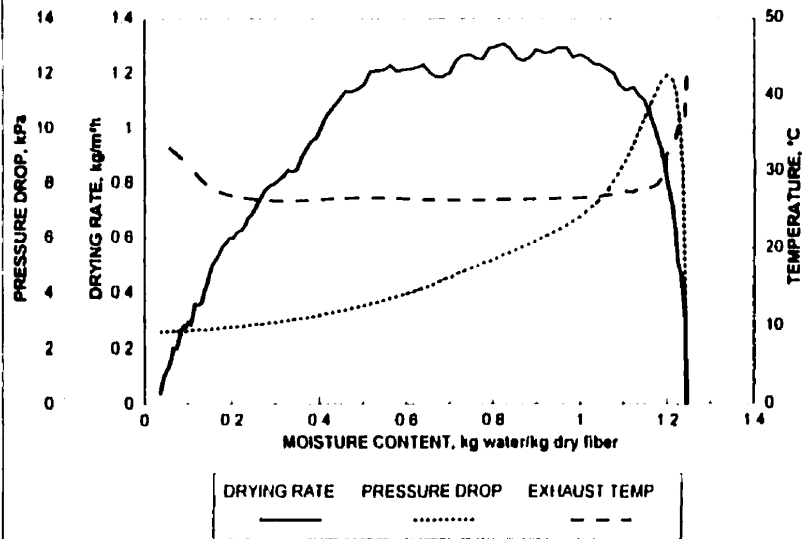
PAPER TYPE #7, $B=44.5\text{g/m}^2$, $T_i=61.2^\circ\text{C}$, $G=0.034\text{kg/m}^2\text{s}$



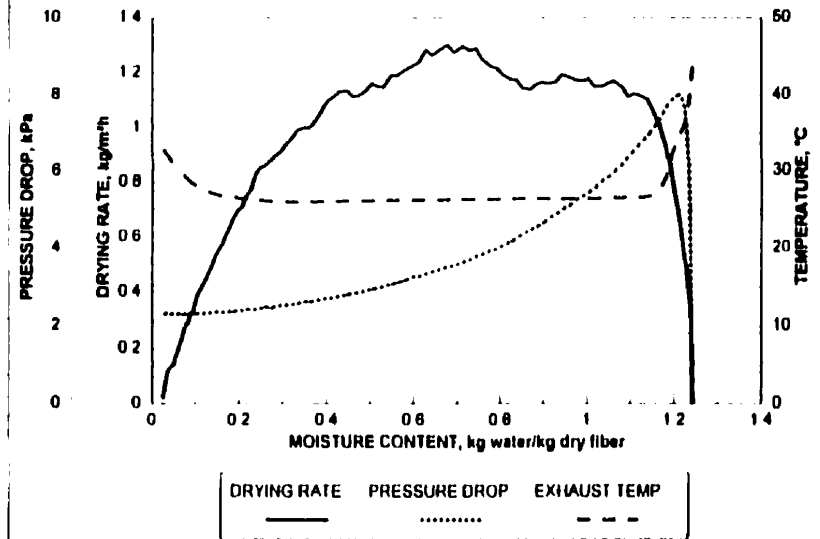
PAPER TYPE #7, $B=44.5\text{g/m}^2$, $T_i=61.4^\circ\text{C}$, $G=0.023\text{kg/m}^2\text{s}$



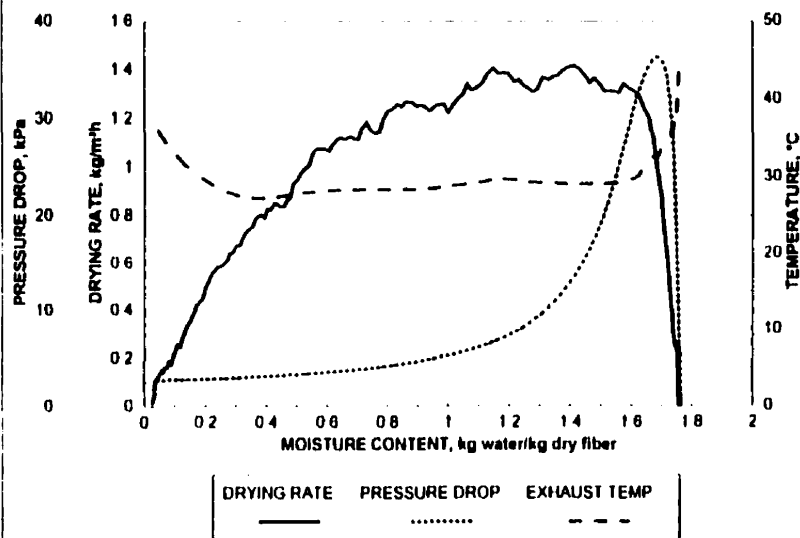
PAPER TYPE #7, $B=44.5\text{g/m}^2$, $T_i=60.9^\circ\text{C}$, $G=0.023\text{kg/m}^2\text{s}$



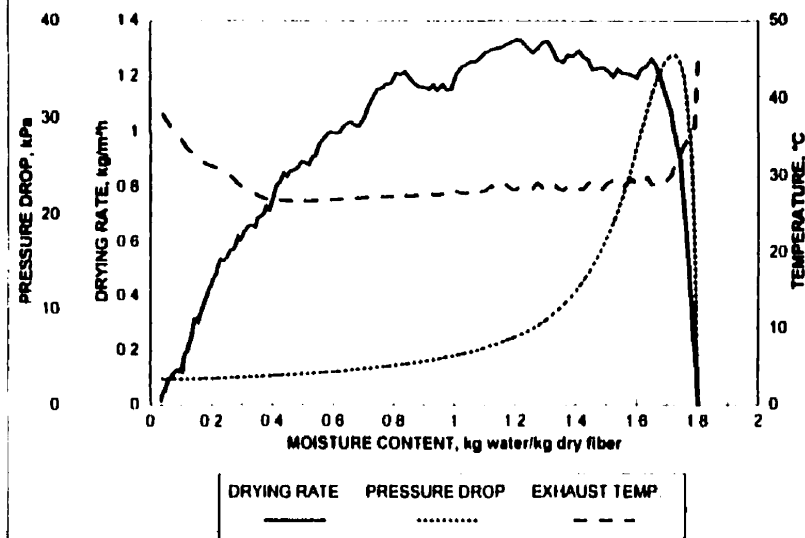
PAPER TYPE #7, $B=44.5\text{g/m}^2$, $T_i=61.2^\circ\text{C}$, $G=0.023\text{kg/m}^2\text{s}$



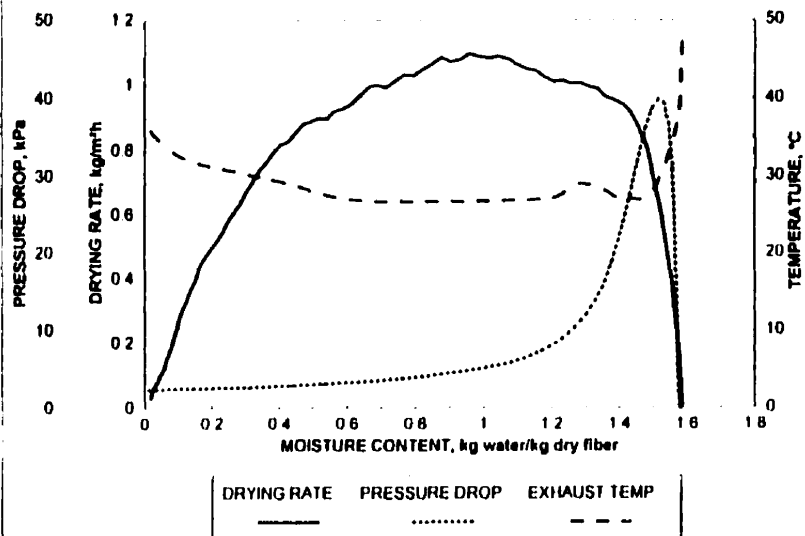
PAPER TYPE #7, B=44.5g/m², Ti=62.1°C, G=0.023kg/m²s



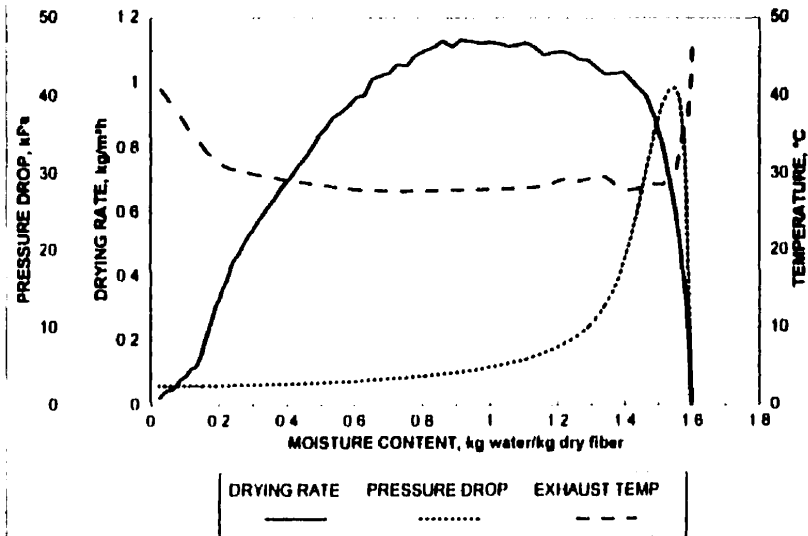
PAPER TYPE #7, B=44.5g/m², Ti=62.2°C, G=0.023kg/m²s



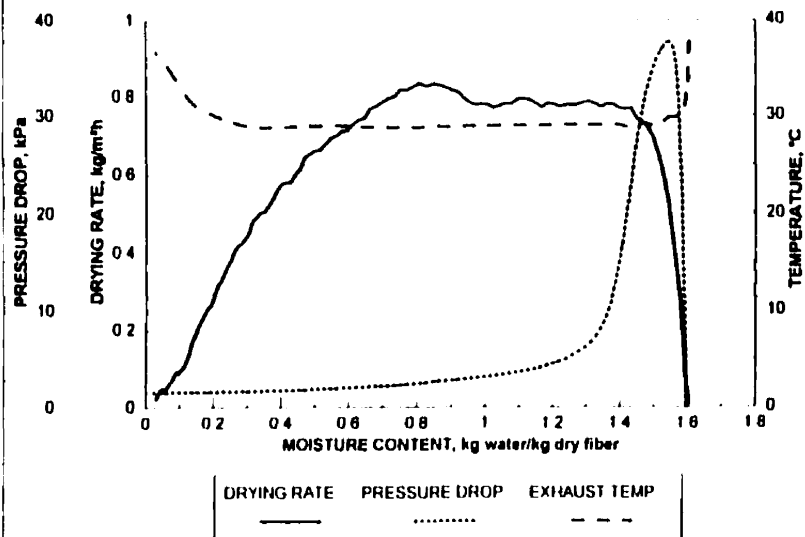
PAPER TYPE #8, $B=47.7\text{g/m}^2$, $T_i=61.4^\circ\text{C}$, $G=0.0195\text{kg/m}^2\text{s}$



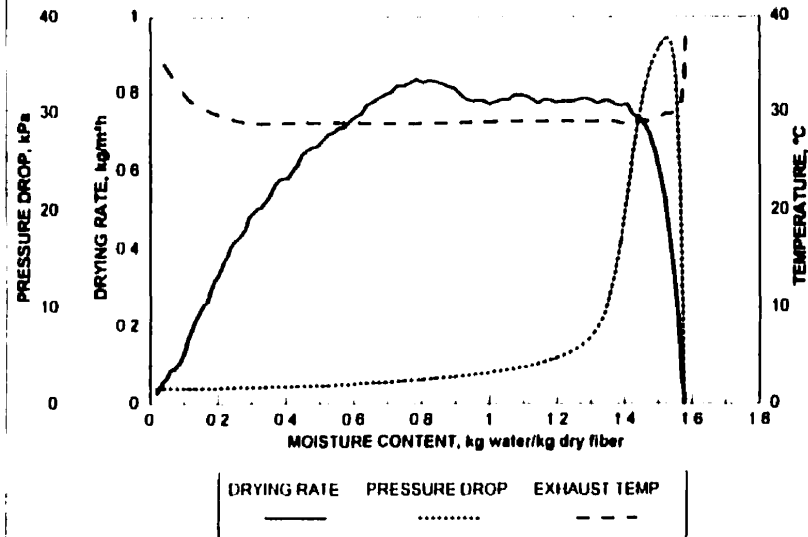
PAPER TYPE #8, $B=47.7\text{g/m}^2$, $T_i=62.4^\circ\text{C}$, $G=0.0195\text{kg/m}^2\text{s}$



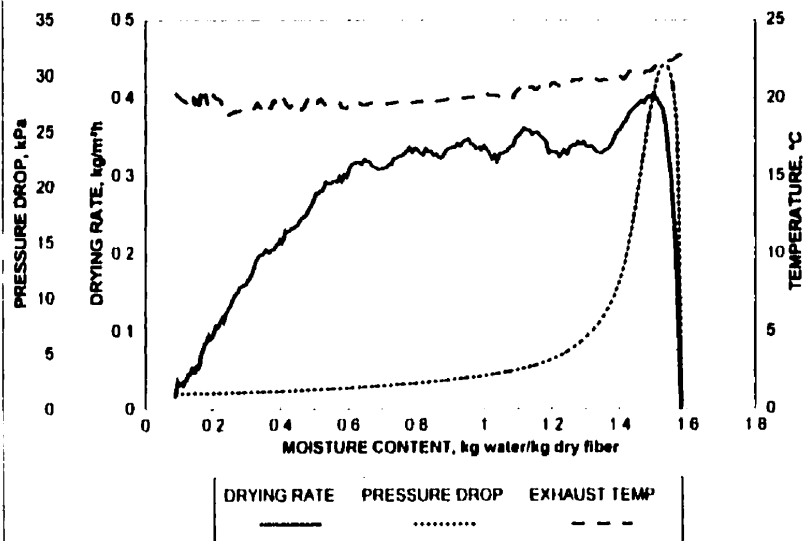
PAPER TYPE #8, $B=47.7\text{g/m}^2$, $T_i=58.8^\circ\text{C}$, $G=0.0127\text{kg/m}^2\text{s}$



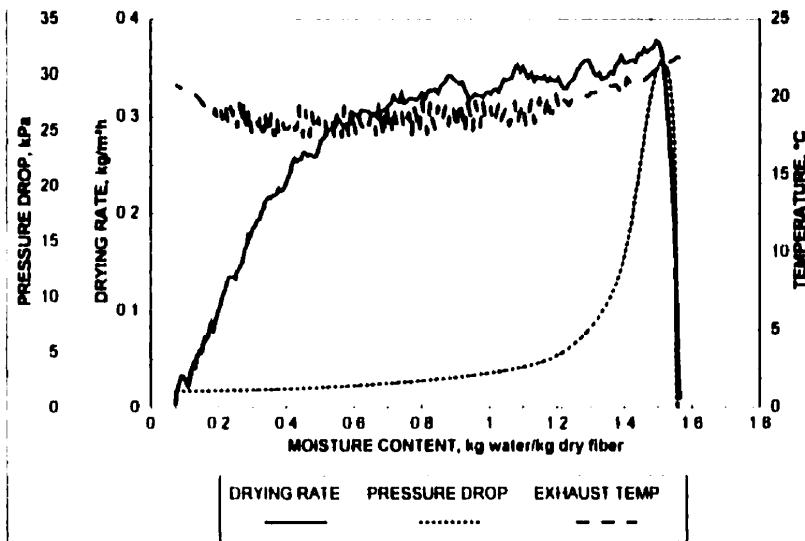
PAPER TYPE #8, $B=47.7\text{g/m}^2$, $T_i=58.7^\circ\text{C}$, $G=0.0127\text{kg/m}^2\text{s}$



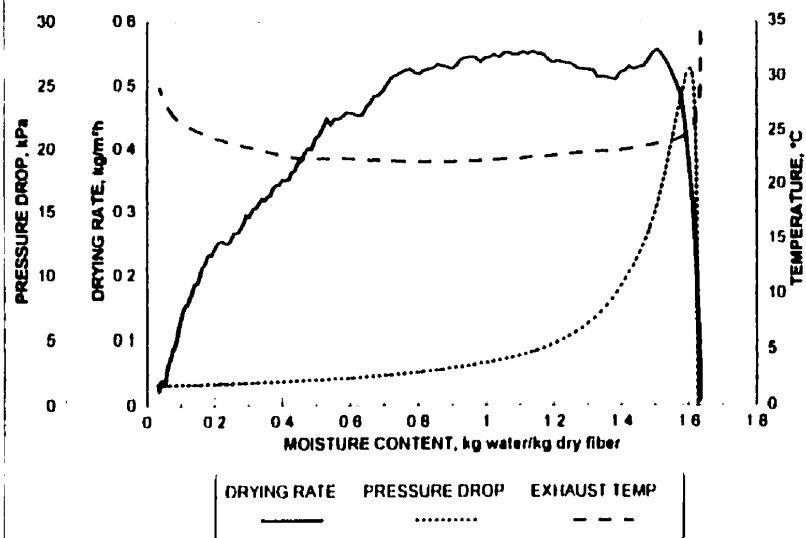
PAPER TYPE #8, B=47.7g/m², Ti=22.3°C, G=0.0127kg/m²s



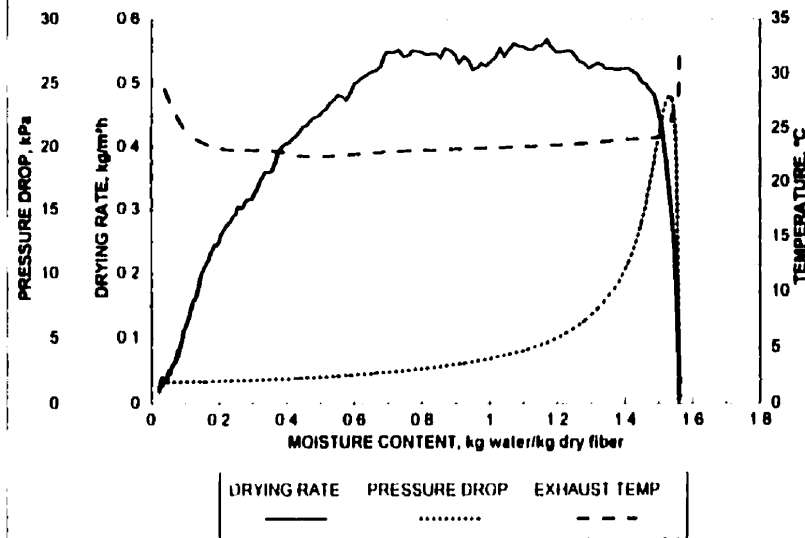
PAPER TYPE #8, B=47.7g/m², Ti=22.3°C, G=0.0127kg/m²s



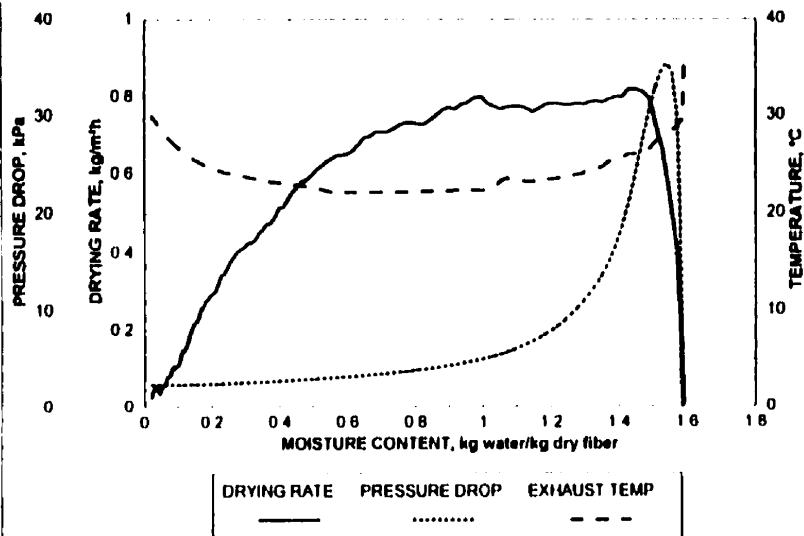
PAPER TYPE #8, B=47.7g/m², Ti=41.7°C, G=0.0127kg/m²s



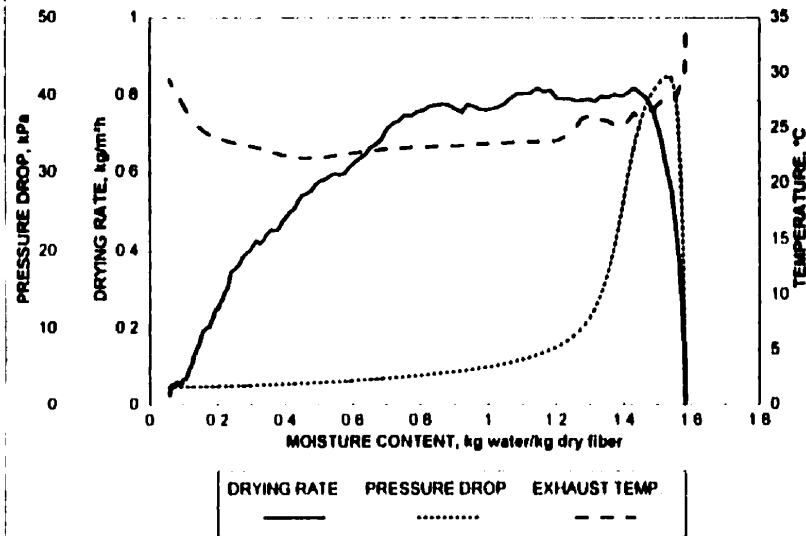
PAPER TYPE #8, B=47.7g/m², Ti=41.7°C, G=0.0127kg/m²s



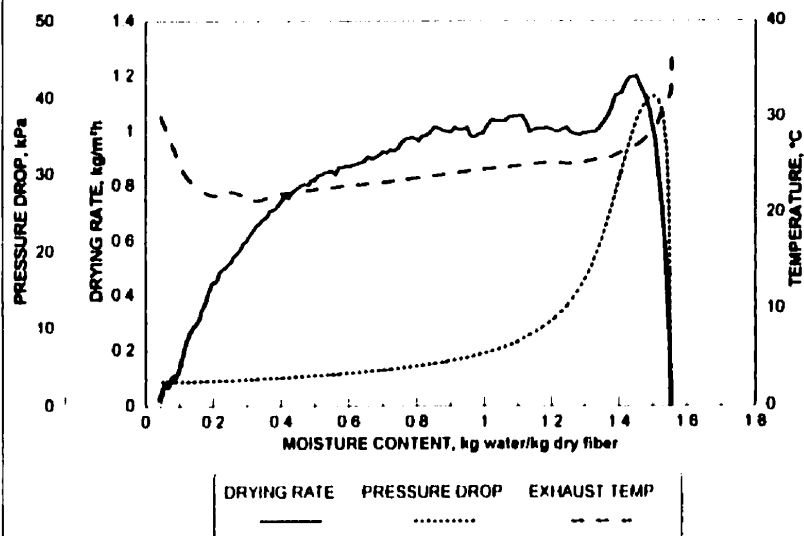
PAPER TYPE #8, B=47.7g/m², Ti=40.9°C, G=0.0195kg/m's



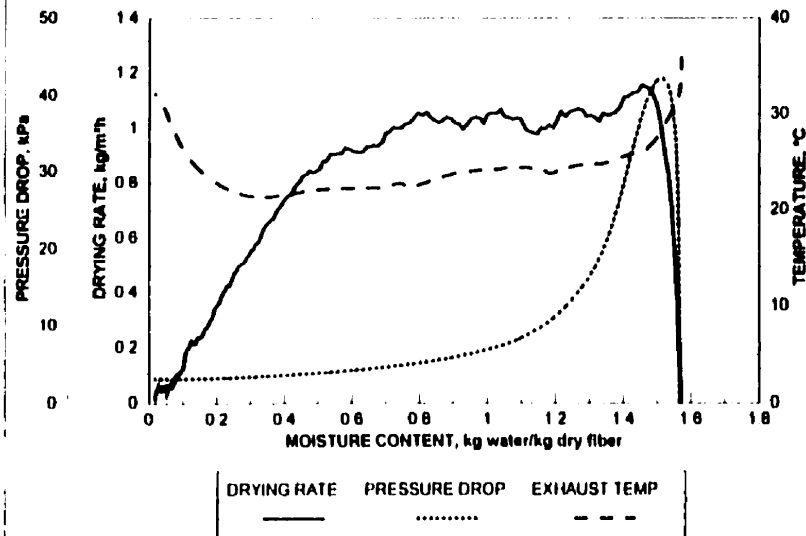
PAPER TYPE #8, B=47.7g/m², Ti=40.4°C, G=0.0195kg/m's



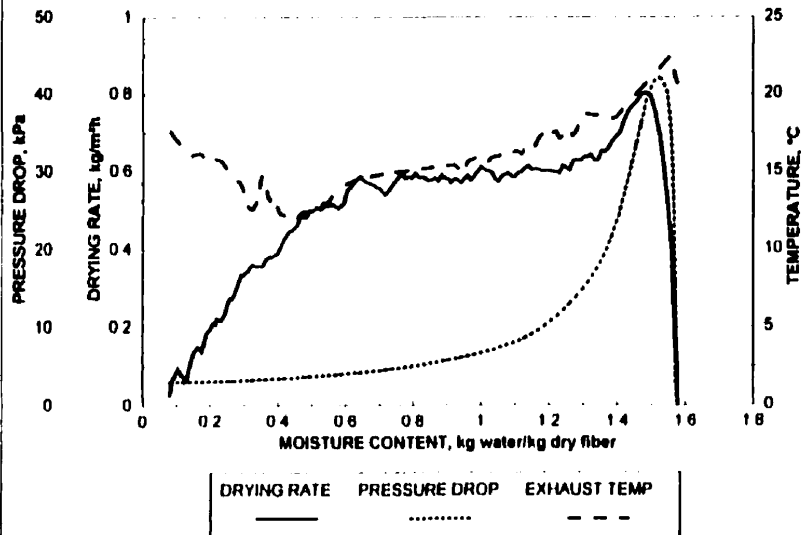
PAPER TYPE #8, B=47.7g/m², Ti=41.0°C, G=0.0265kg/m's



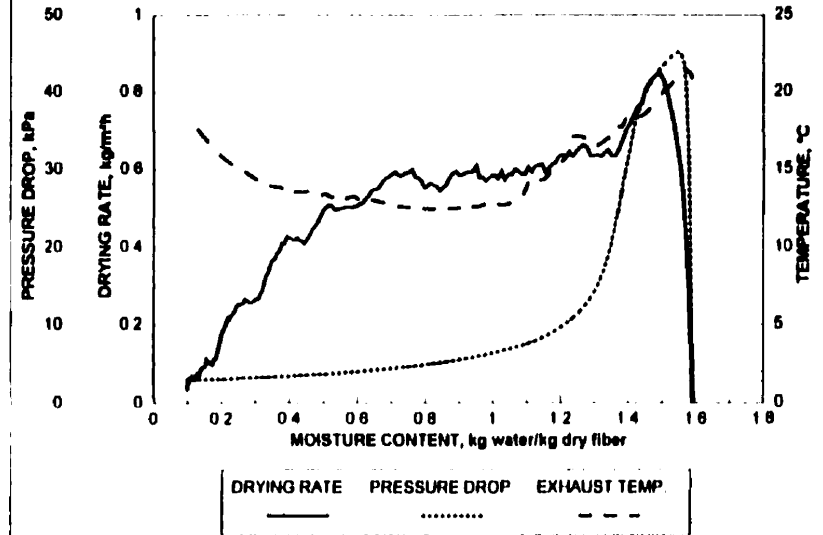
PAPER TYPE #8, B=47.7g/m², Ti=40.0°C, G=0.0265kg/m's



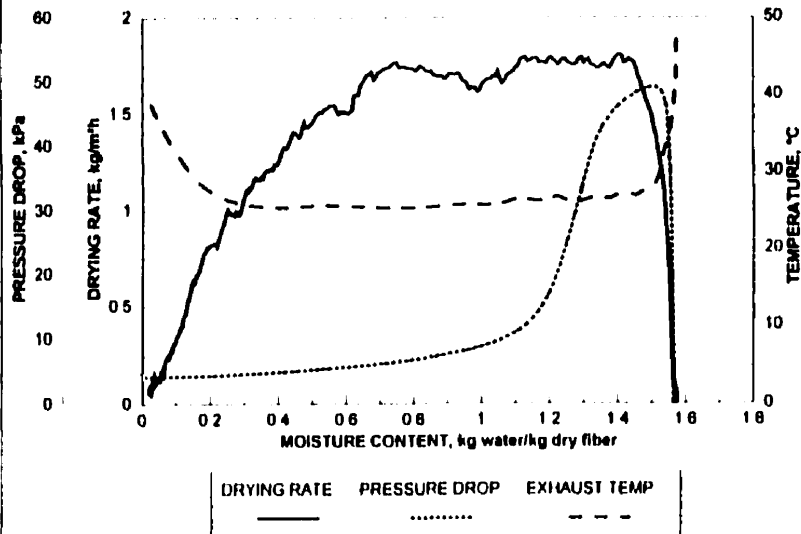
PAPER TYPE #8, B=47.7g/m², Ti=20.3°C, G=0.0265kg/m²s



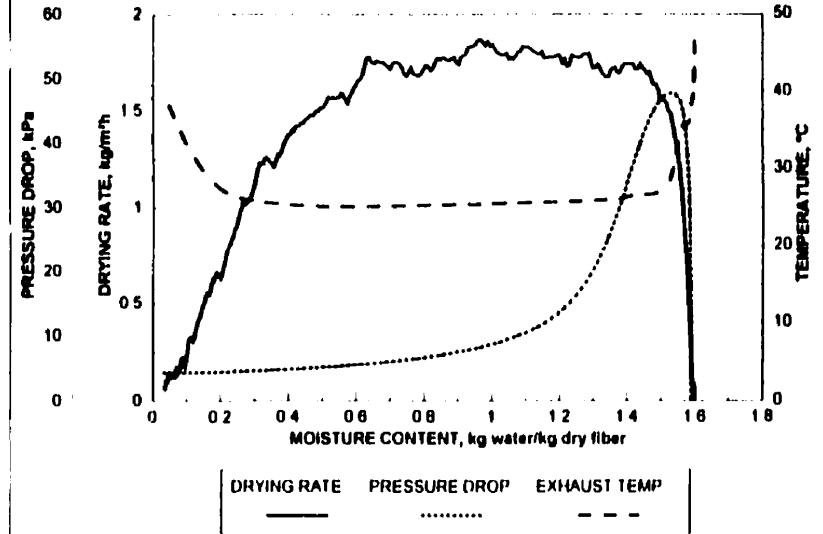
PAPER TYPE #8, B=47.7g/m², Ti=20.5°C, G=0.0265kg/m²s



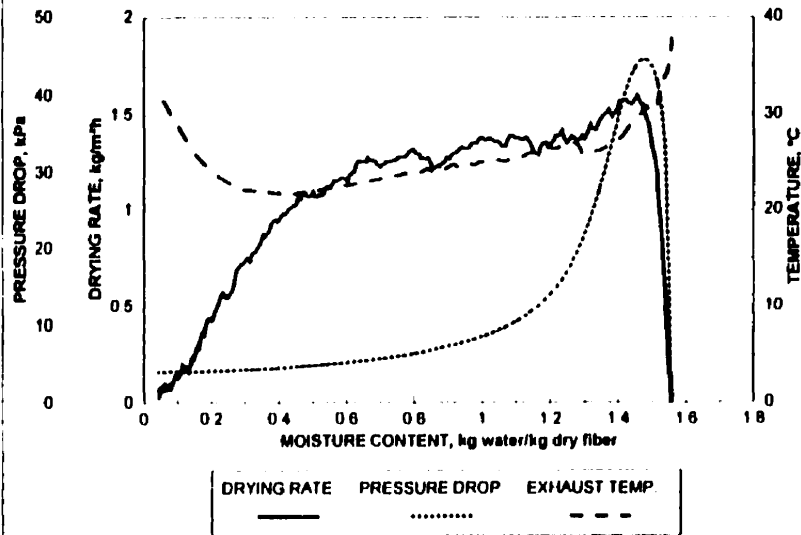
PAPER TYPE #8, B=47.7g/m², Ti=59.9°C, G=0.034kg/m²s



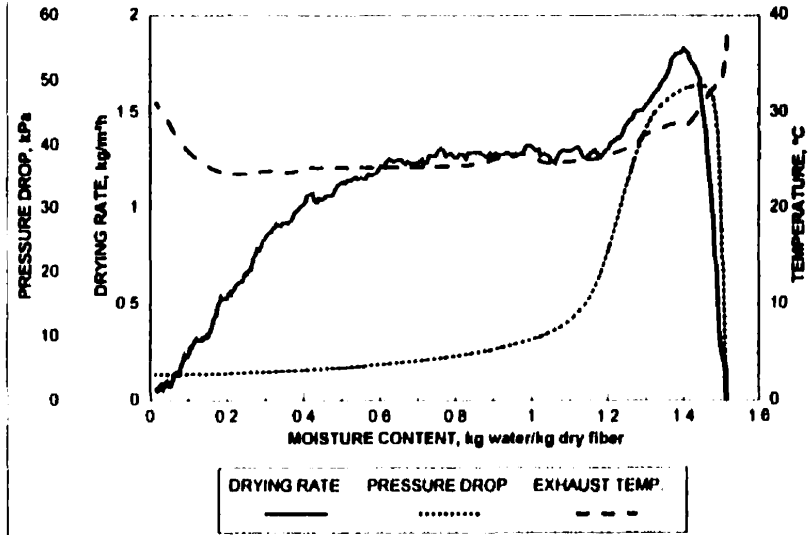
PAPER TYPE #8, B=47.7g/m², Ti=60.0°C, G=0.034kg/m²s



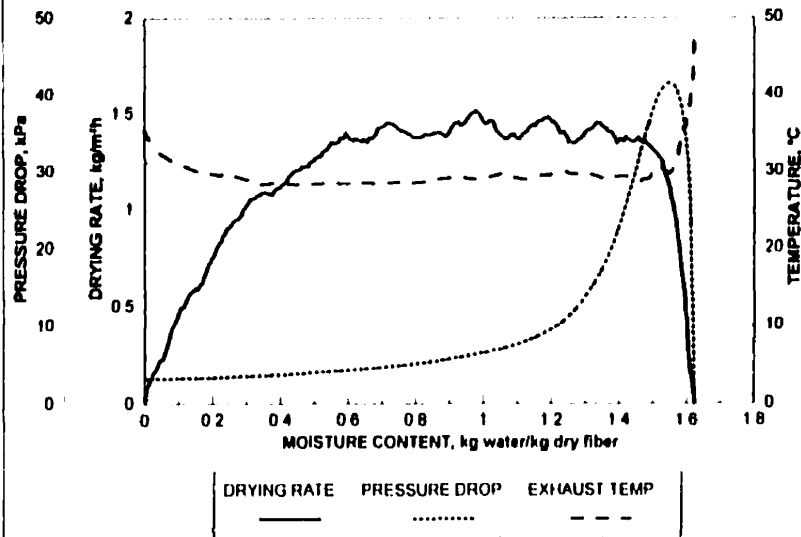
PAPER TYPE #8, B=47.7g/m², Ti=42.3°C, G=0.034kg/m²s



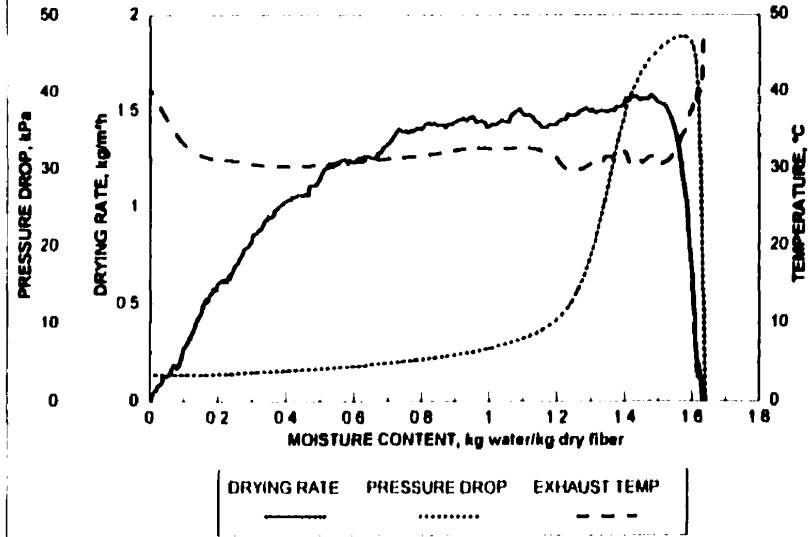
PAPER TYPE #8, B=47.7g/m², Ti=41.9°C, G=0.034kg/m²s



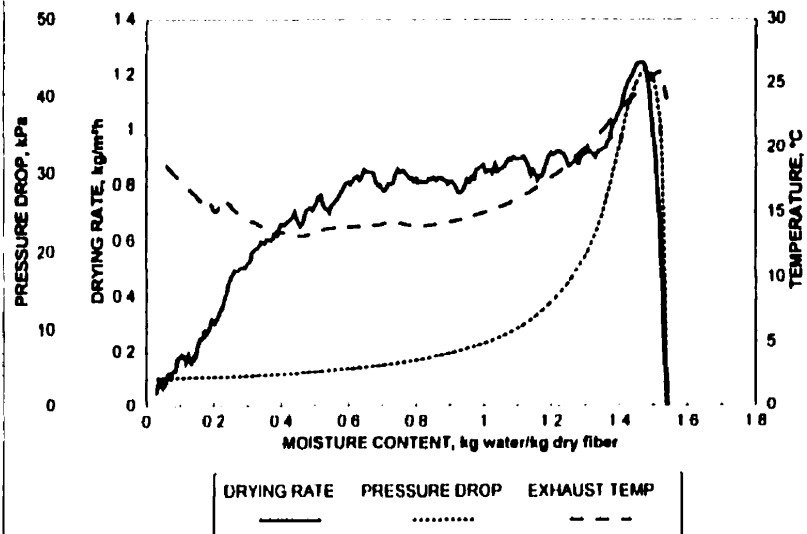
PAPER TYPE #8, B=47.7g/m², Ti=61.1°C, G=0.0265kg/m²s



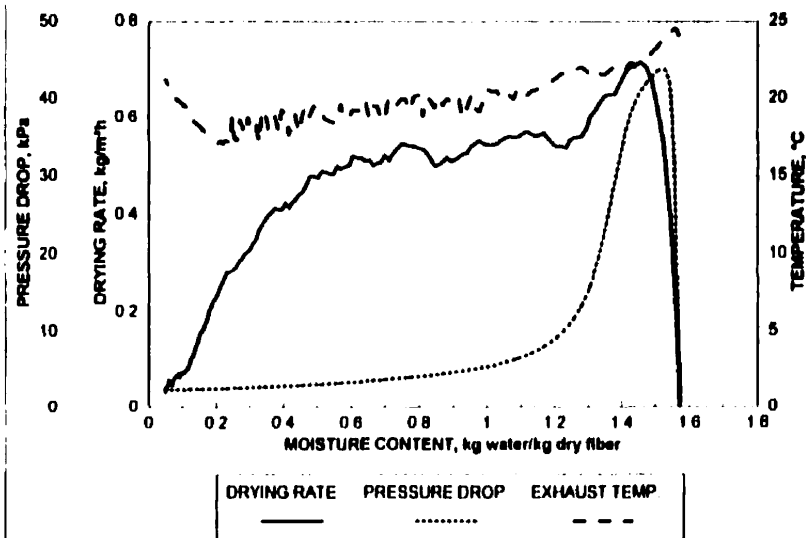
PAPER TYPE #8, B=47.7g/m², Ti=61.2°C, G=0.0265kg/m²s



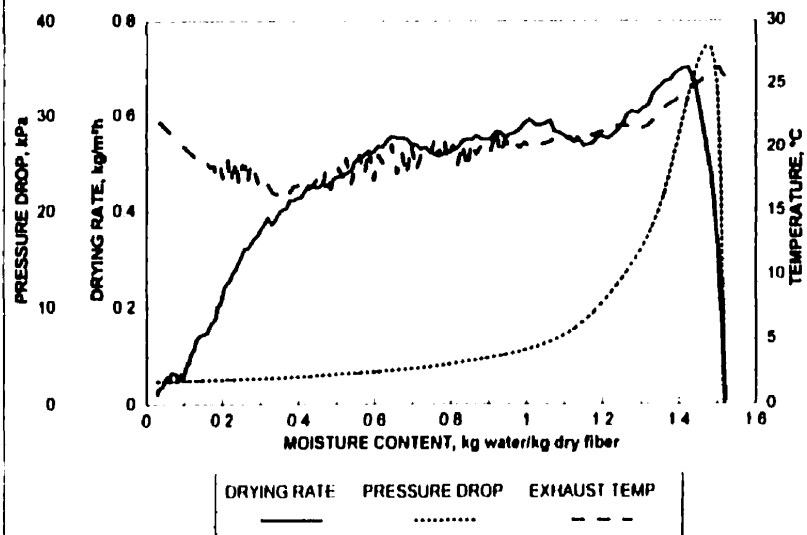
PAPER TYPE #8, $B=47.7\text{g/m}^2$, $T_i=23.2^\circ\text{C}$, $G=0.034\text{kg/m}^2\text{s}$



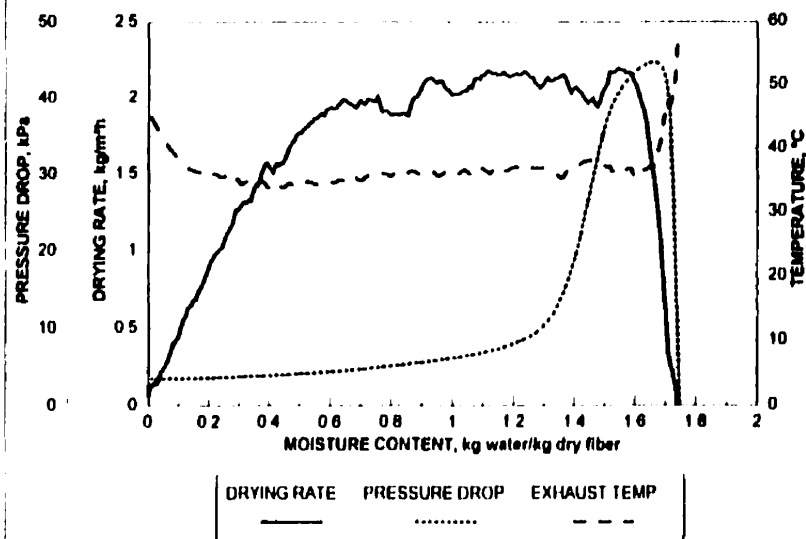
PAPER TYPE #8, $B=47.7\text{g/m}^2$, $T_i=23.8^\circ\text{C}$, $G=0.0195\text{kg/m}^2\text{s}$



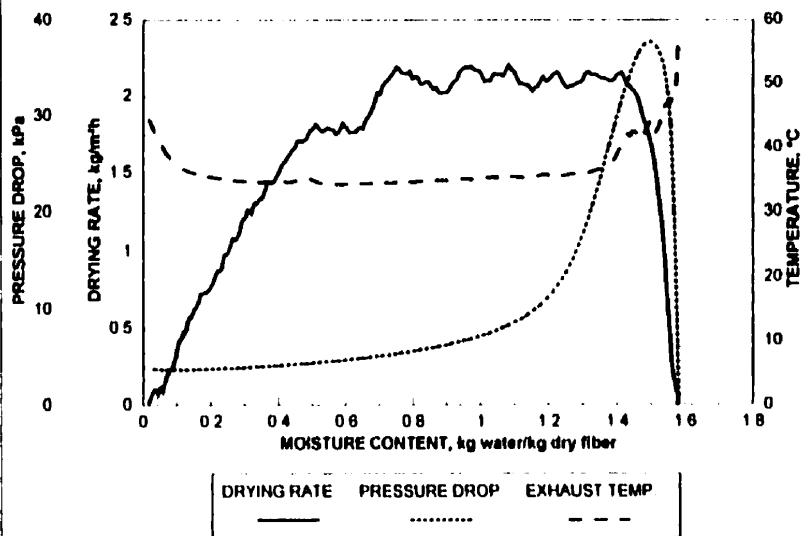
PAPER TYPE #8, $B=47.7\text{g/m}^2$, $T_i=25.2^\circ\text{C}$, $G=0.0195\text{kg/m}^2\text{s}$



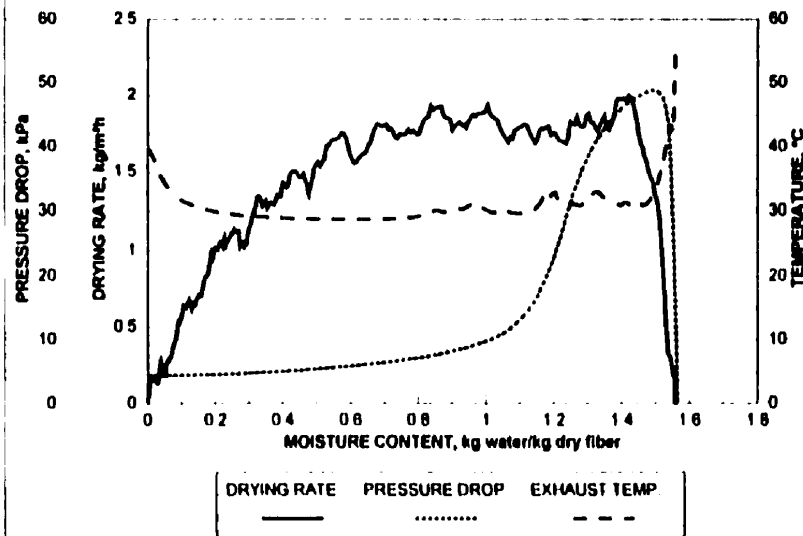
PAPER TYPE #8, $B=47.7\text{g/m}^2$, $T_i=80.1^\circ\text{C}$, $G=0.0265\text{kg/m}^2\text{s}$



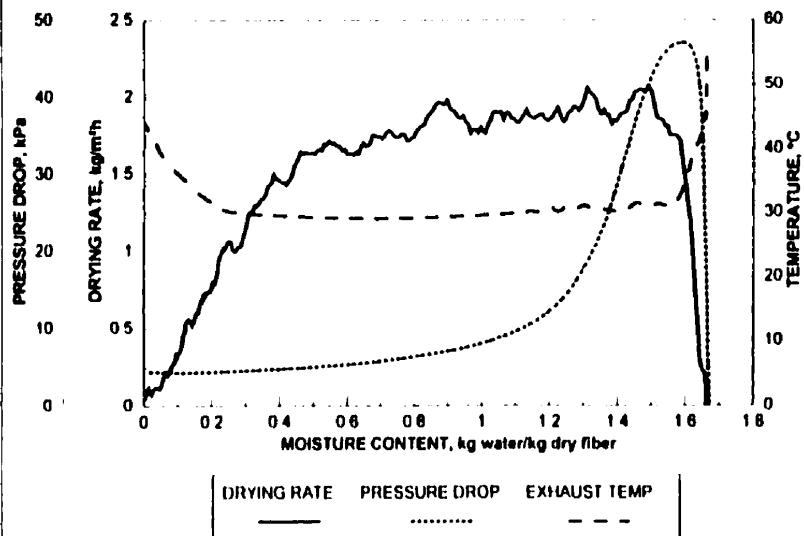
PAPER TYPE #8, B=47.7g/m², Ti=80.3°C, G=0.0265kg/m²s



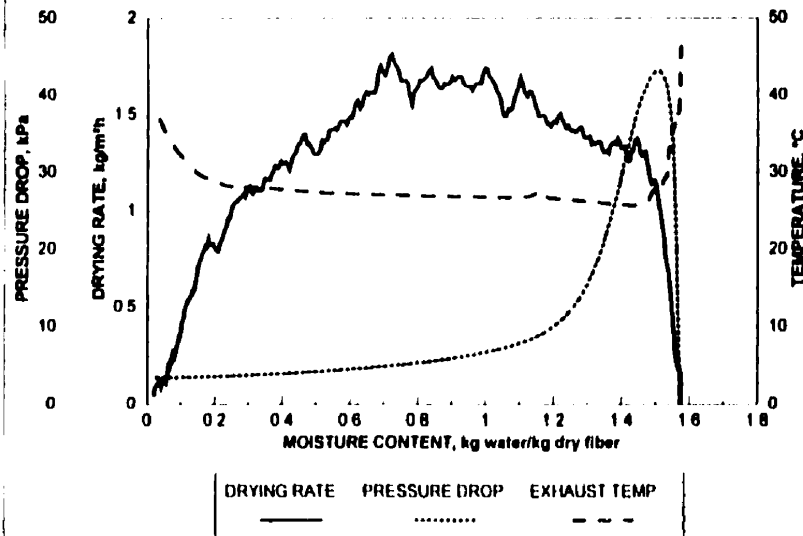
PAPER TYPE #8, B=47.7g/m², Ti=70.2°C, G=0.034kg/m²s



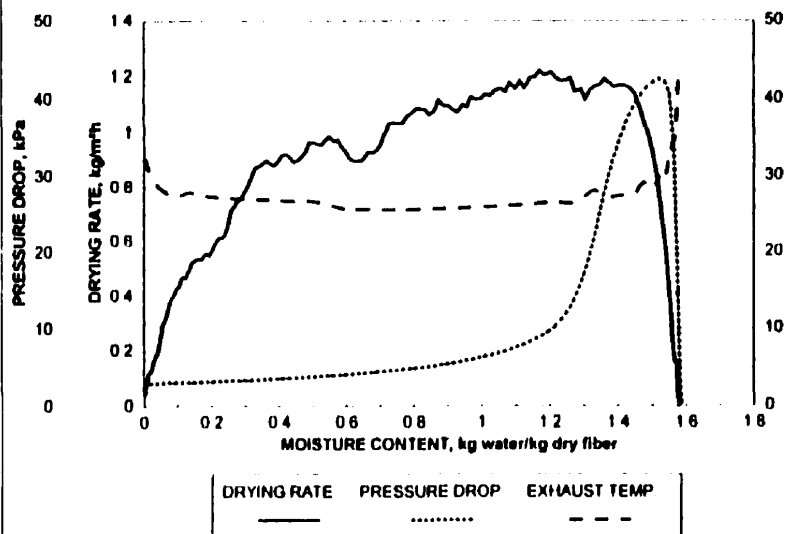
PAPER TYPE #8, B=47.7g/m², Ti=70.2°C, G=0.034kg/m²s



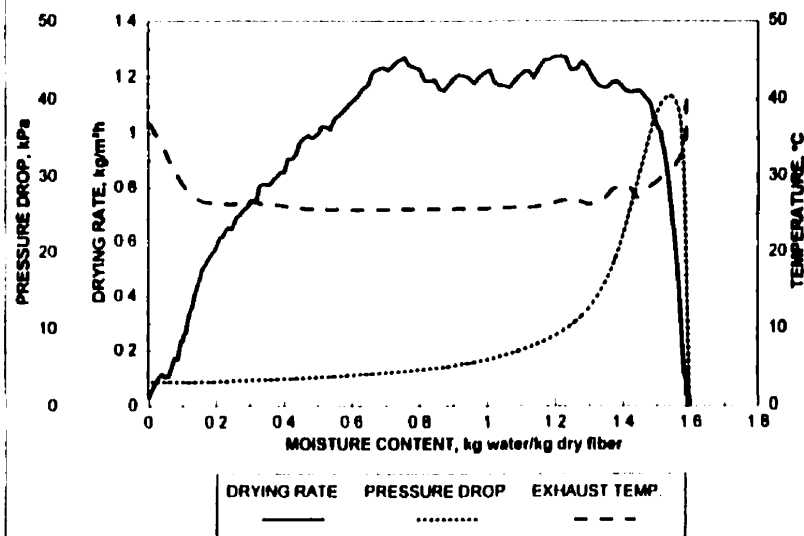
PAPER TYPE #8, B=47.7g/m², Ti=69.0°C, G=0.0265kg/m²s



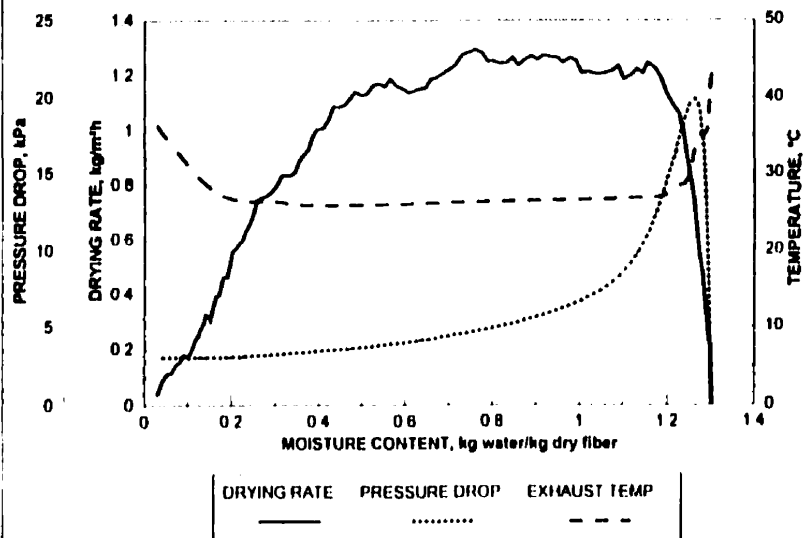
PAPER TYPE #8, B=47.7g/m², Ti=61.3°C, G=0.023kg/m²s



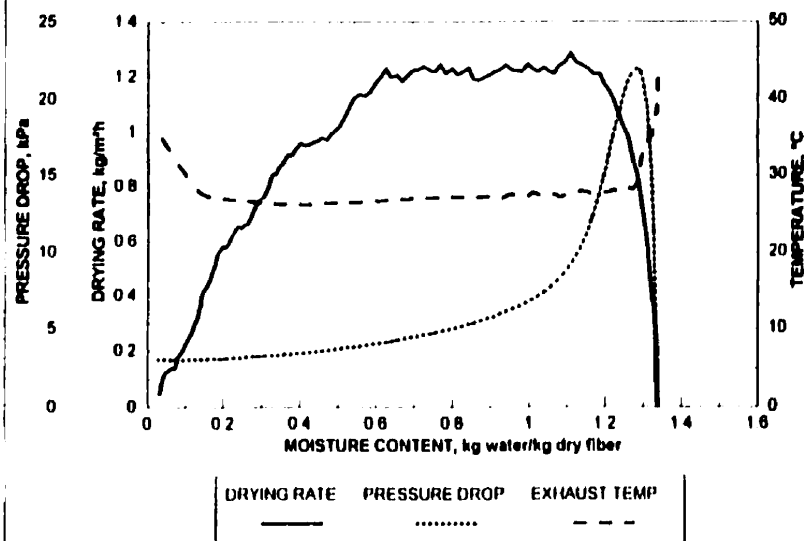
PAPER TYPE #8, B=47.7g/m², Ti=61.2°C, G=0.023kg/m²s



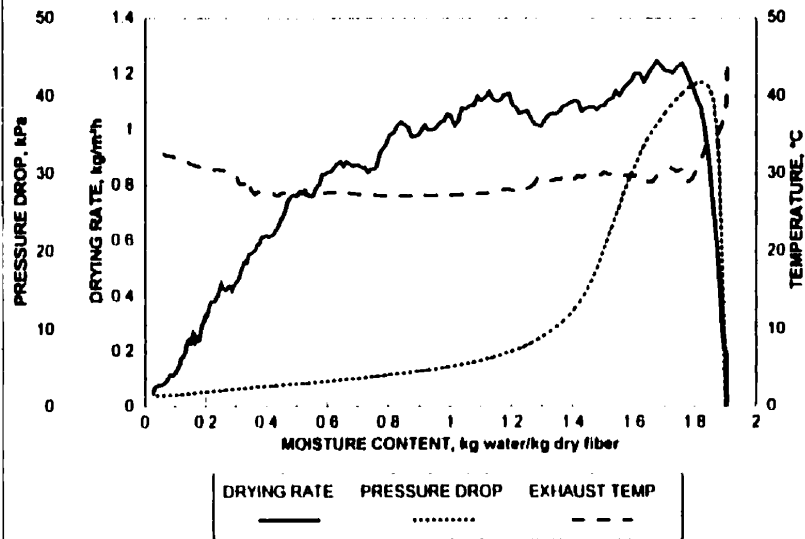
PAPER TYPE #8, B=47.7g/m², Ti=61.0°C, G=0.023kg/m²s



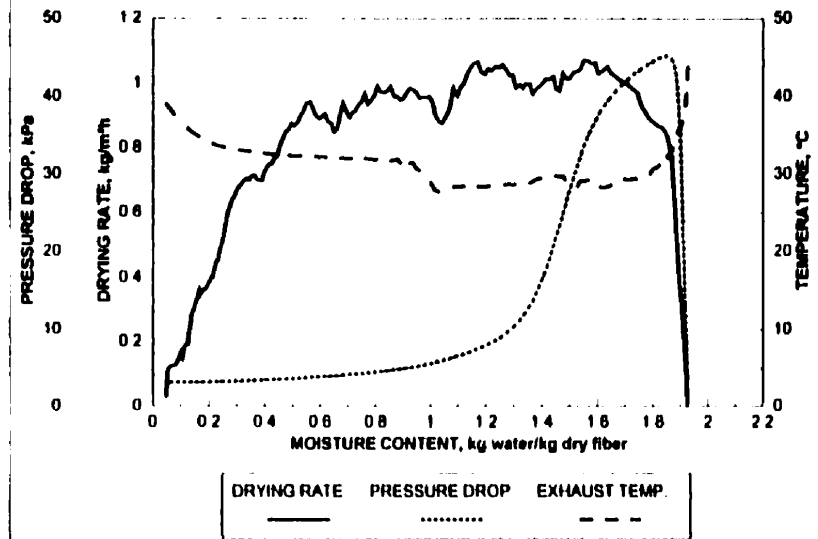
PAPER TYPE #8, B=47.7g/m², Ti=61.1°C, G=0.023kg/m²s



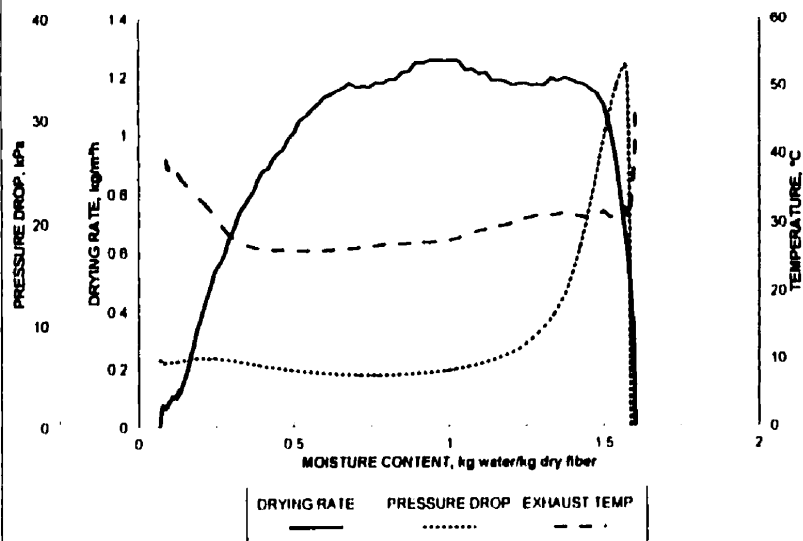
PAPER TYPE #8, B=47.7g/m², Ti=60.7°C, G=0.023kg/m²s



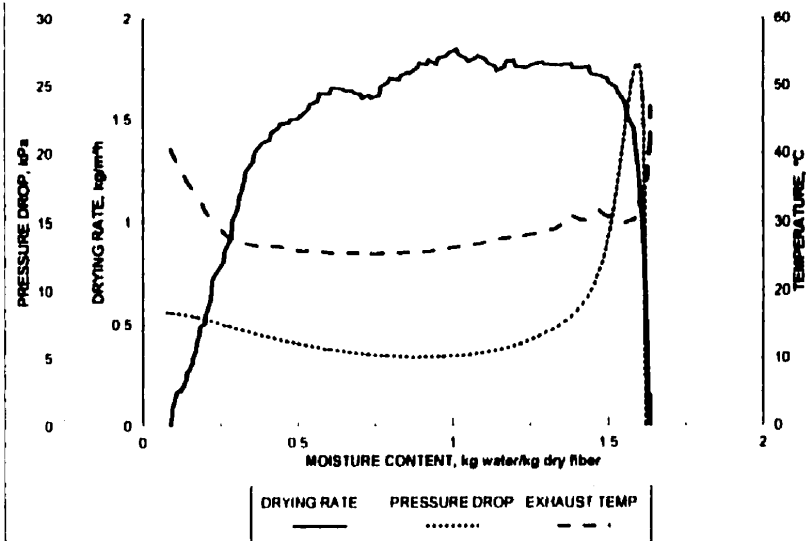
PAPER TYPE #8, B=47.7g/m², Ti=62.0°C, G=0.023kg/m²s



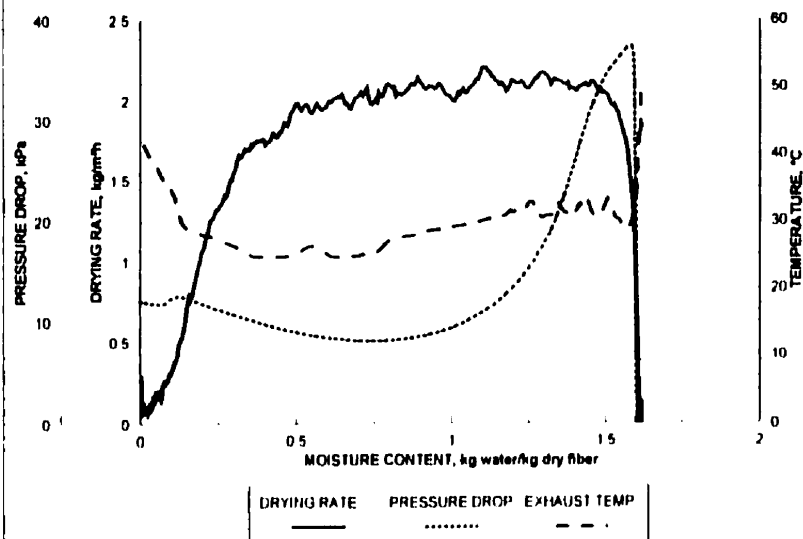
KRAFT HANDSHEET, FREENESS 258 ml, B=60 g/m², Ti=58.7°C, G=0.025kg/m²s



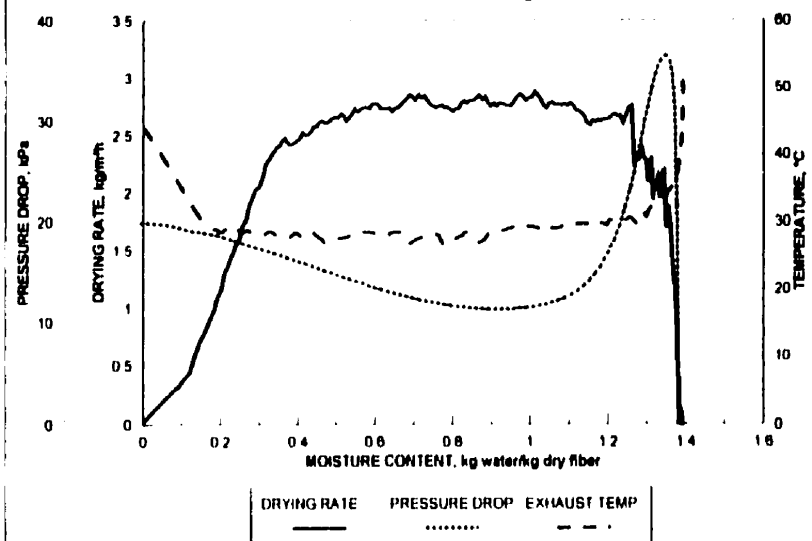
KRAFT HANDSHEET, FREENESS 258 ml, B=60 g/m², Ti=63.2°C, G=0.036kg/m²s



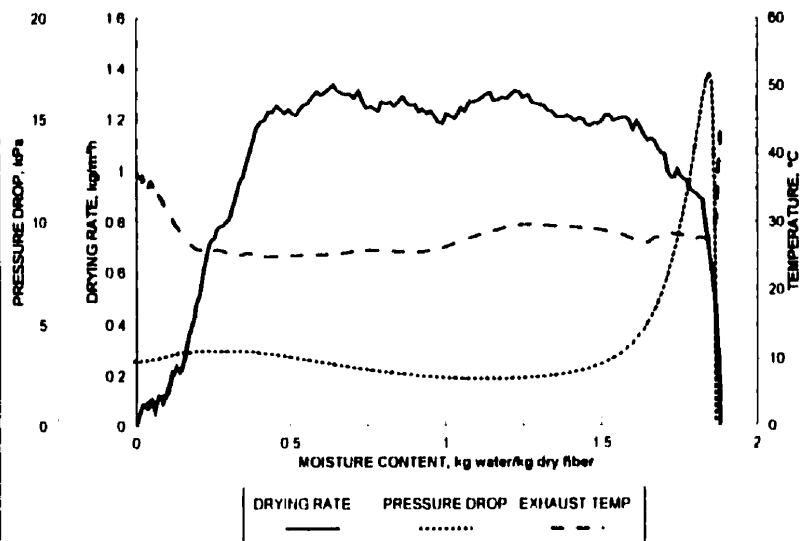
KRAFT HANDSHEET, FREENESS 258 ml, B=60 g/m², Ti=63.2°C, G=0.044kg/m²s



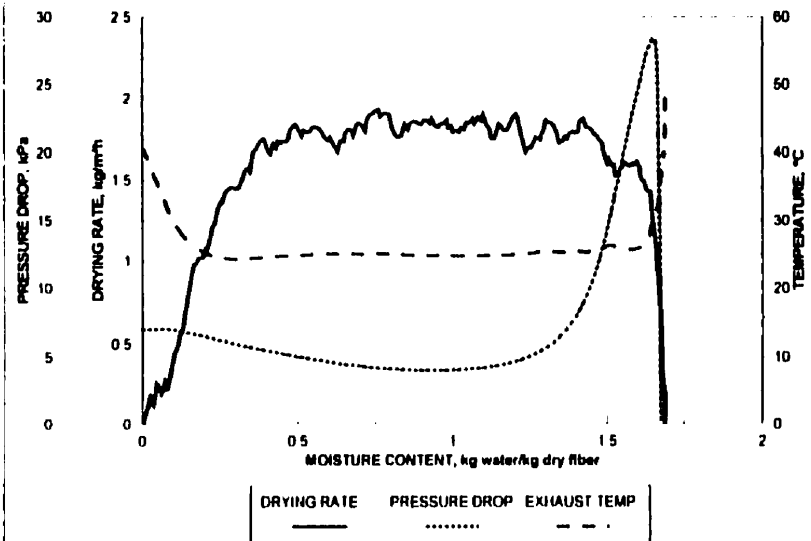
KRAFT HANDSHEET, FREENESS 258 ml, B=60 g/m², Ti=67.2°C, G=0.051kg/m²s



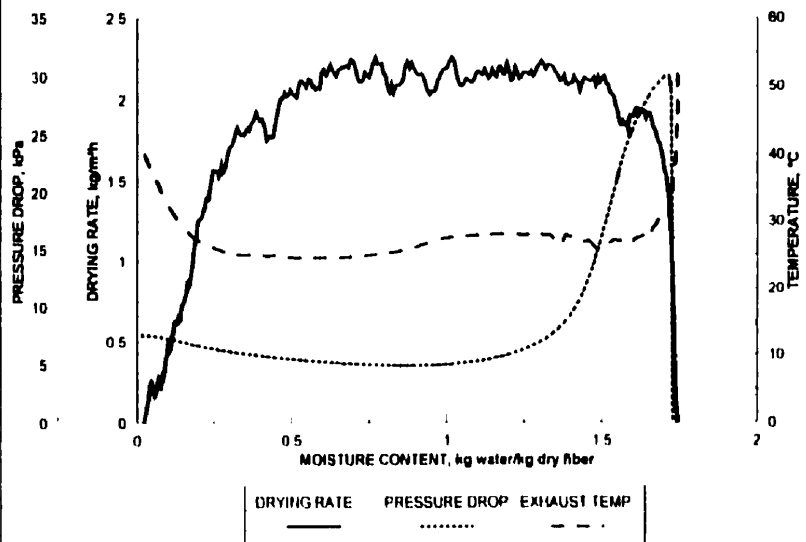
KRAFT HANDSHEET, FREENESS 435 ml, B=60 g/m², Tl=60.3°C, G=0.025kg/m²s



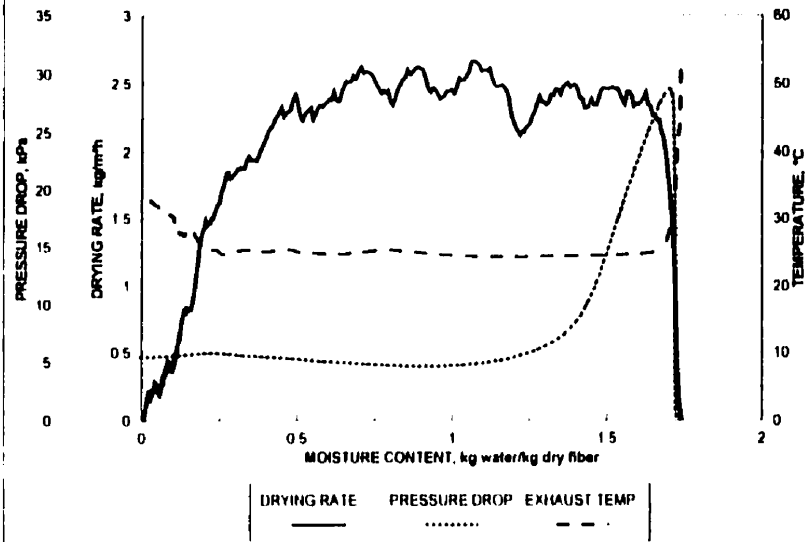
KRAFT HANDSHEET, FREENESS 435 ml, B=60 g/m², Tl=60.4°C, G=0.036kg/m²s



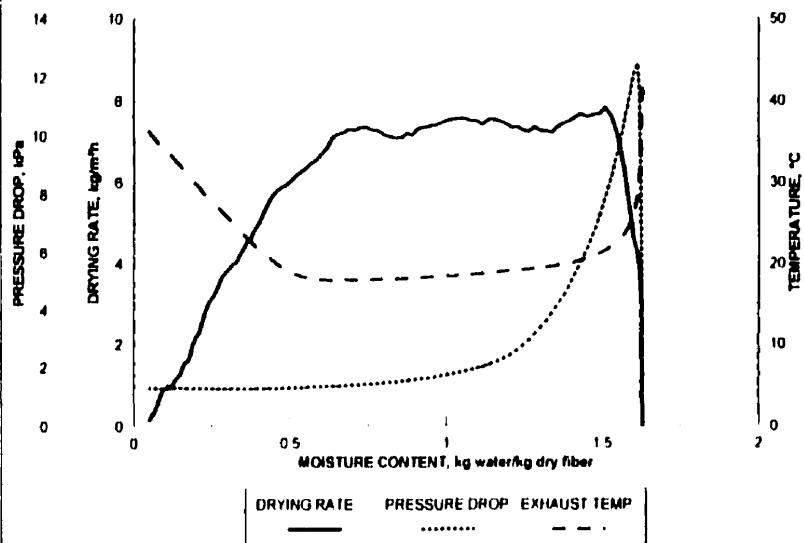
KRAFT HANDSHEET, FREENESS 435 ml, B=60 g/m², Tl=60.5°C, G=0.044kg/m²s



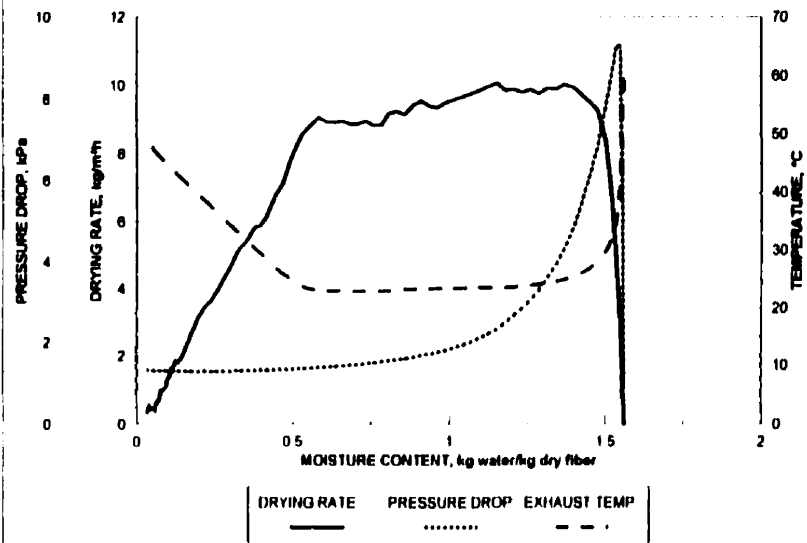
KRAFT HANDSHEET, FREENESS 435 ml, B=60 g/m², Tl=60.0°C, G=0.051kg/m²s



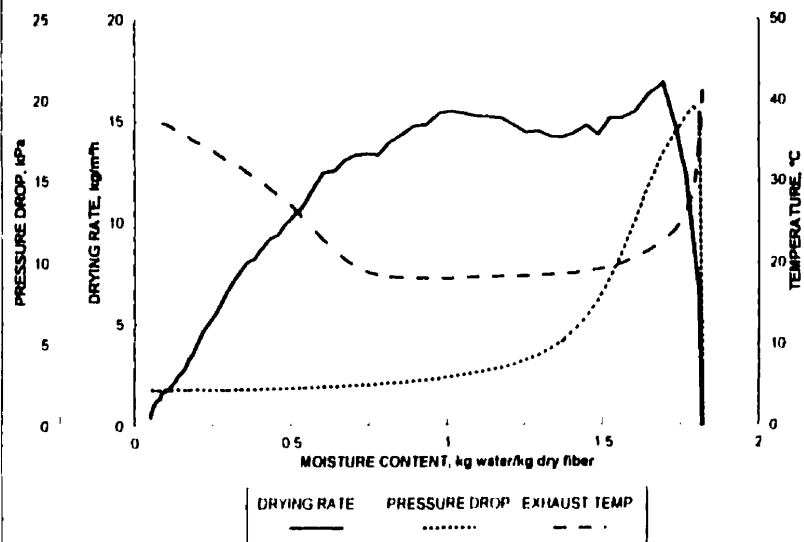
KRAFT HANDSHEET, BLEACHED, B=60 g/m², T_i=42.8°C, G=0.207kg/m²s



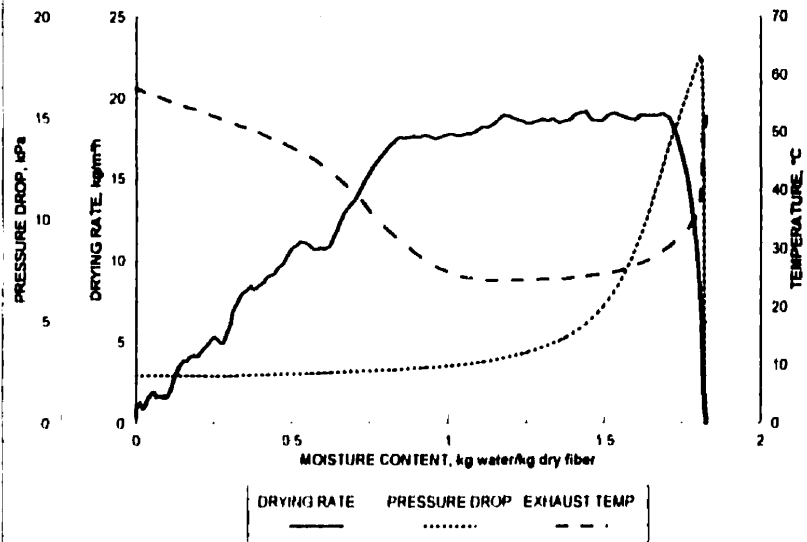
KRAFT HANDSHEET, BLEACHED, B=60 g/m², T_i=62.6°C, G=0.207kg/m²s



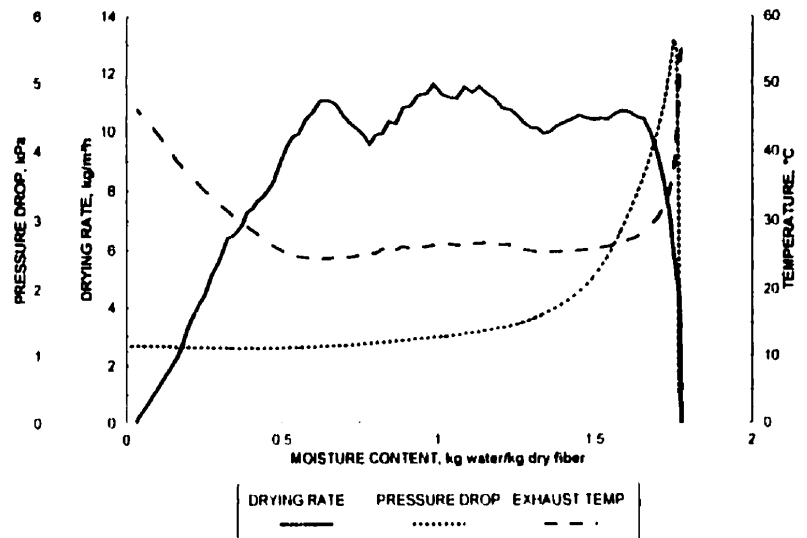
KRAFT HANDSHEET, BLEACHED, B=60 g/m², T_i=42.0°C, G=0.401kg/m²s



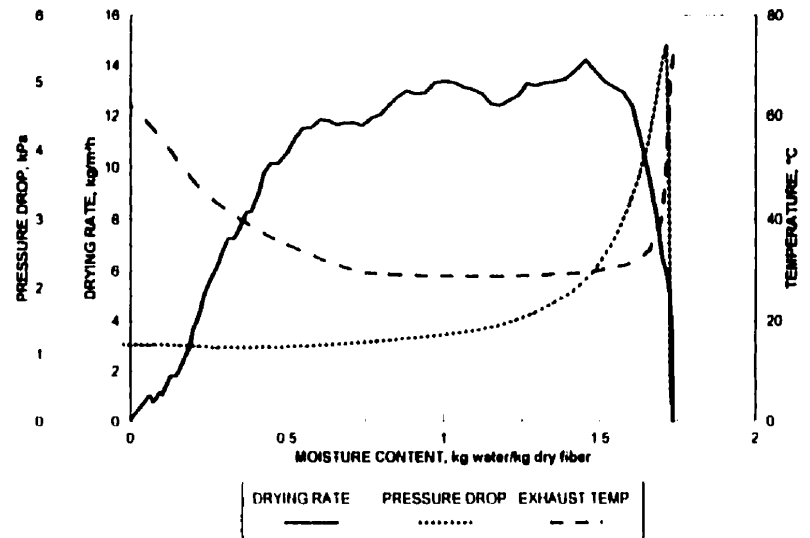
KRAFT HANDSHEET, BLEACHED, B=60 g/m², T_i=61.7°C, G=0.401kg/m²s



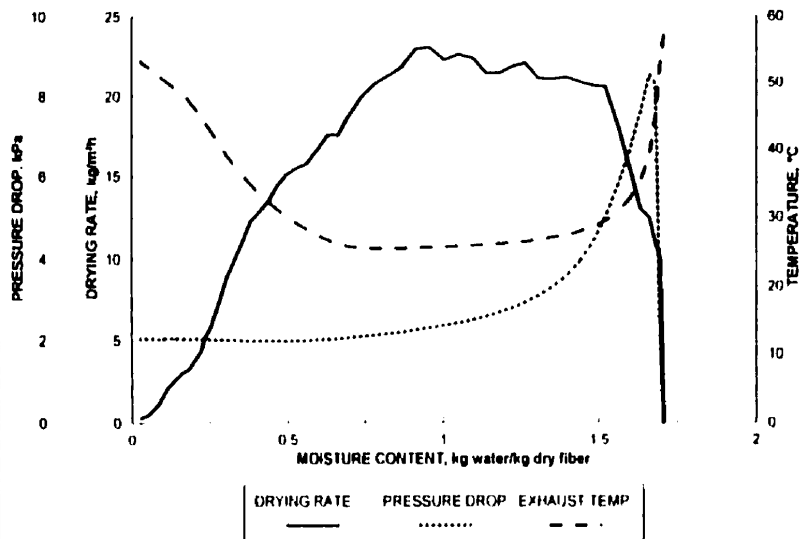
KRAFT HANDSHEET, WET PRESSED AT 150 psi, B=60 g/m², Tl=57.0°C, G=0.207kg/m²s



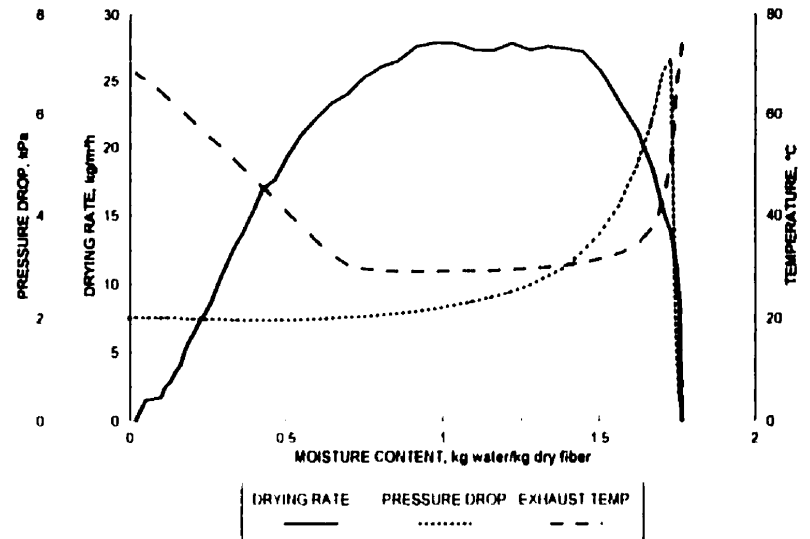
KRAFT HANDSHEET, WET PRESSED AT 150 psi, B=60 g/m², Tl=60.0°C, G=0.207kg/m²s



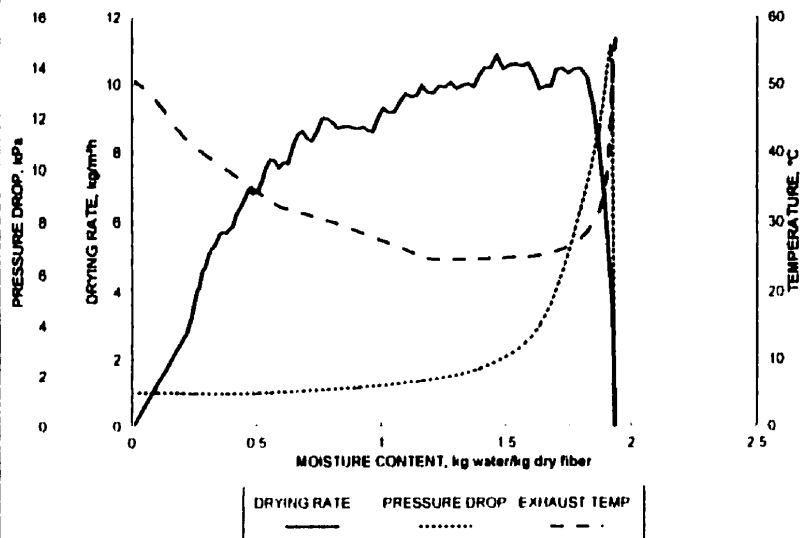
KRAFT HANDSHEET, WET PRESSED AT 150 psi, B=60 g/m², Tl=59.6°C, G=0.402kg/m²s



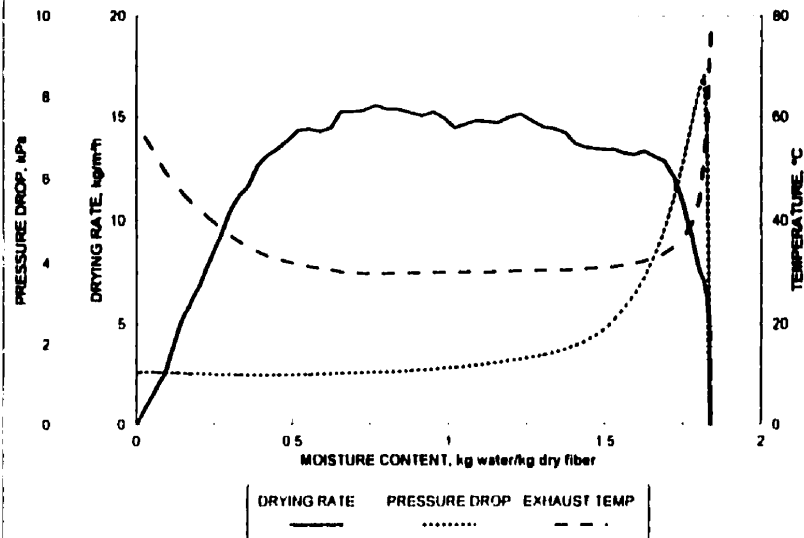
KRAFT HANDSHEET, WET PRESSED AT 150 psi, B=60 g/m², Tl=78.8°C, G=0.402kg/m²s



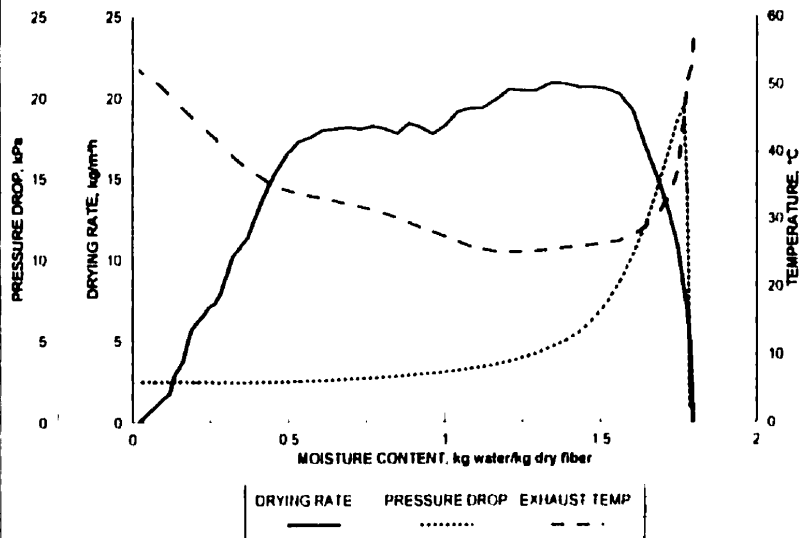
KRAFT HANDSHEET, WET PRESSED AT 300 psi, B=60 g/m², T_i=59.3°C, G=0.207kg/m's



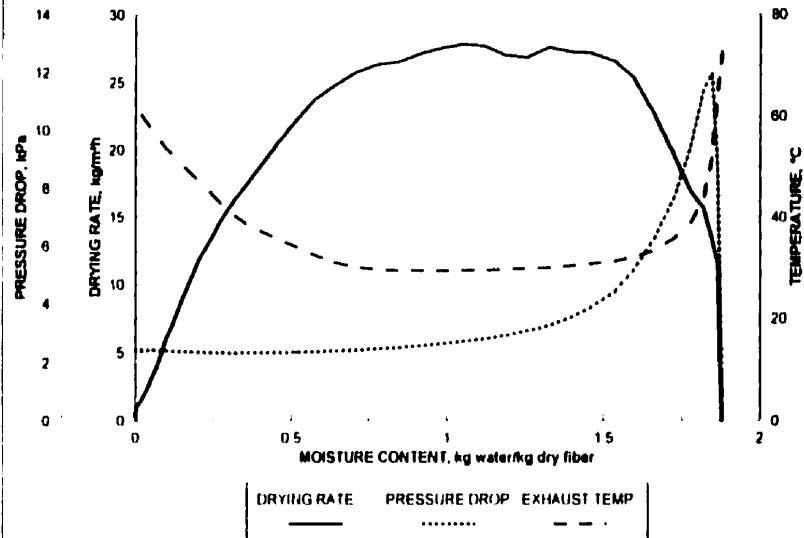
KRAFT HANDSHEET, WET PRESSED AT 300 psi, B=60 g/m², T_i=82.0°C, G=0.207kg/m's



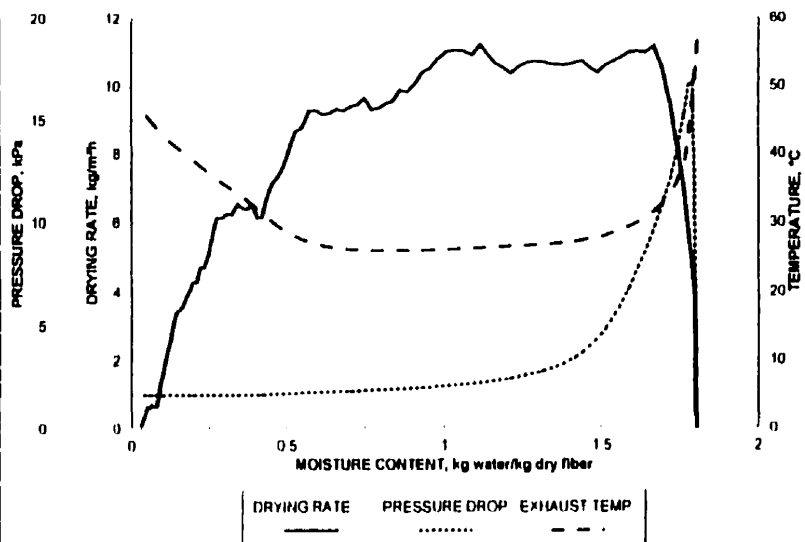
KRAFT HANDSHEET, WET PRESSED AT 300 psi, B=60 g/m², T_i=59.0°C, G=0.402kg/m's



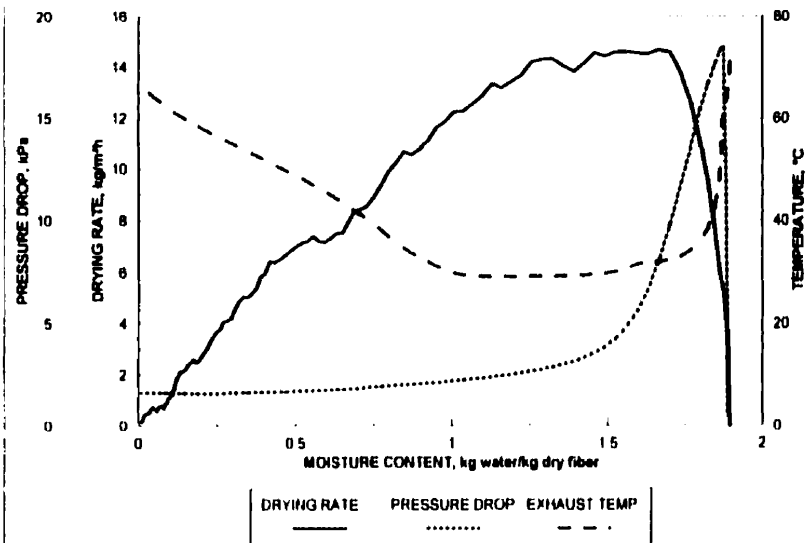
KRAFT HANDSHEET, WET PRESSED AT 300 psi, B=60 g/m², T_i=77.5°C, G=0.402kg/m's



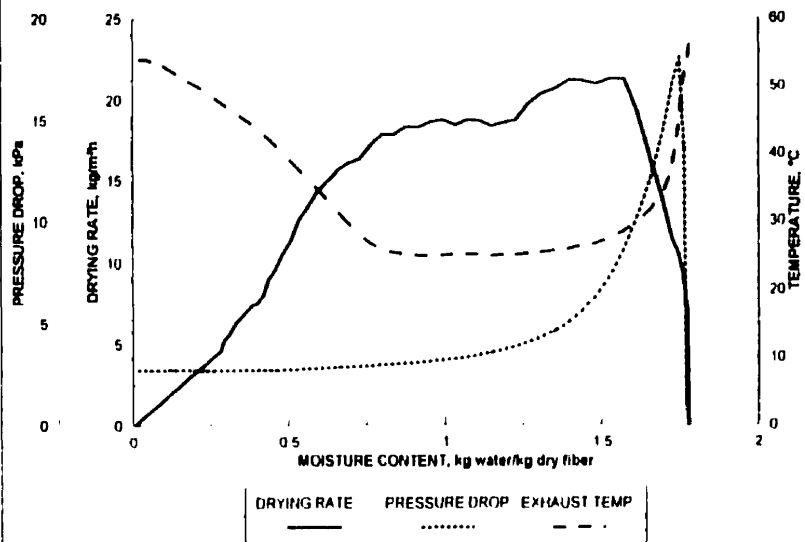
KRAFT HANDSHEET, WET PRESSED AT 600 psi, B=60 g/m², Tl=59.2°C, G=0.207kg/m's



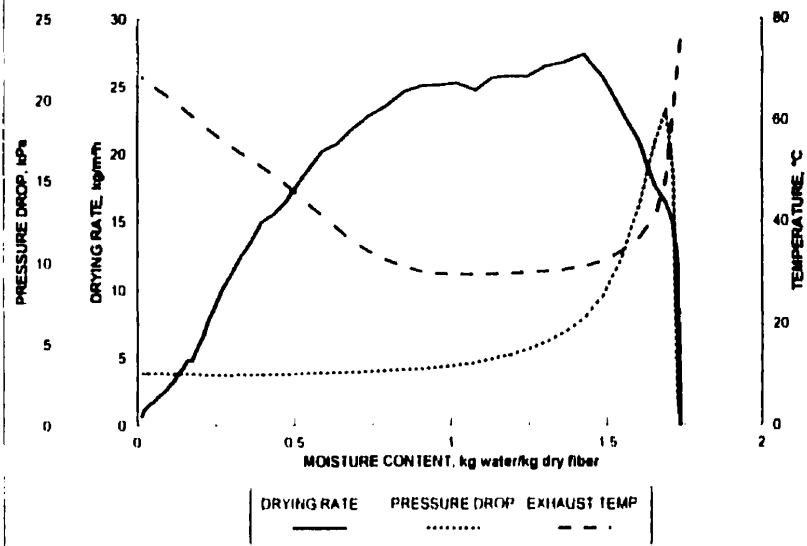
KRAFT HANDSHEET, WET PRESSED AT 600 psi, B=60 g/m², Tl=79.2°C, G=0.207kg/m's



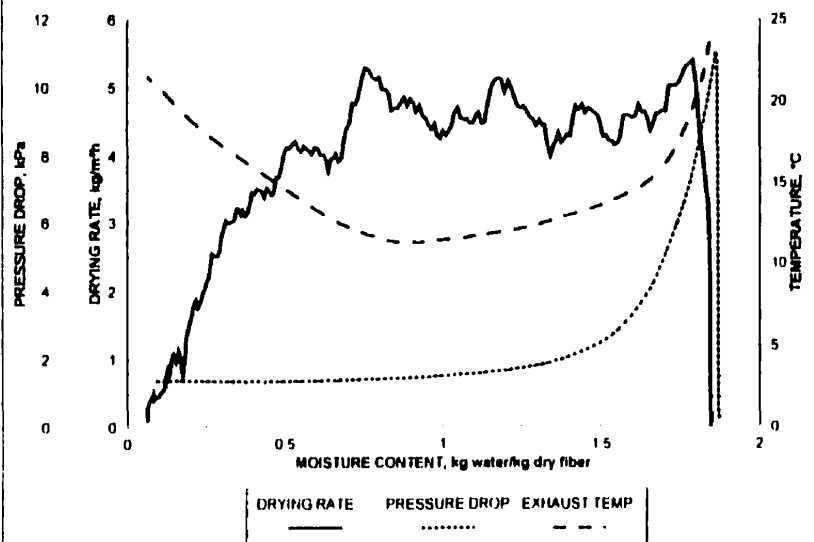
KRAFT HANDSHEET, WET PRESSED AT 600 psi, B=60 g/m², Tl=58.7°C, G=0.402kg/m's



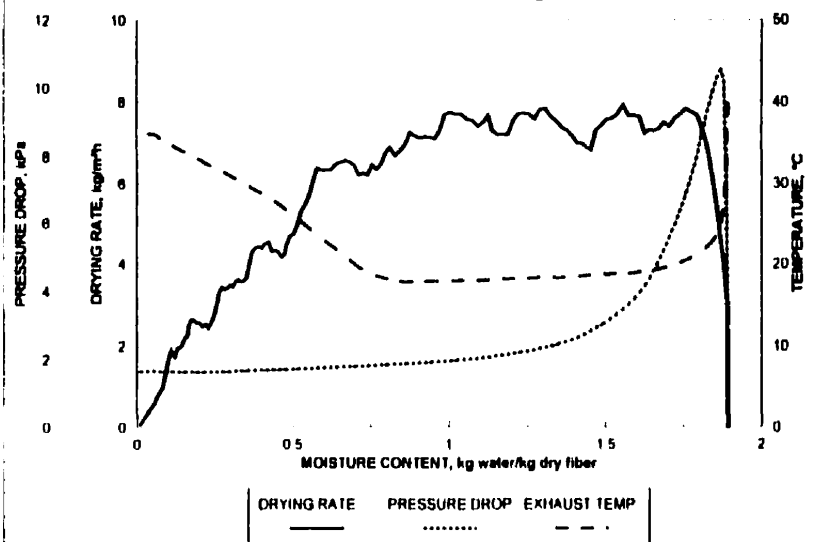
KRAFT HANDSHEET, WET PRESSED AT 600 psi, B=60 g/m², Tl=79.8°C, G=0.402kg/m's



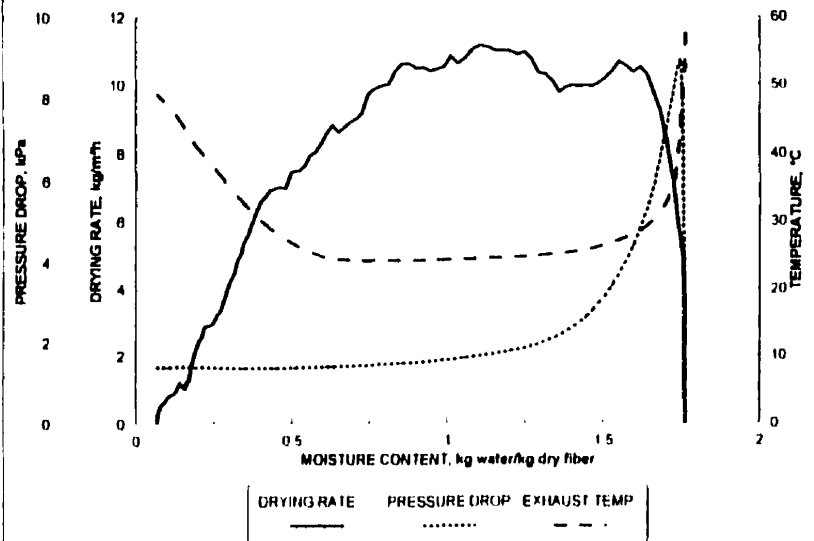
KRAFT HANDSHEET, RETENTION TIME 10s, B=60 g/m², T_i=23.3°C, G=0.207kg/m²s



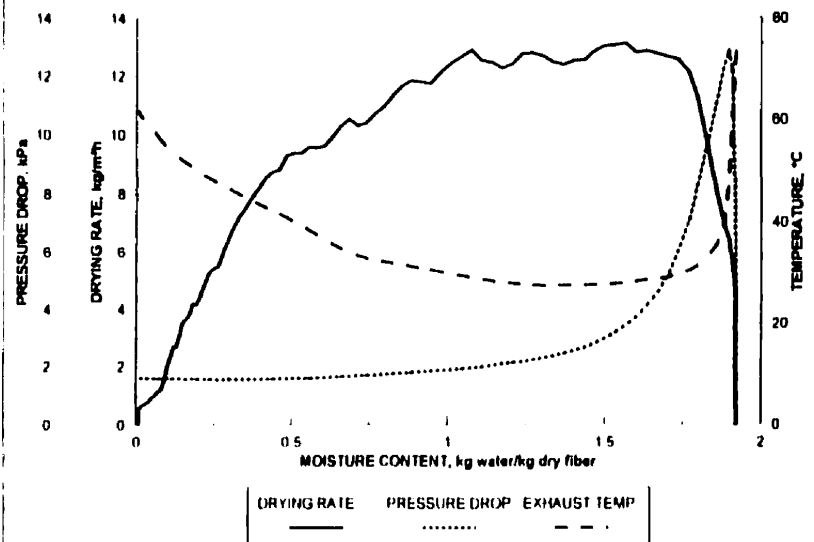
KRAFT HANDSHEET, RETENTION TIME 10s, B=60 g/m², T_i=42.2°C, G=0.207kg/m²s



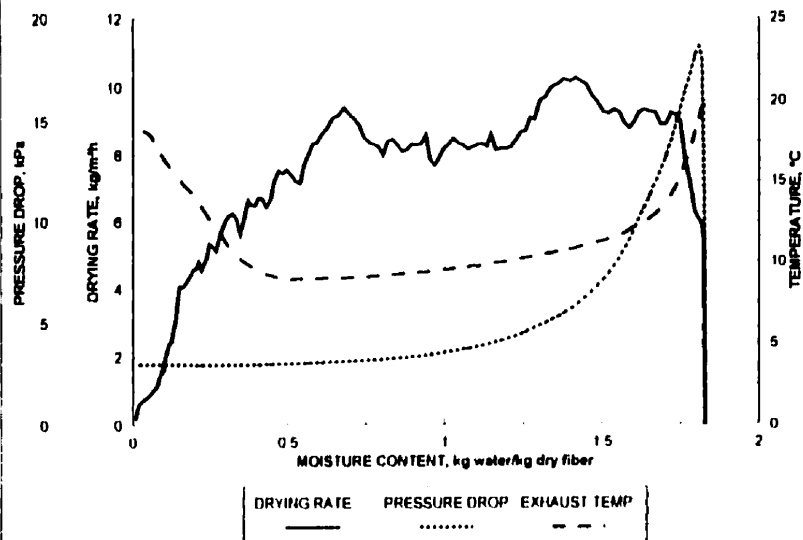
KRAFT HANDSHEET, RETENTION TIME 10s, B=60 g/m², T_i=60.0°C, G=0.207kg/m²s



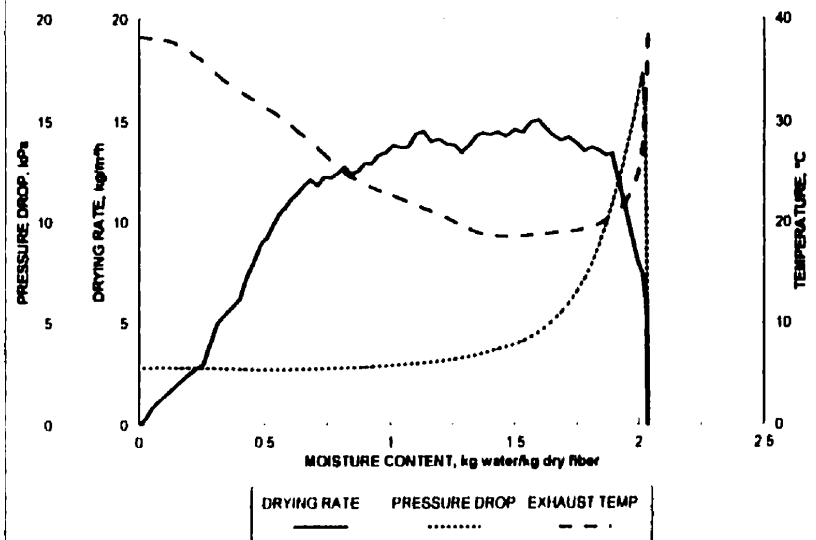
KRAFT HANDSHEET, RETENTION TIME 10s, B=60 g/m², T_i=80.1°C, G=0.207kg/m²s



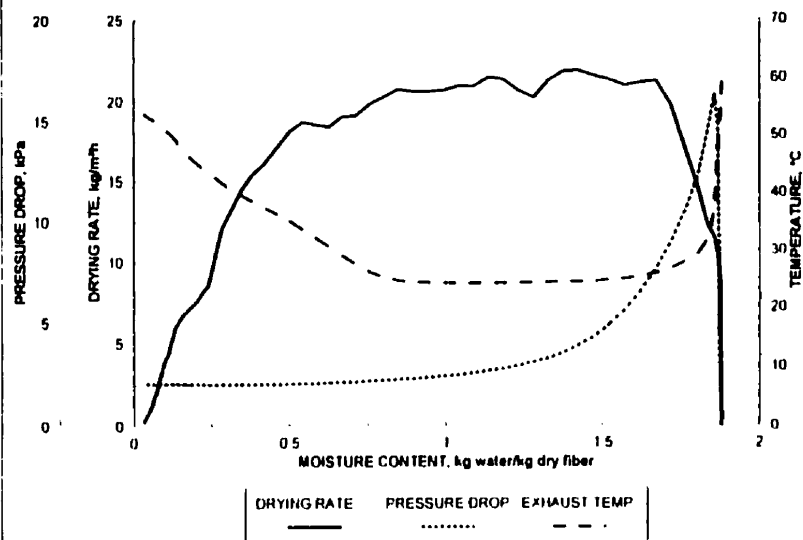
KRAFT HANDSHEET, RETENTION TIME 10s, B=60 g/m², Ti=19.7°C, G=0.402kg/m²s



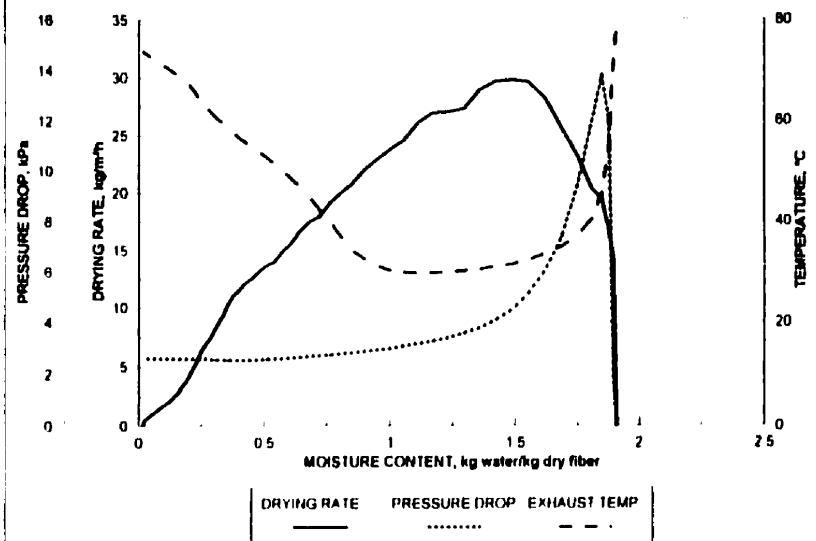
KRAFT HANDSHEET, RETENTION TIME 10s, B=60 g/m², Ti=40.4°C, G=0.402kg/m²s



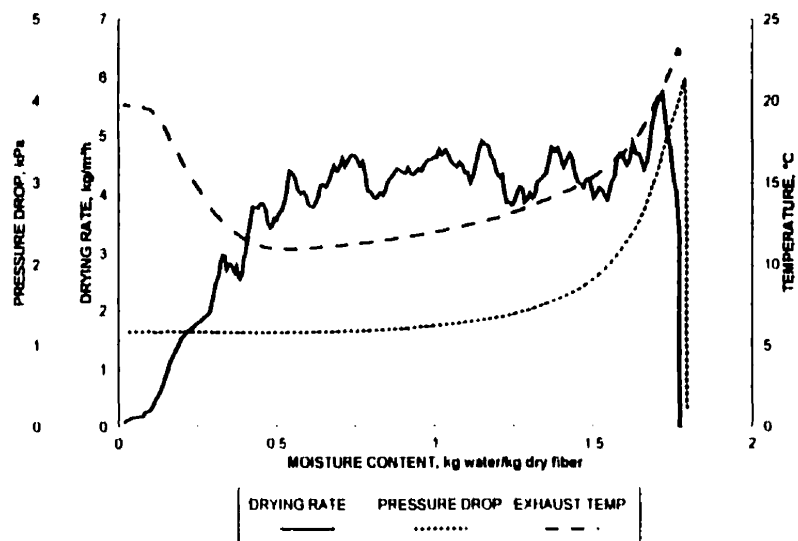
KRAFT HANDSHEET, RETENTION TIME 10s, B=60 g/m², Ti=60.0°C, G=0.402kg/m²s



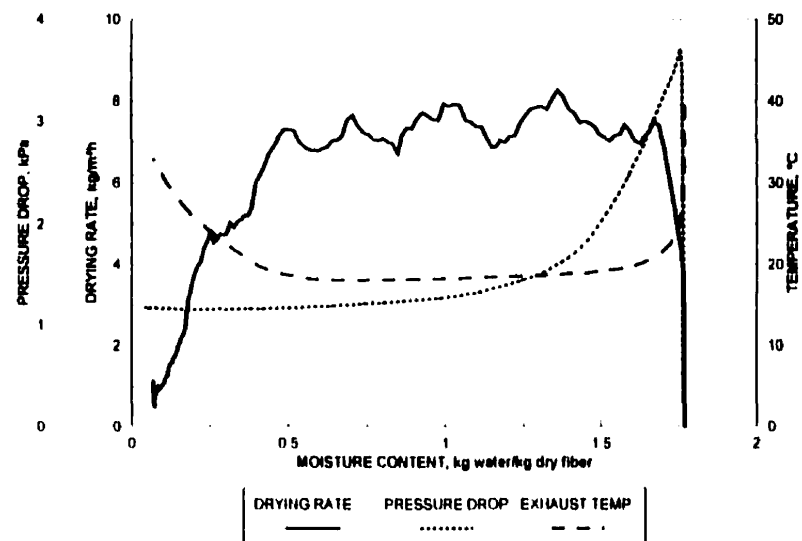
KRAFT HANDSHEET, RETENTION TIME 10s, B=60 g/m², Ti=80.3°C, G=0.402kg/m²s



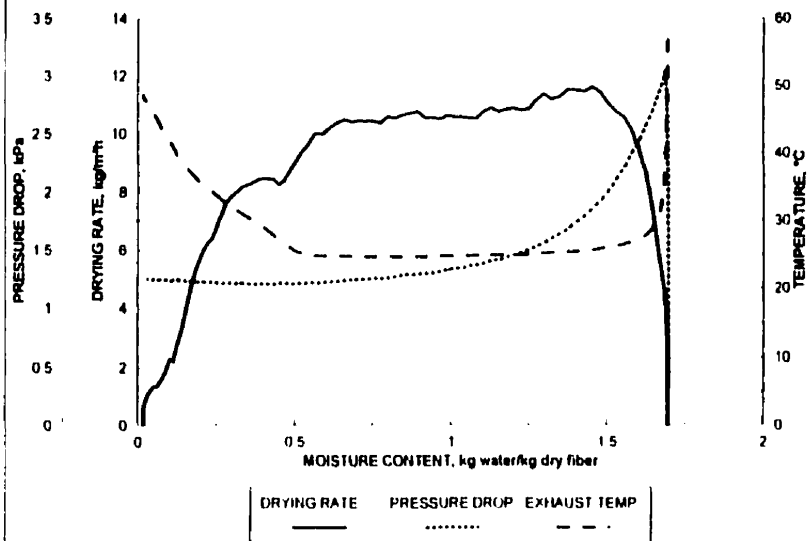
KRAFT HANDSHEET, RETENTION TIME 100s, B=60 g/m², Tl=22.7°C, G=0.207kg/m²s



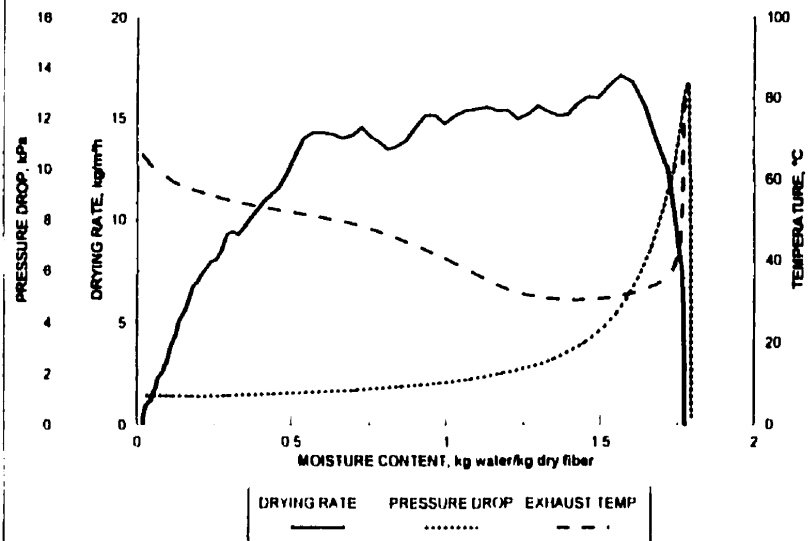
KRAFT HANDSHEET, RETENTION TIME 100s, B=60 g/m², Tl=41.1°C, G=0.207kg/m²s



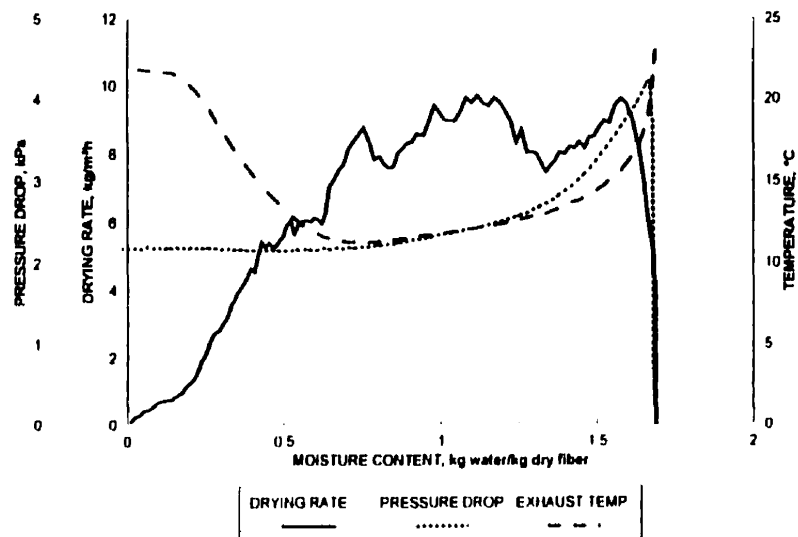
KRAFT HANDSHEET, RETENTION TIME 100s, B=60 g/m², Tl=62.7°C, G=0.207kg/m²s



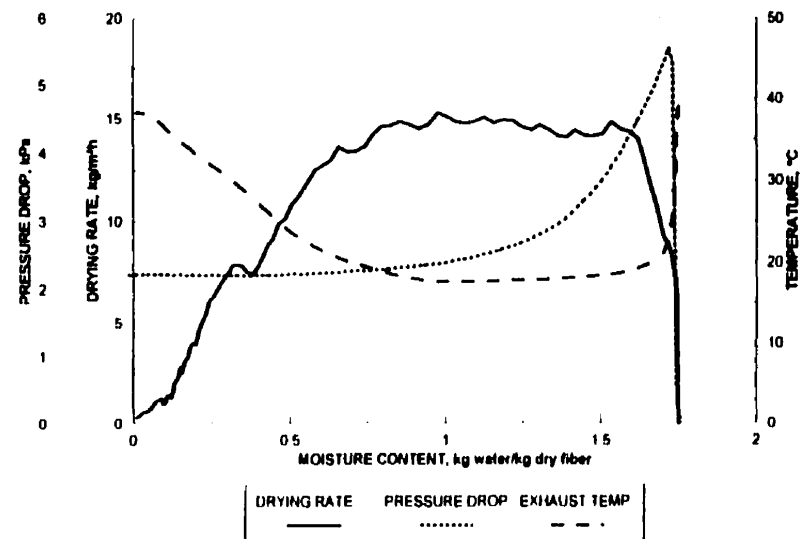
KRAFT HANDSHEET, RETENTION TIME 100s, B=60 g/m², Tl=84.9°C, G=0.207kg/m²s



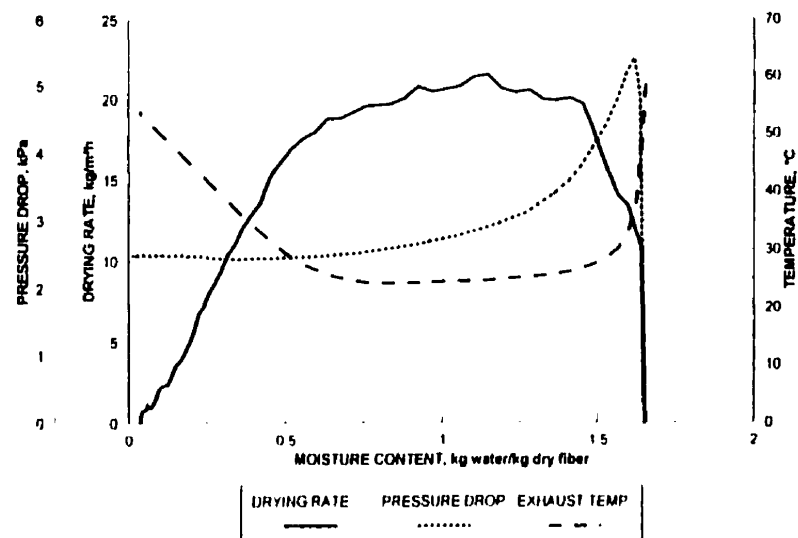
KRAFT HANDSHEET, RETENTION TIME 100s, B=60 g/m², T_i=23.1°C, G=0.402kg/m²s



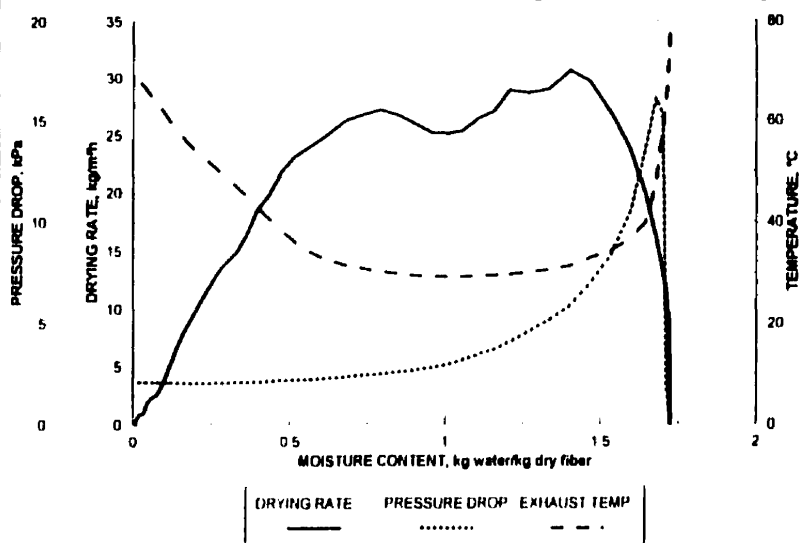
KRAFT HANDSHEET, RETENTION TIME 100s, B=60 g/m², T_i=40.7°C, G=0.402kg/m²s



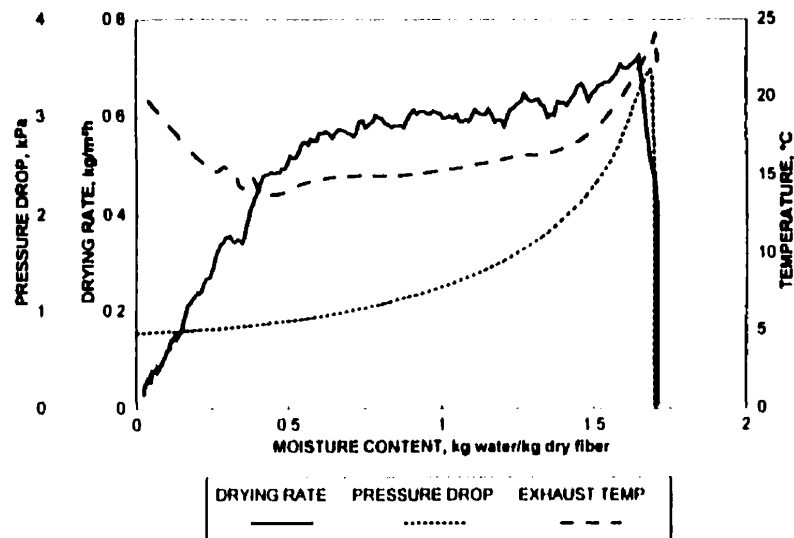
KRAFT HANDSHEET, RETENTION TIME 100s, B=60 g/m², T_i=60.6°C, G=0.402kg/m²s



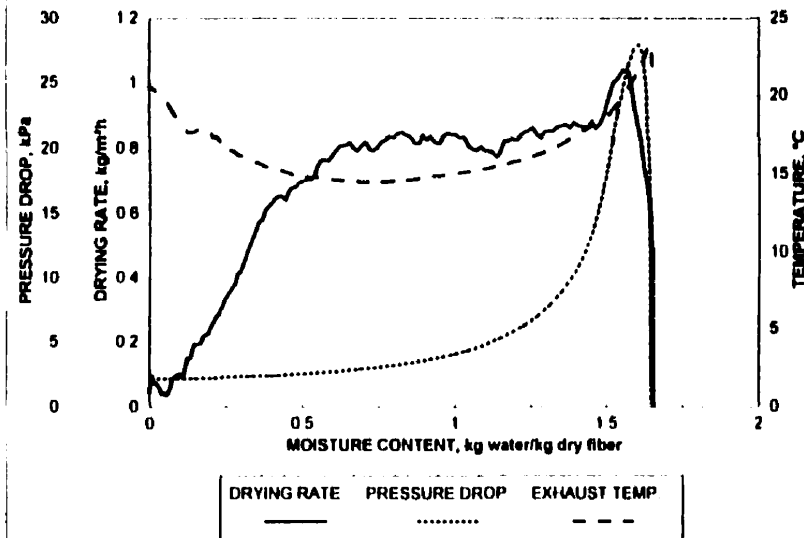
KRAFT HANDSHEET, RETENTION TIME 100s, B=60 g/m², T_i=79.4°C, G=0.402kg/m²s



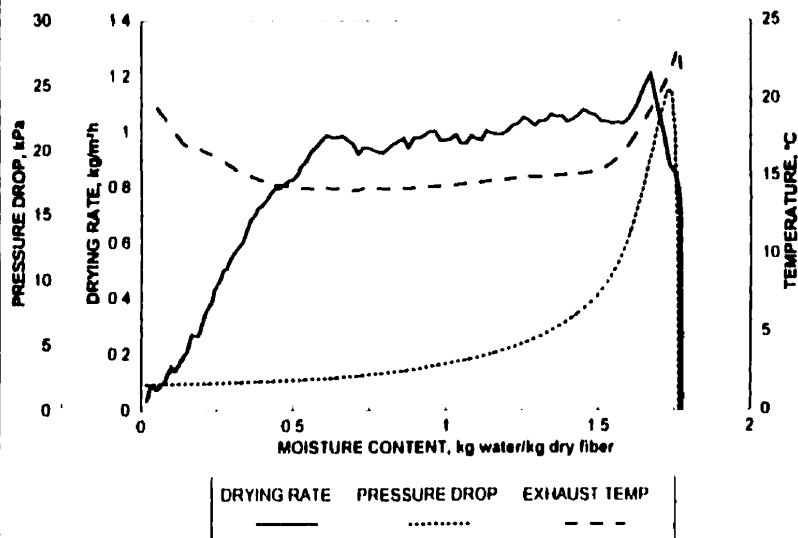
HANDSHEET FROM TMP WITH FINES, B=59.639g/m², Tl=22.0°C, G=0.0246kg/m²s



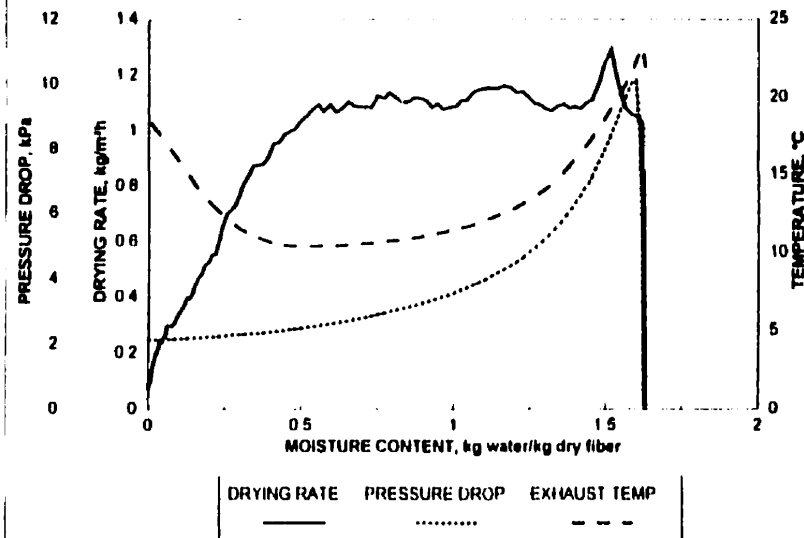
HANDSHEET FROM TMP WITH FINES, B=59.639g/m², Tl=21.0°C, G=0.0362kg/m²s



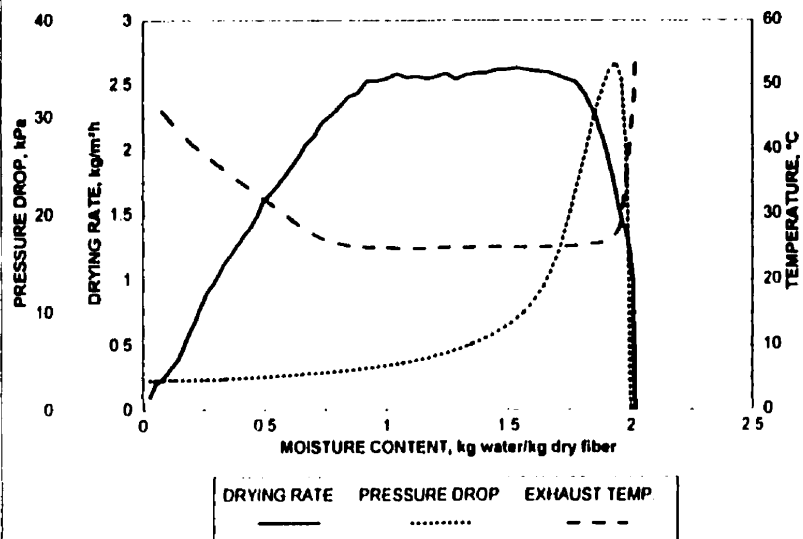
HANDSHEET FROM TMP WITH FINES, B=59.639g/m², Tl=21.0°C, G=0.0444kg/m²s



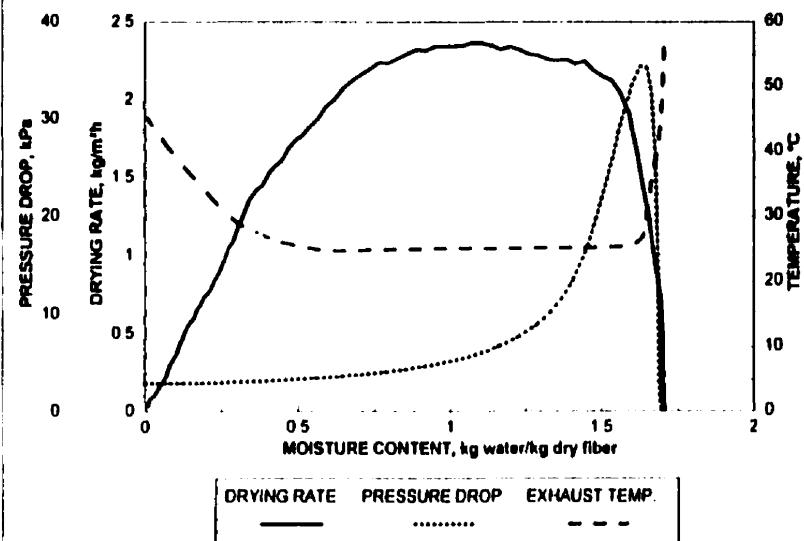
HANDSHEET FROM TMP WITH FINES, B=59.639g/m², Tl=21.0°C, G=0.051kg/m²s



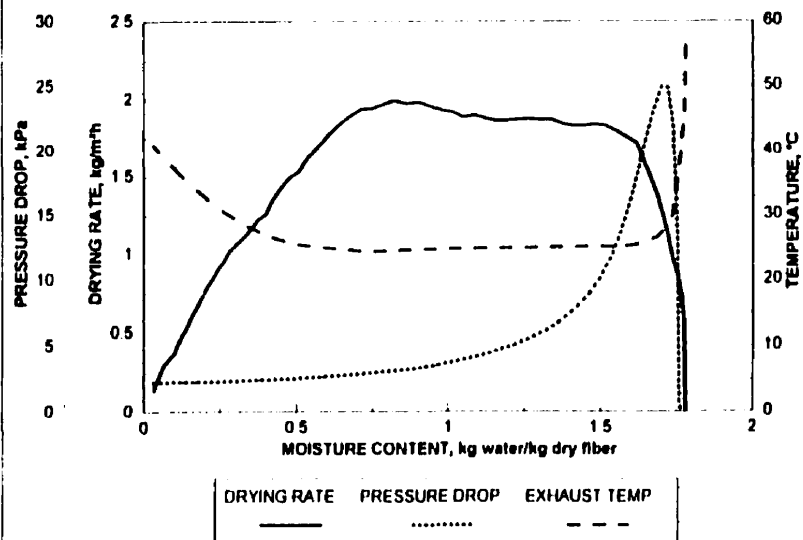
HANDSHEET FROM TMP WITH FINES, $B=59.639\text{g/m}^3$, $T_i=62.0^\circ\text{C}$, $G=0.051\text{kg/m}^3\text{s}$



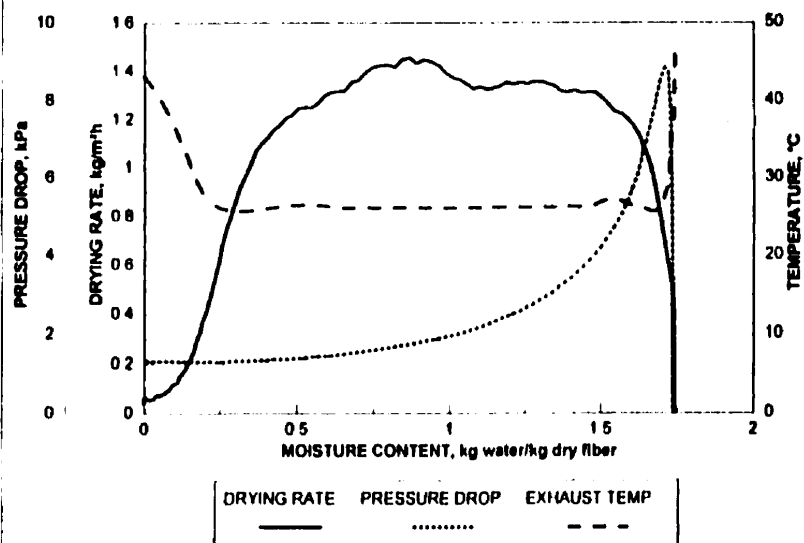
HANDSHEET FROM TMP WITH FINES, $B=59.639\text{g/m}^3$, $T_i=62.0^\circ\text{C}$, $G=0.0444\text{kg/m}^3\text{s}$



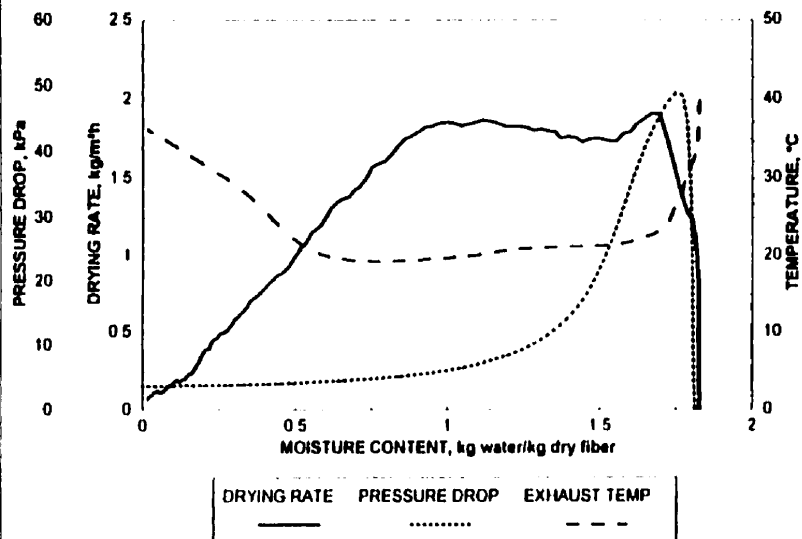
HANDSHEET FROM TMP WITH FINES, $B=59.639\text{g/m}^3$, $T_i=61.5^\circ\text{C}$, $G=0.0362\text{kg/m}^3\text{s}$



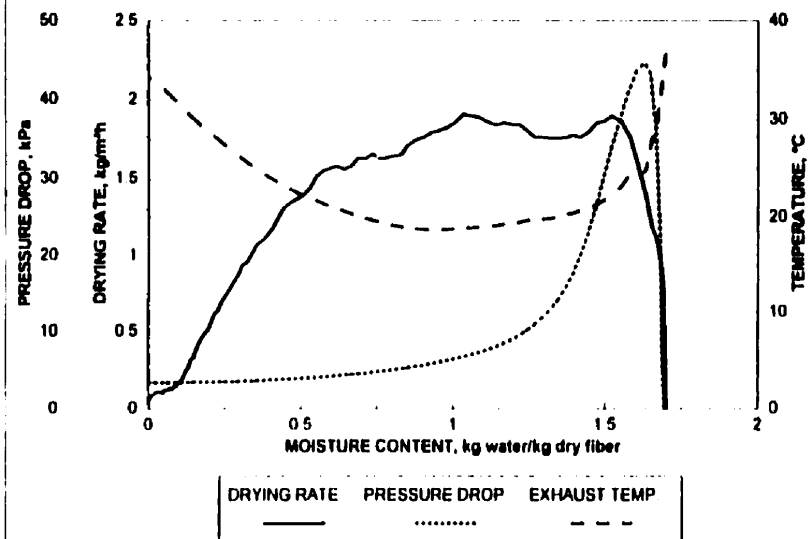
HANDSHEET FROM TMP WITH FINES, $B=59.639\text{g/m}^3$, $T_i=61.0^\circ\text{C}$, $G=0.0246\text{kg/m}^3\text{s}$



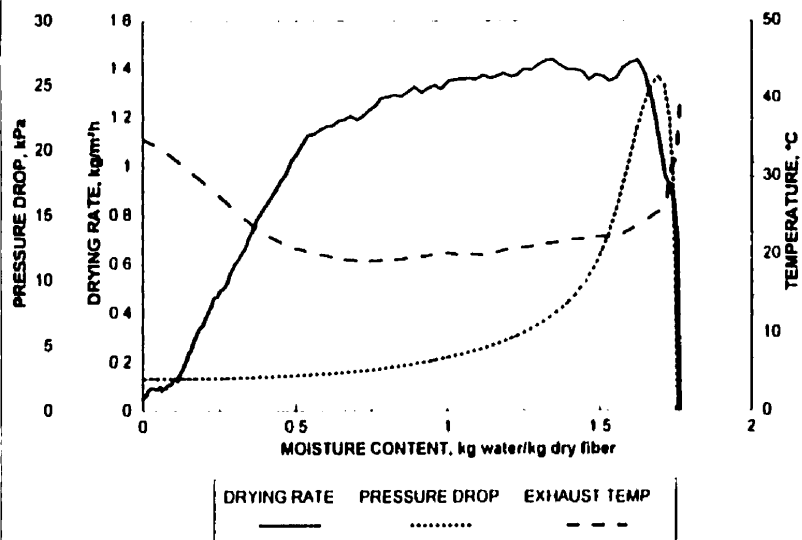
HANDSHEET FROM TMP WITH FINES, $B=59.639\text{g/m}^3$, $T_i=43.0^\circ\text{C}$, $G=0.051\text{kg/m}^3\text{s}$



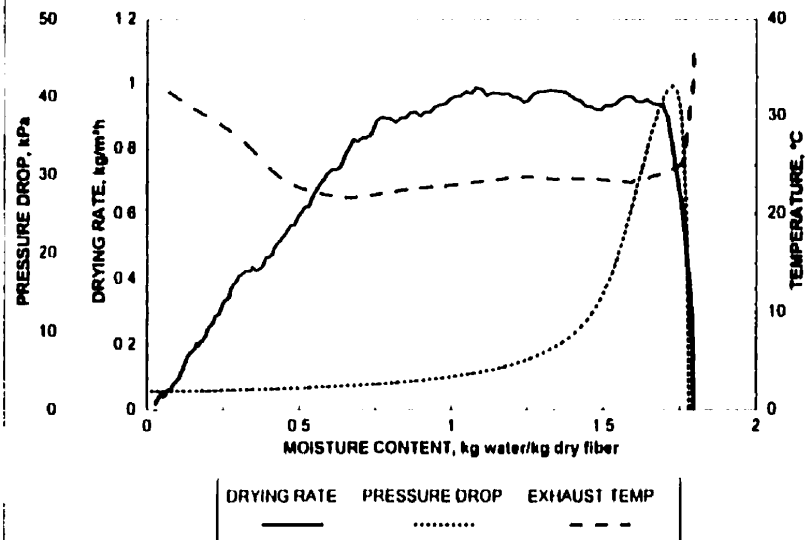
HANDSHEET FROM TMP WITH FINES, $B=59.639\text{g/m}^3$, $T_i=^\circ\text{C}$, $G=0.0\text{kg/m}^3\text{s}$



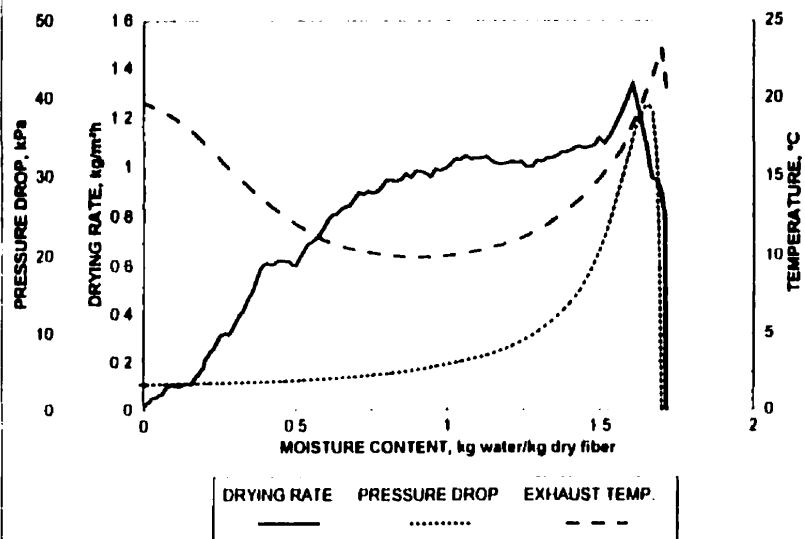
HANDSHEET FROM TMP WITH FINES, $B=59.639\text{g/m}^3$, $T_i=41.0^\circ\text{C}$, $G=0.0362\text{kg/m}^3\text{s}$



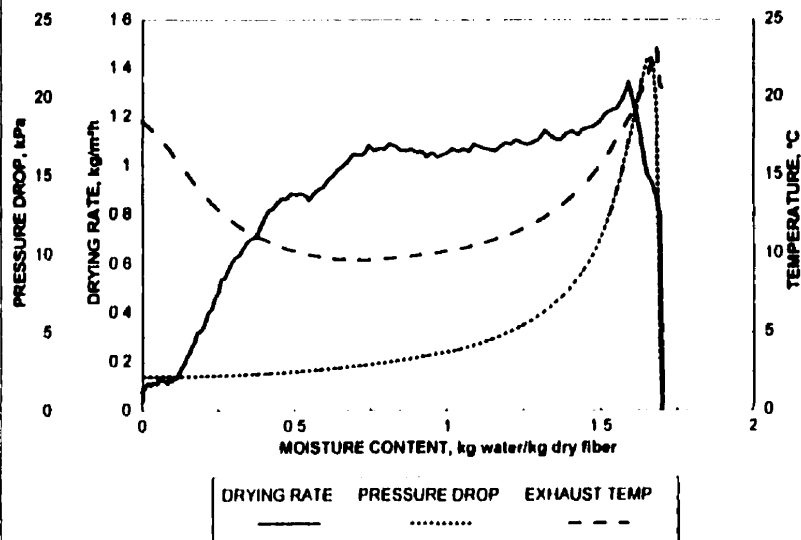
HANDSHEET FROM TMP WITH FINES, $B=59.639\text{g/m}^3$, $T_i=41.0^\circ\text{C}$, $G=0.0246\text{kg/m}^3\text{s}$



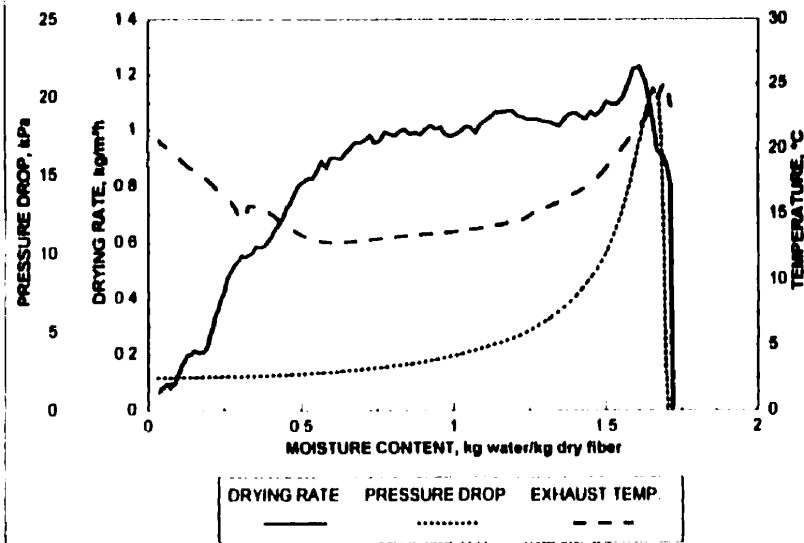
HANDSHEET FROM TMP WITH FINES, $B=59.638\text{g/m}^2$, $T_i=20.0^\circ\text{C}$, $G=0.051\text{kg/m}^2\text{s}$



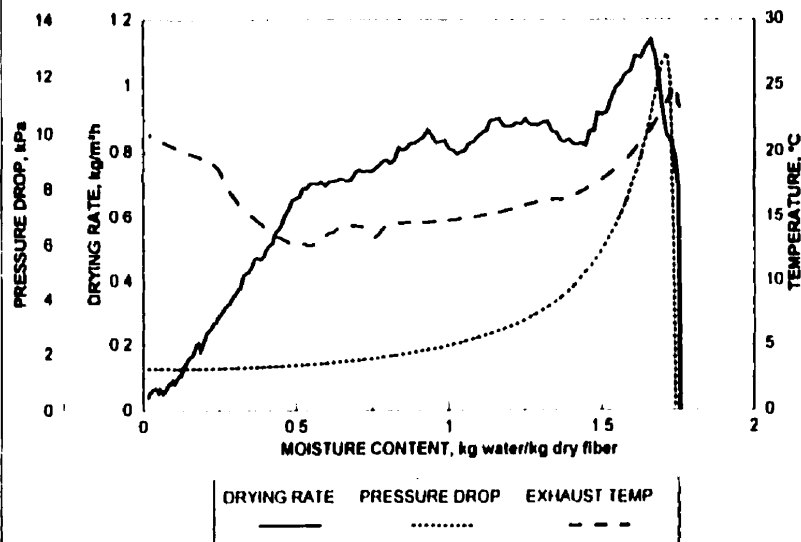
HANDSHEET FROM TMP NO FINES, B=59.639g/m², Ti=23.0°C, G=0.051kg/m²s



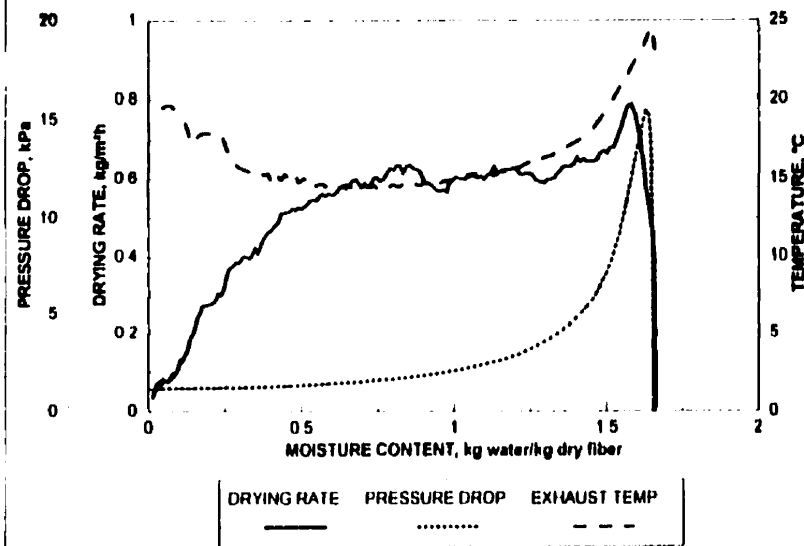
HANDSHEET FROM TMP NO FINES, B=59.639g/m², Ti=23.0°C, G=0.0444kg/m²s



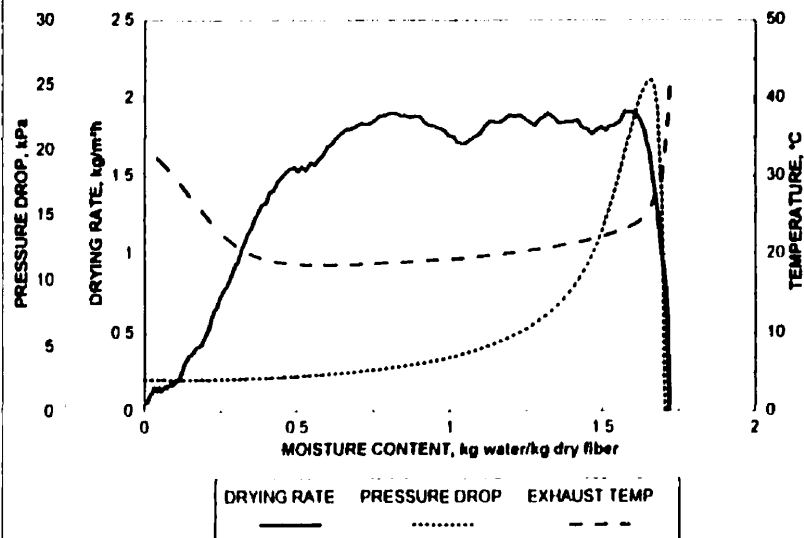
HANDSHEET FROM TMP NO FINES, B=59.639g/m², Ti=23.0°C, G=0.0362kg/m²s



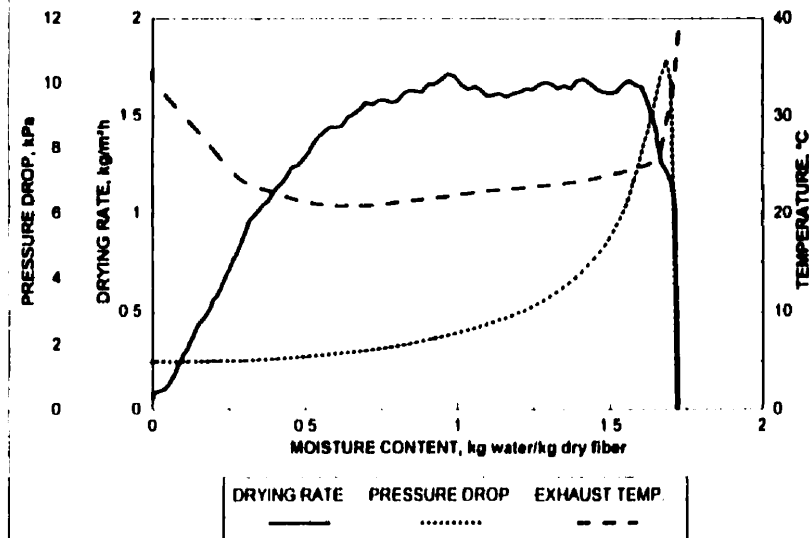
HANDSHEET FROM TMP NO FINES, B=59.639g/m², Ti=22.5°C, G=0.0248kg/m²s



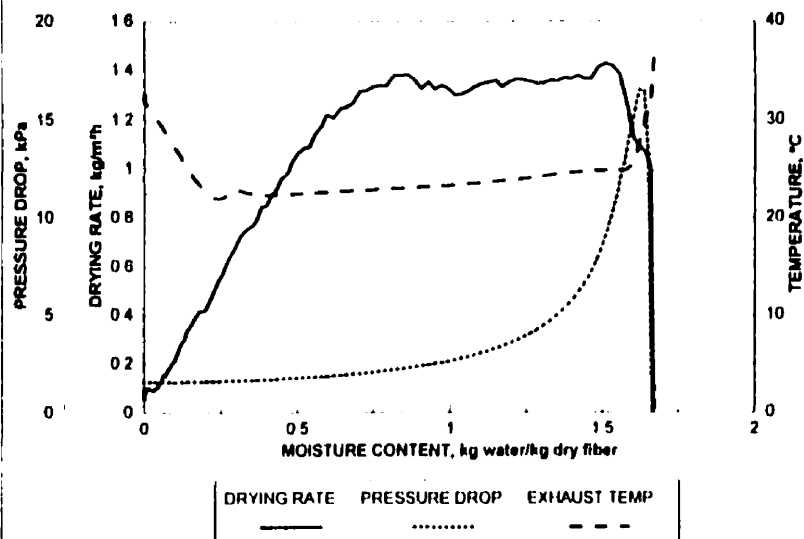
HANDSHEET FROM TMP NO FINES, B=59.639g/m², Ti=42.5°C, G=0.051kg/m²s



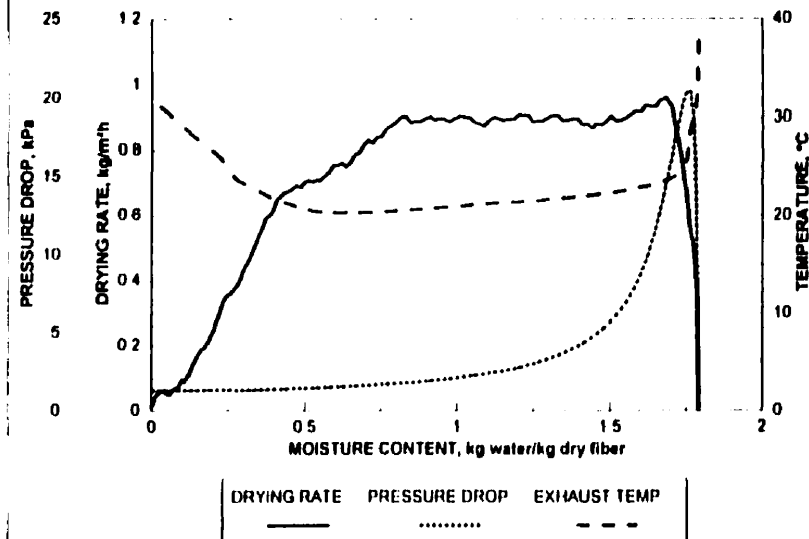
HANDSHEET FROM TMP NO FINES, B=59.639g/m², Ti=43.0°C, G=0.0444kg/m²s



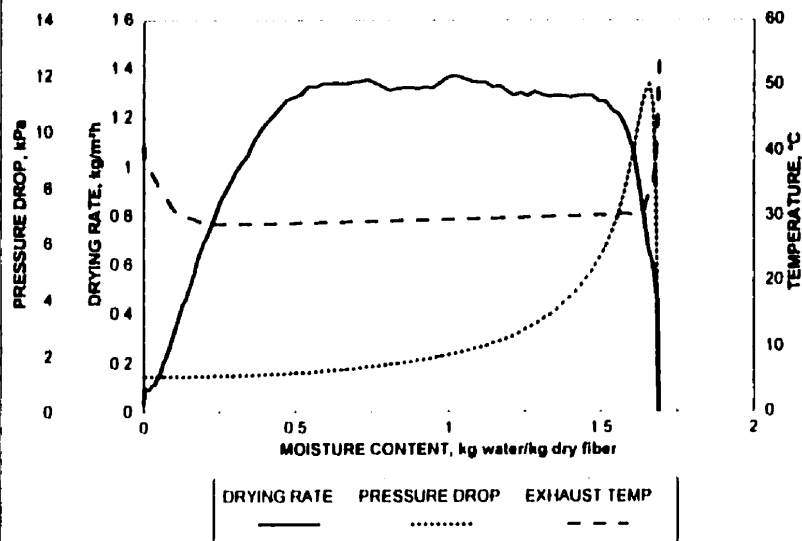
HANDSHEET FROM TMP NO FINES, B=59.639g/m², Ti=43.0°C, G=0.0362kg/m²s



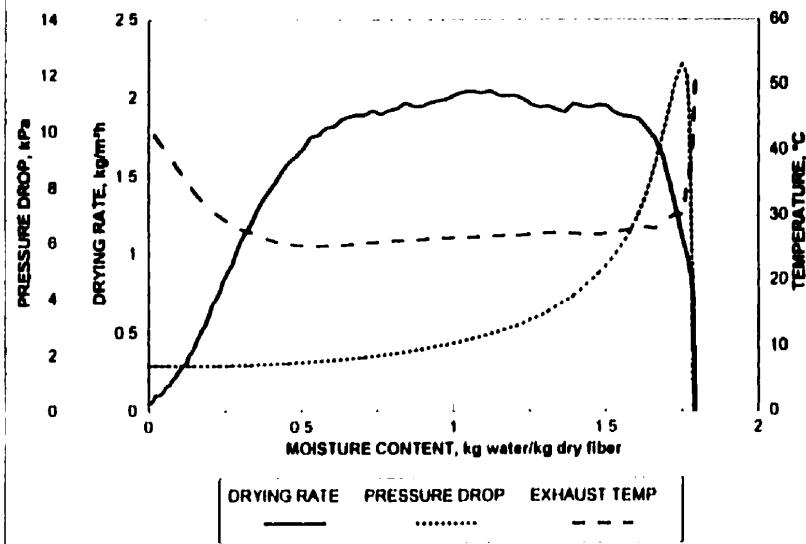
HANDSHEET FROM TMP NO FINES, B=59.639g/m², Ti=40.0°C, G=0.0246kg/m²s



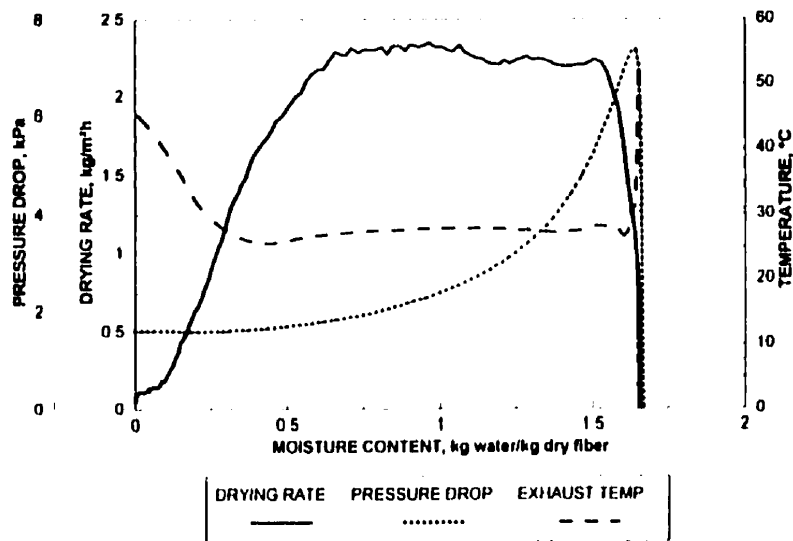
HANDSHEET FROM TMP NO FINES, B=59.639g/m², Tl=62.0°C, G=0.0246kg/m²s



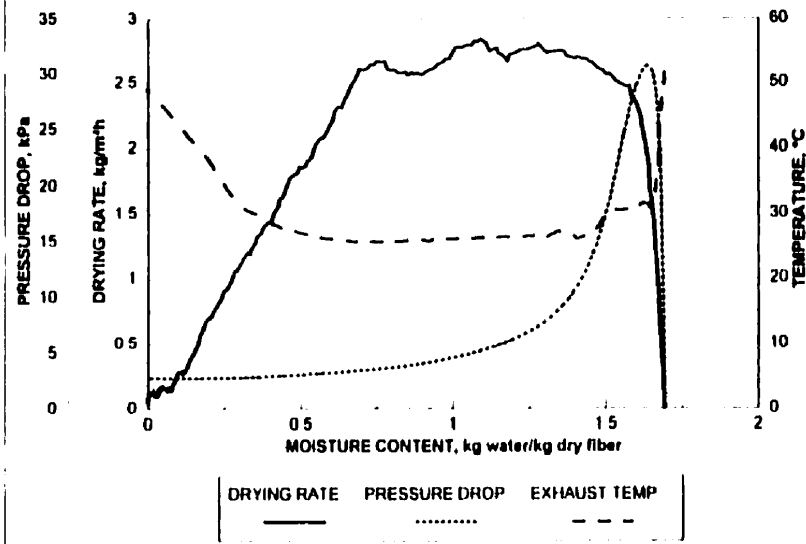
HANDSHEET FROM TMP NO FINES, B=59.639g/m², Tl=62.0°C, G=0.0362kg/m²s



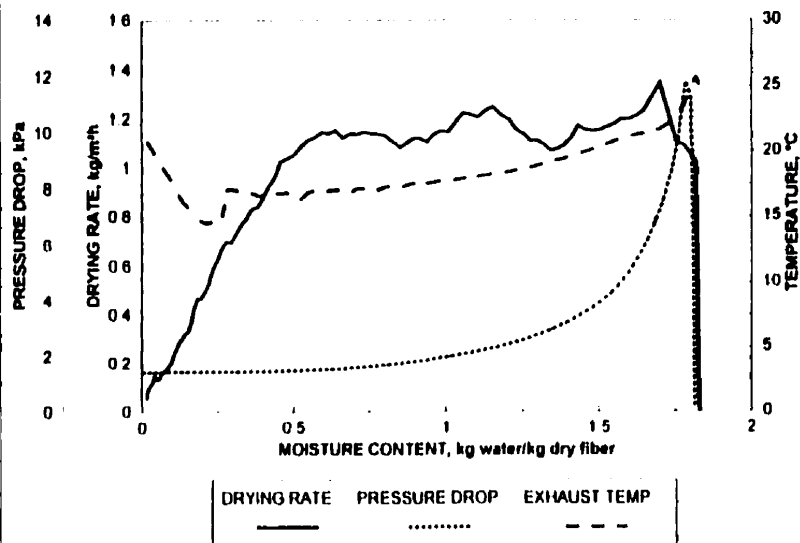
HANDSHEET FROM TMP NO FINES, B=59.639g/m², Tl=61.0°C, G=0.0444kg/m²s



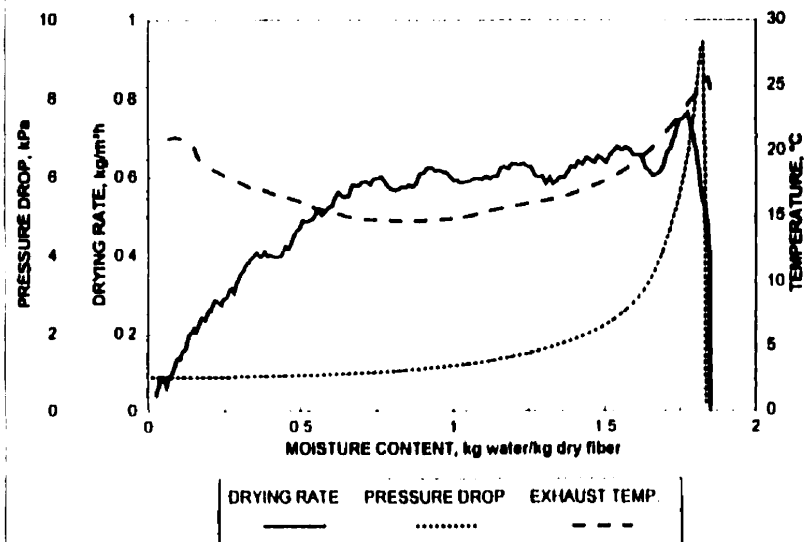
HANDSHEET FROM TMP NO FINES, B=59.639g/m², Tl=63.0°C, G=0.051kg/m²s



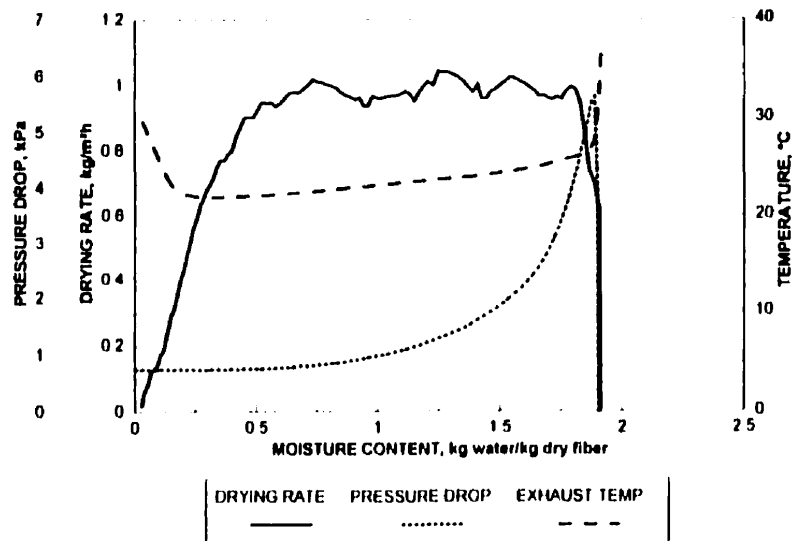
HANDSHEET FROM 76% TMP 25% KRAFT, B=55.780g/m², T_i=26.0°C, G=0.051kg/m²s



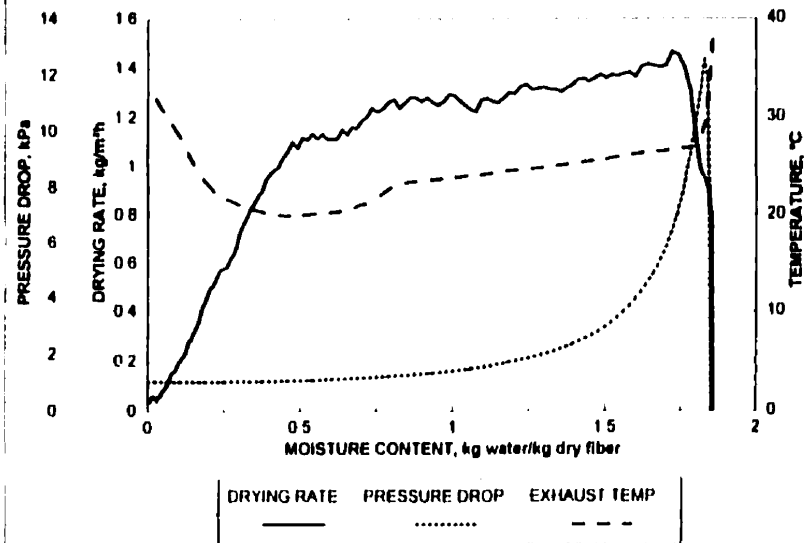
HANDSHEET FROM 76% TMP 25% KRAFT, B=55.780g/m², T_i=24.5°C, G=0.0246kg/m²s



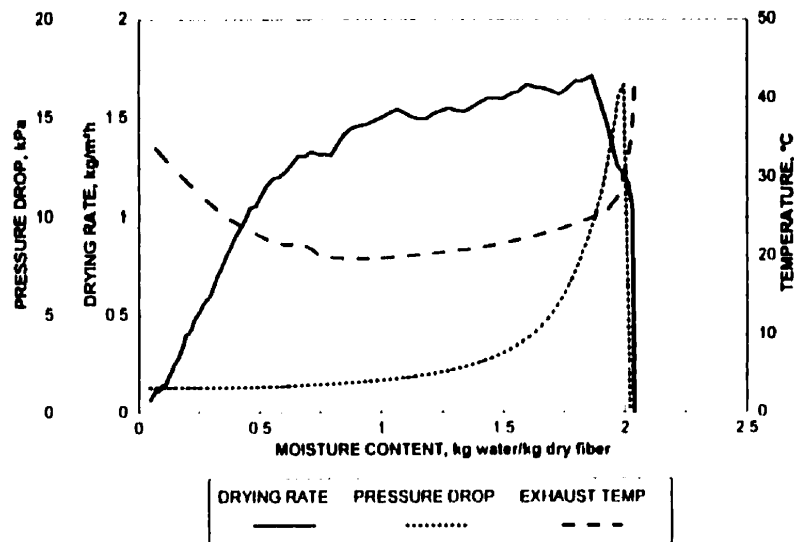
HANDSHEET FROM 76% TMP 25% KRAFT, B=55.780g/m², T_i=43.5°C, G=0.0246kg/m²s



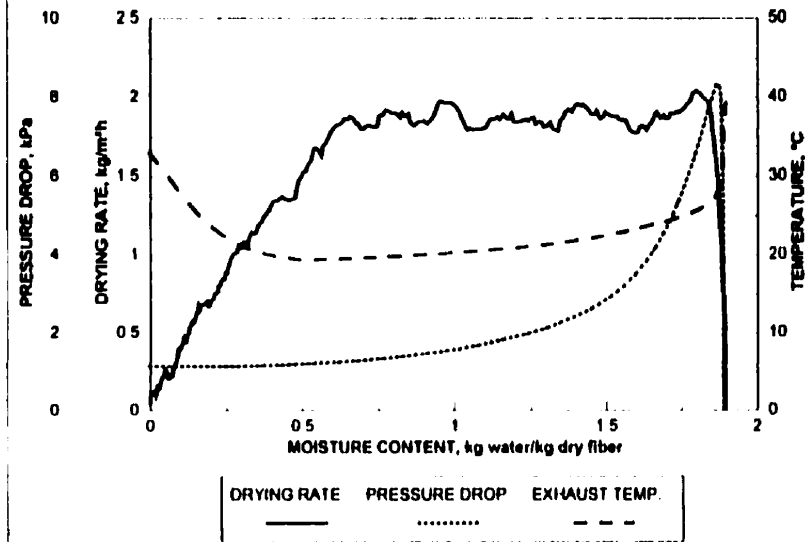
HANDSHEET FROM 76% TMP 25% KRAFT, B=55.780g/m², T_i=42.0°C, G=0.0362kg/m²s



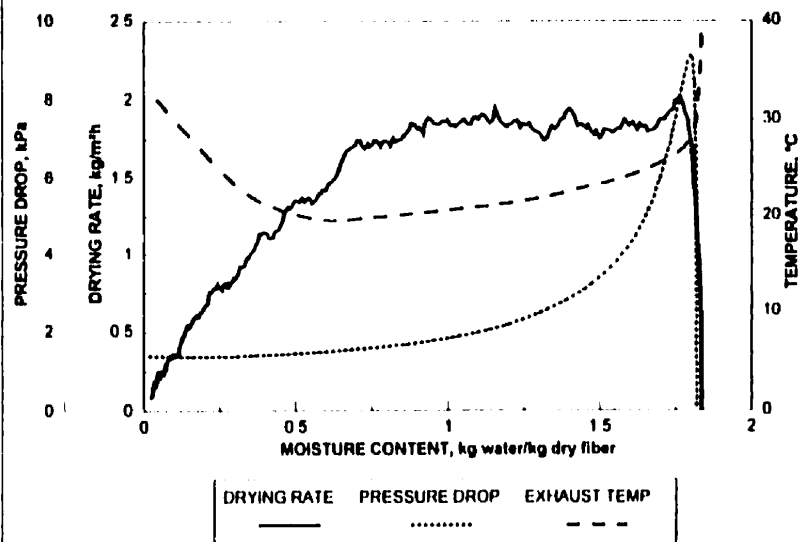
HANDSHEET FROM 75% TMP 25% KRAFT, B=55.780g/m², Tl=42.0°C, G=0.0444kg/m²s



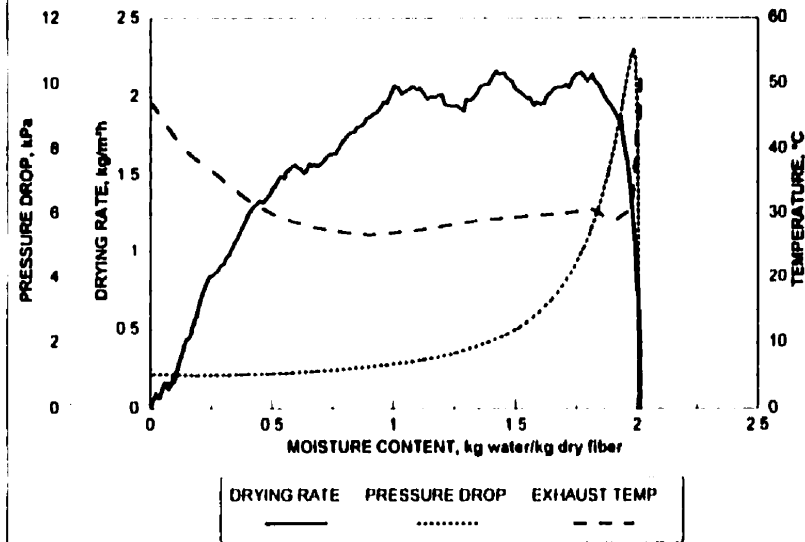
HANDSHEET FROM 75% TMP 25% KRAFT, B=55.780g/m², Tl=43.0°C, G=0.051kg/m²s



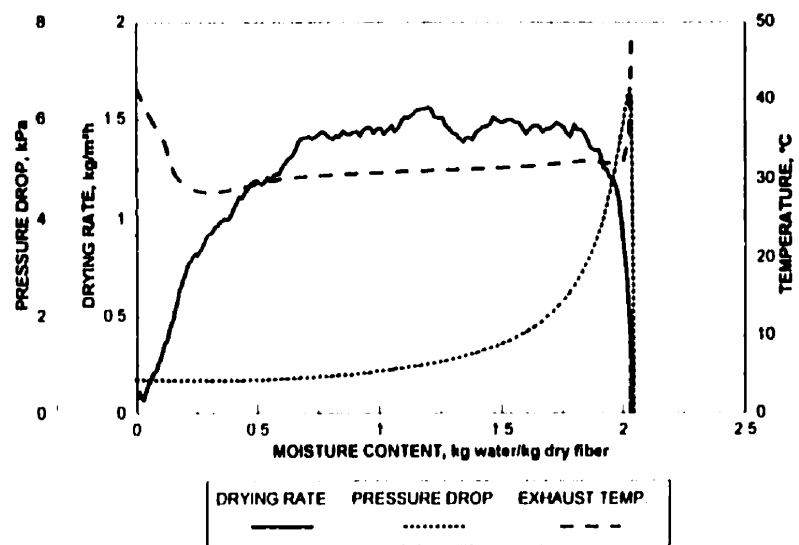
HANDSHEET FROM 75% TMP 25% KRAFT, B=55.780g/m², Tl=43.0°C, G=0.051kg/m²s



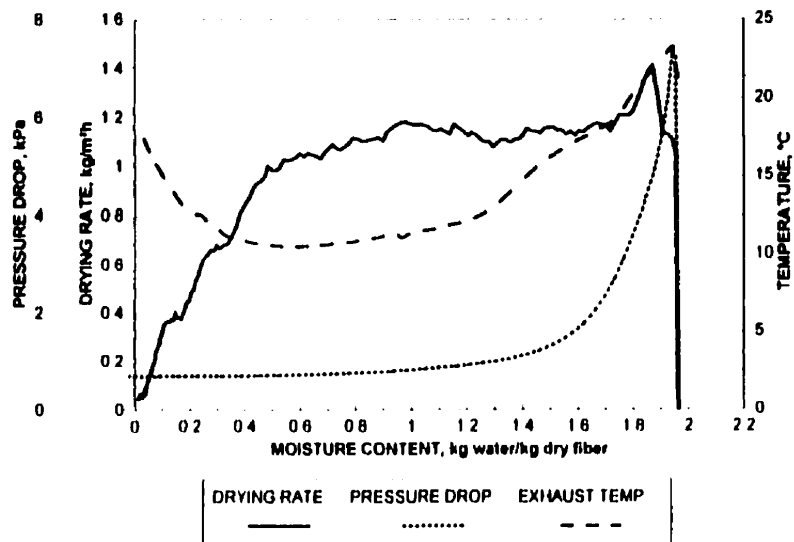
HANDSHEET FROM 75% TMP 25% KRAFT, B=55.780g/m², Tl=43.5°C, G=0.0362kg/m²s



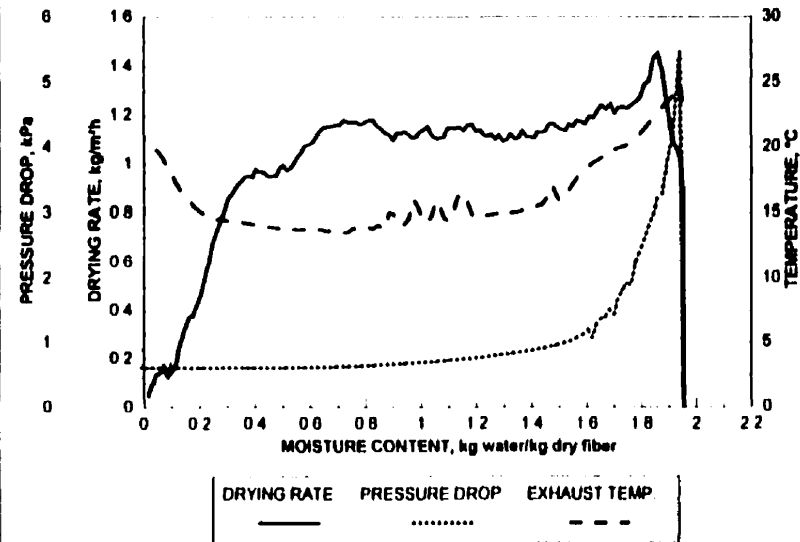
HANDSHEET FROM 76% TMP 25% KRAFT, B=65.780g/m², Tl=63°C, G=0.0246kg/m²s



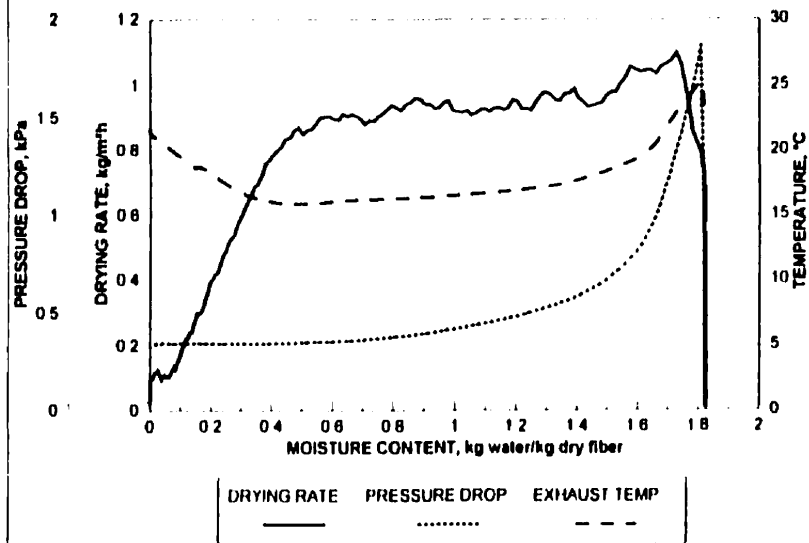
HANDSHEET FROM 50% TMP 50% KRAFT, B=55.443g/m², T_i=21°C, G=0.051kg/m²s



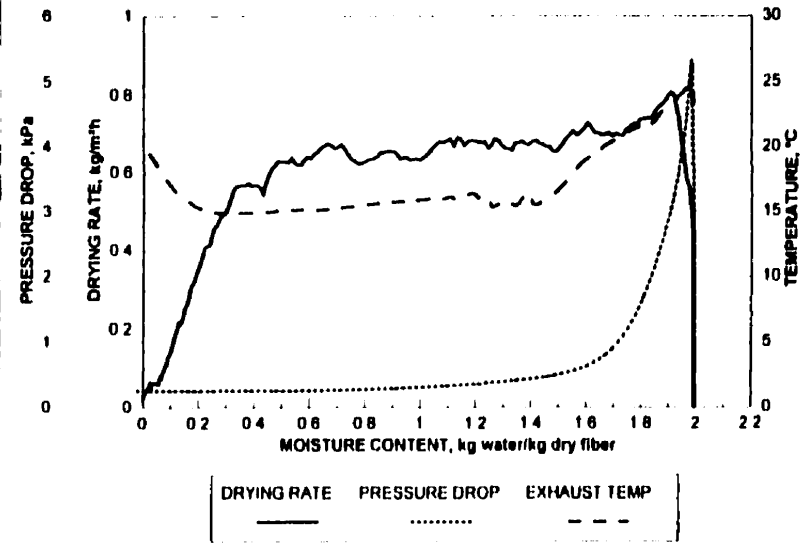
HANDSHEET FROM 50% TMP 50% KRAFT, B=55.443g/m², T_i=23.5°C, G=0.0444kg/m²s



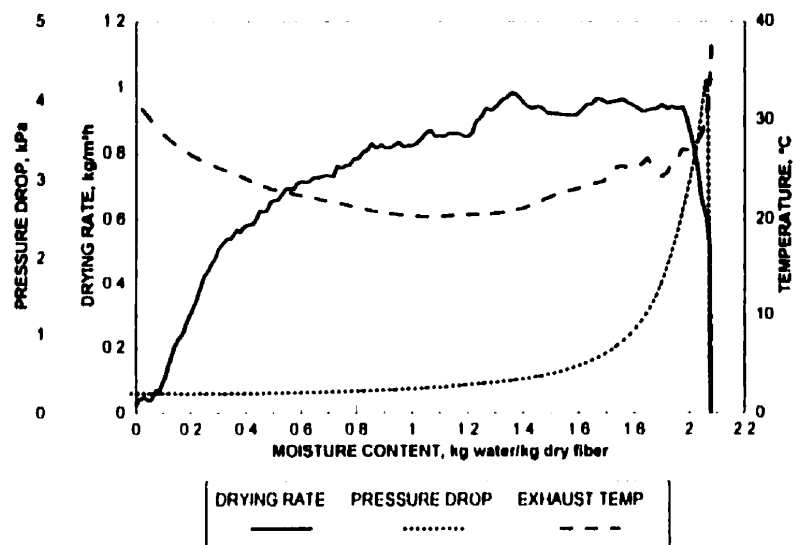
HANDSHEET FROM 50% TMP 50% KRAFT, B=55.443g/m², T_i=23.5°C, G=0.0362kg/m²s



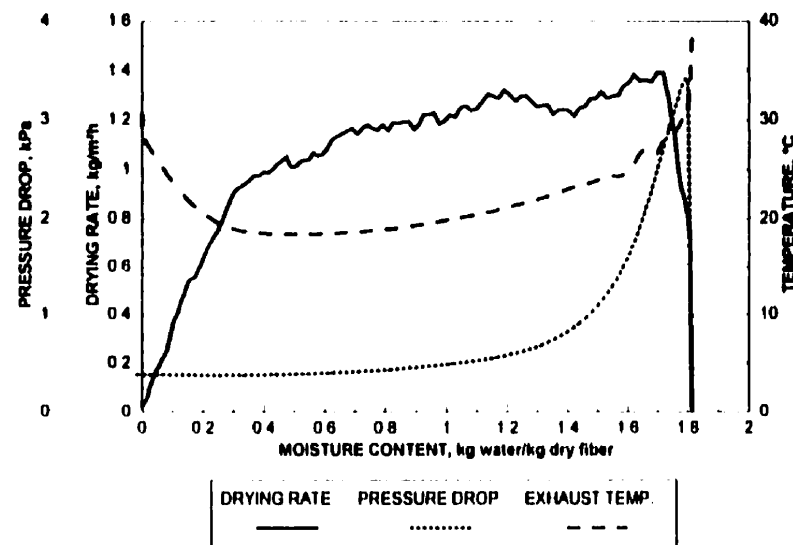
HANDSHEET FROM 50% TMP 50% KRAFT, B=55.443g/m², T_i=23.5°C, G=0.0246kg/m²s



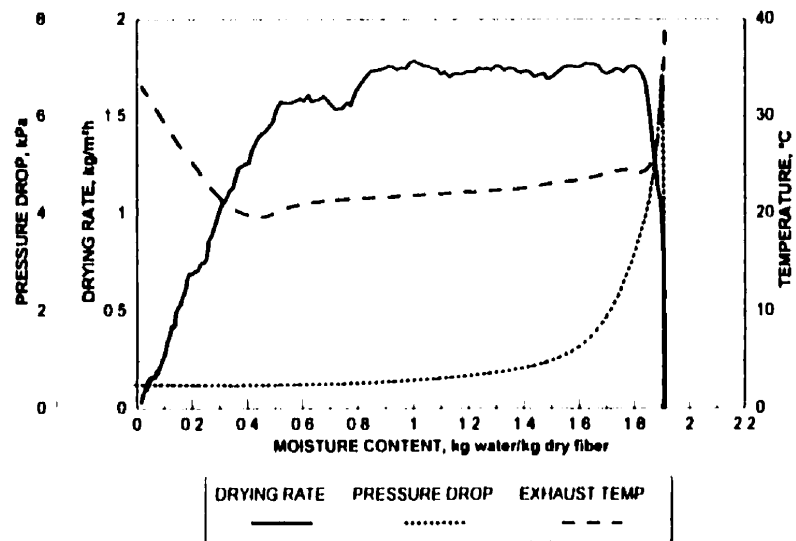
HANDSHEET FROM 50% TMP 50% KRAFT, B=55.537g/m², Tl=41°C, G=0.0248kg/m²s



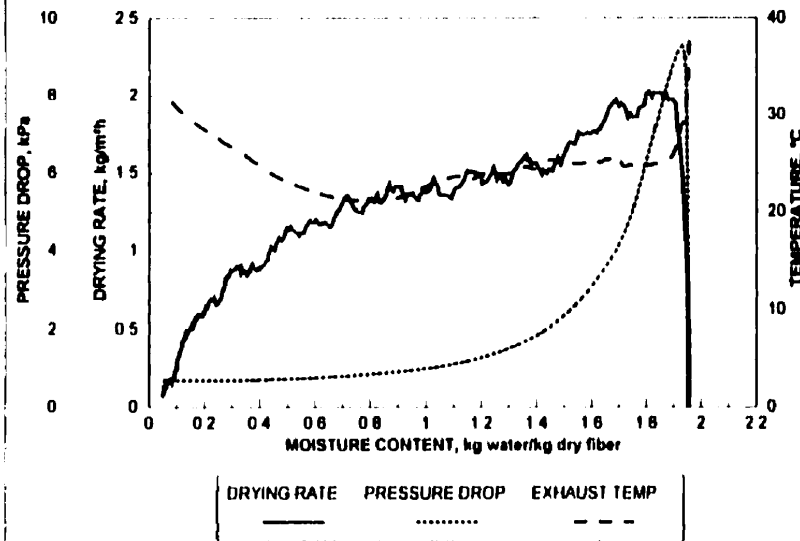
HANDSHEET FROM 50% TMP 50% KRAFT, B=55.537g/m², Tl=40.0°C, G=0.0382kg/m²s



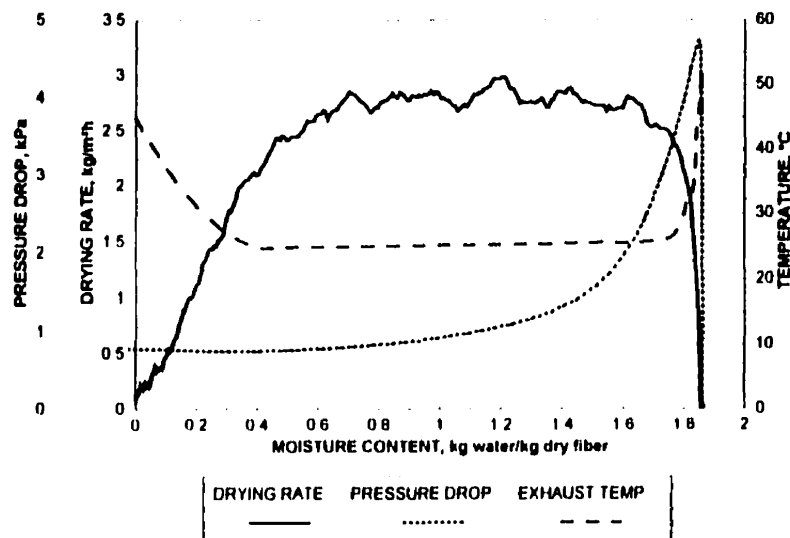
HANDSHEET FROM 50% TMP 50% KRAFT, B=55.537g/m², Tl=42.0°C, G=0.0444kg/m²s



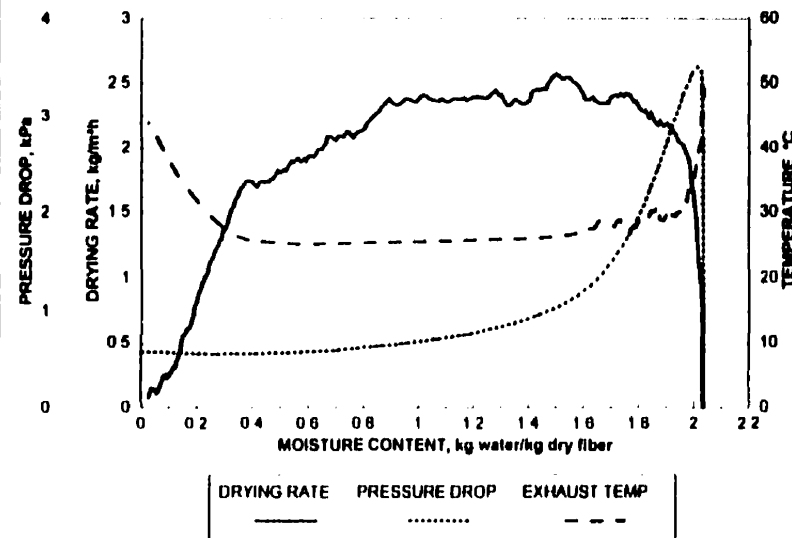
HANDSHEET FROM 50% TMP 50% KRAFT, B=55.537g/m², Tl=42.5°C, G=0.051kg/m²s



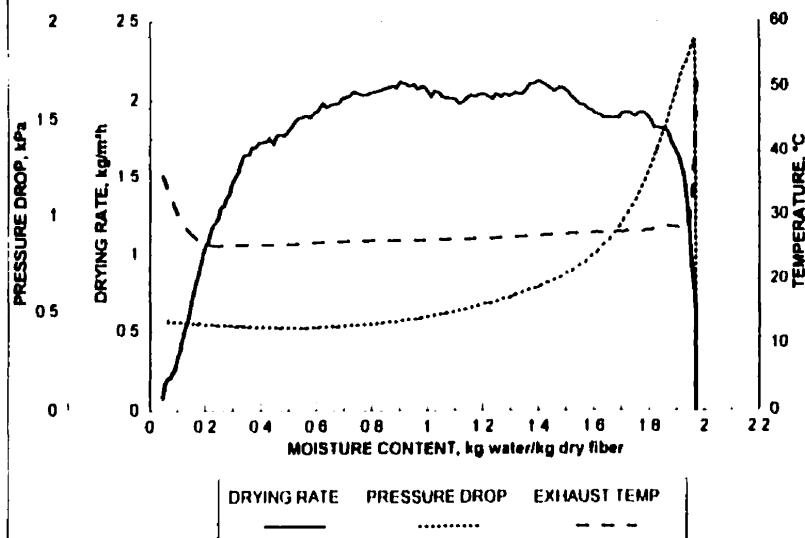
HANDSHEET FROM 60% TMP 60% KRAFT, B=55.537g/m², Tl=64.0°C, G=0.051kg/m²s



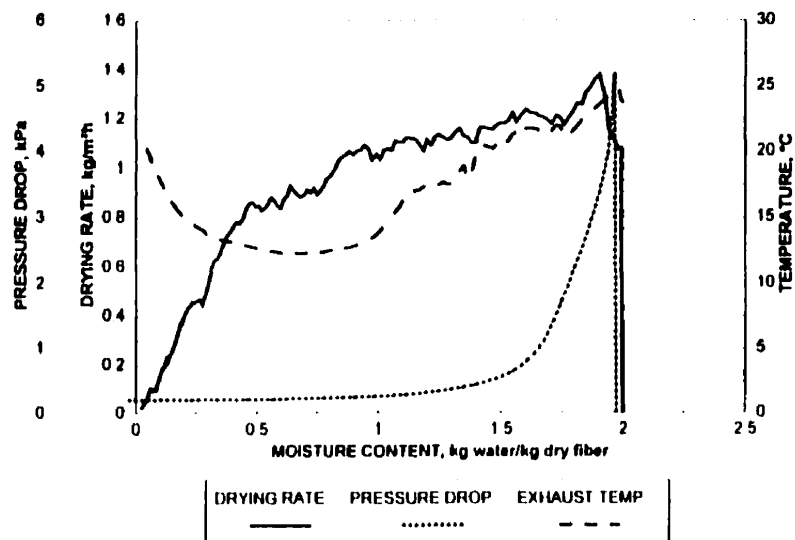
HANDSHEET FROM 60% TMP 60% KRAFT, B=55.537g/m², Tl=63.9°C, G=0.0444kg/m²s



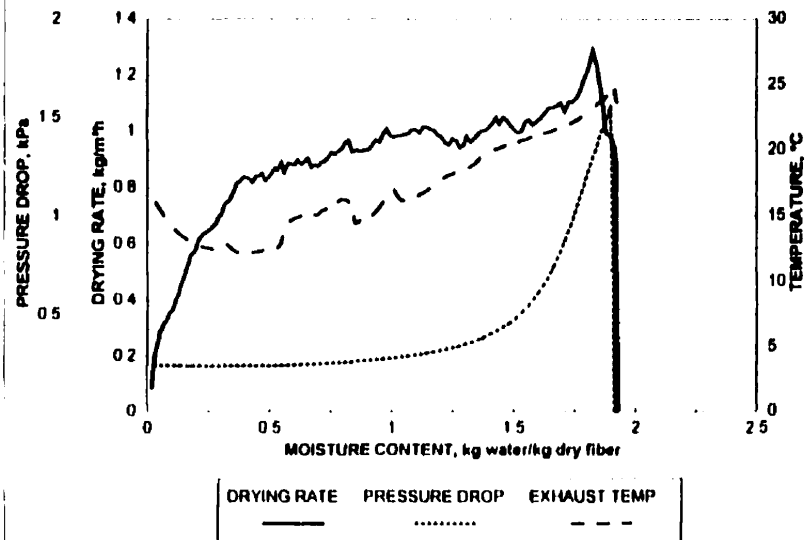
HANDSHEET FROM 60% TMP 60% KRAFT, B=55.537g/m², Tl=64.0°C, G=0.0362kg/m²s



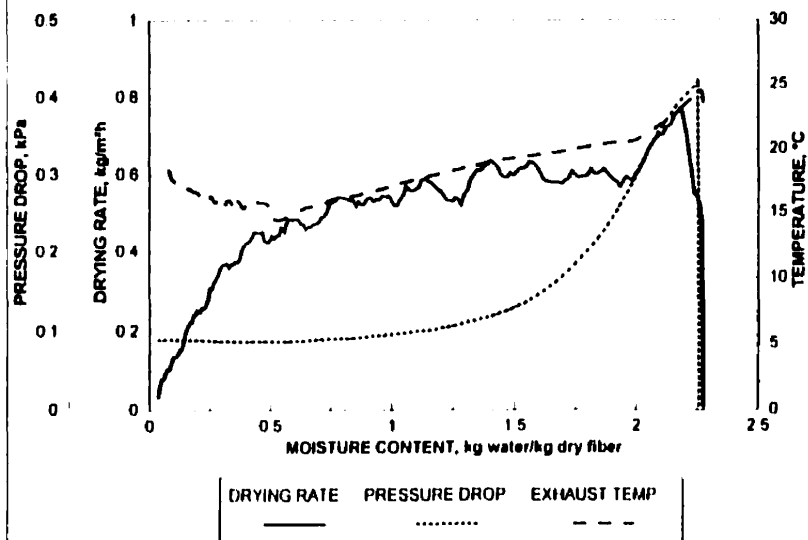
HANDSHEET FROM 26% TMP 76% KRAFT, B=55.443g/m², Tl=23.6°C, G=0.051kg/m²s



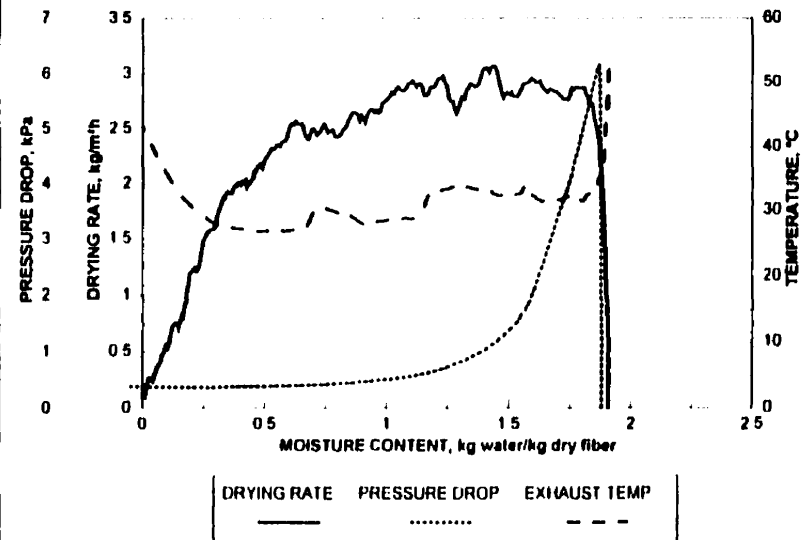
HANDSHEET FROM 26% TMP 76% KRAFT, B=55.443g/m², Tl=23.66°C, G=0.0444kg/m²s



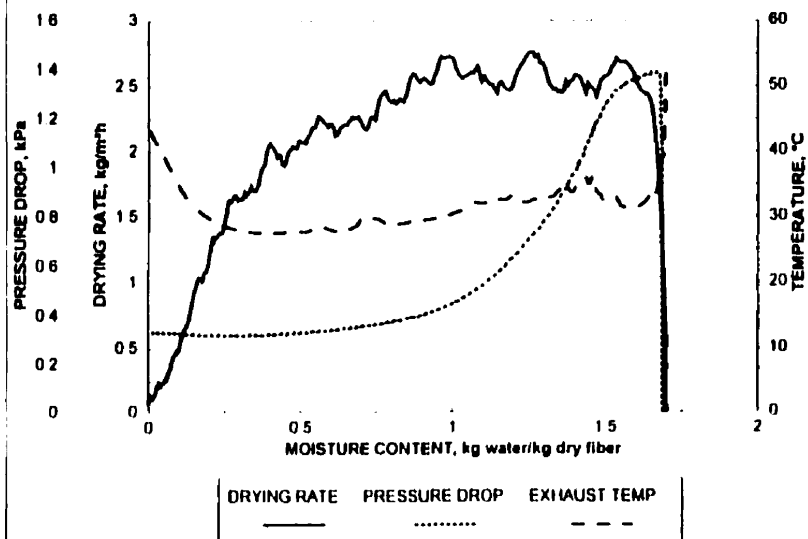
HANDSHEET FROM 26% TMP 76% KRAFT, B=55.443g/m², Tl=23.5°C, G=0.0244kg/m²s



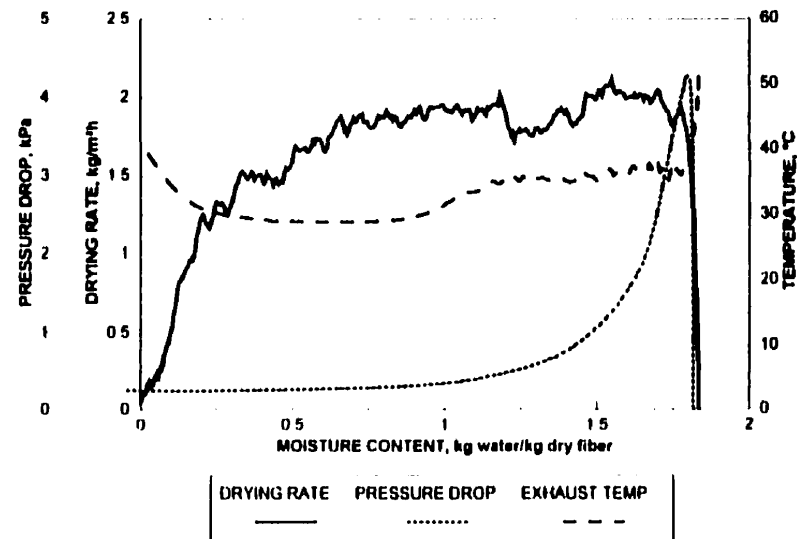
HANDSHEET FROM 26% TMP 76% KRAFT, B=55.443g/m², Tl=24.5°C, G=0.051kg/m²s



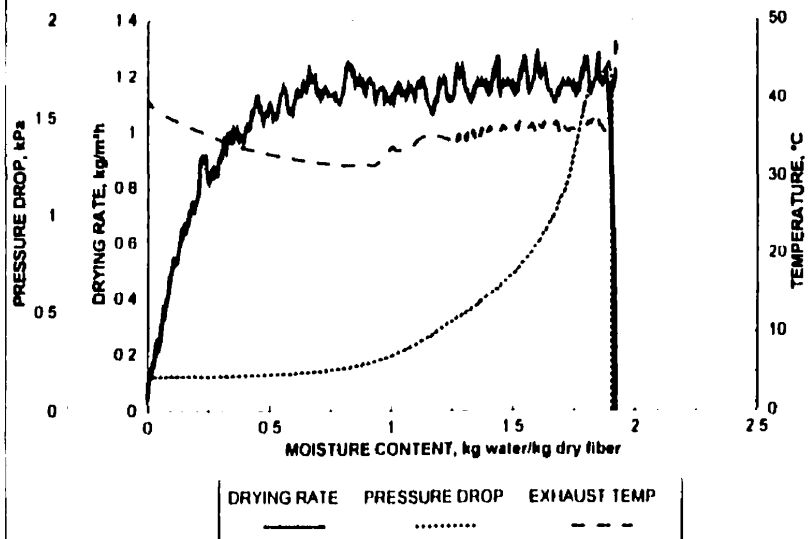
HANDSHEET FROM 25% TMP 75% KRAFT, $B=55.443\text{g/m}^3$, $T_i=63.0^\circ\text{C}$, $G=0.0444\text{kg/m}^3\text{s}$



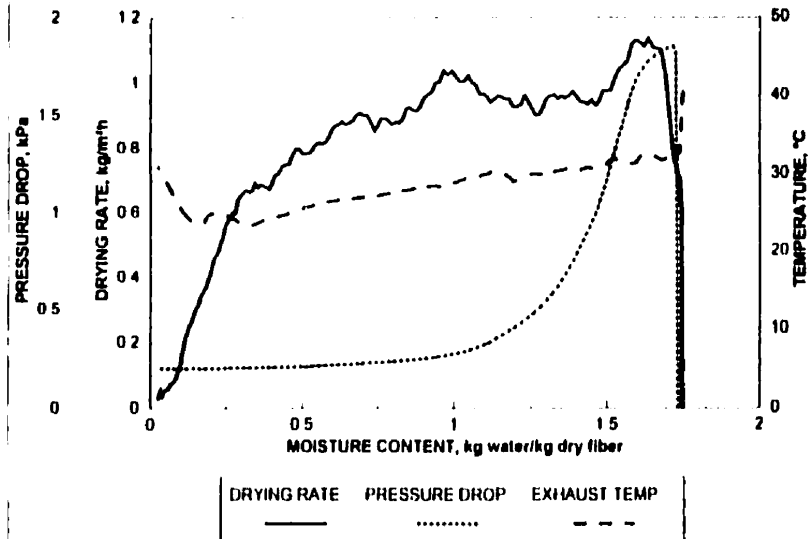
HANDSHEET FROM 25% TMP 75% KRAFT, $B=55.443\text{g/m}^3$, $T_i=62.3^\circ\text{C}$, $G=0.0362\text{kg/m}^3\text{s}$



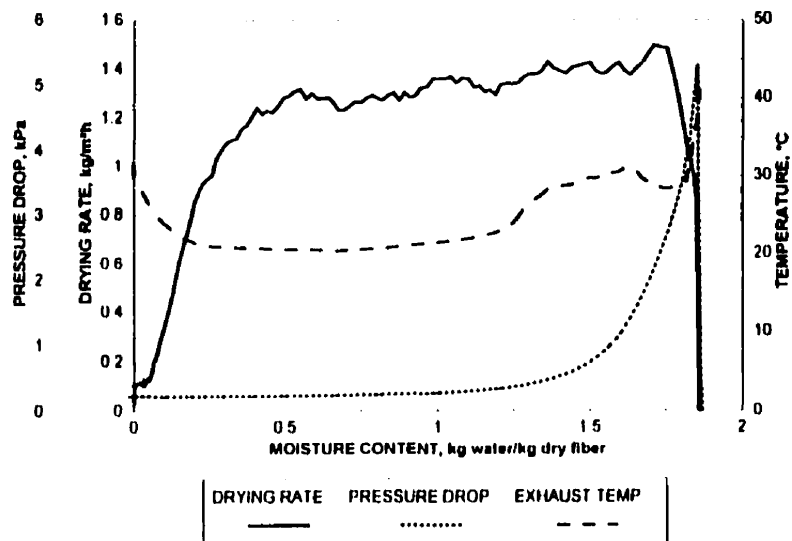
HANDSHEET FROM 25% TMP 75% KRAFT, $B=55.443\text{g/m}^3$, $T_i=60.0^\circ\text{C}$, $G=0.0246\text{kg/m}^3\text{s}$



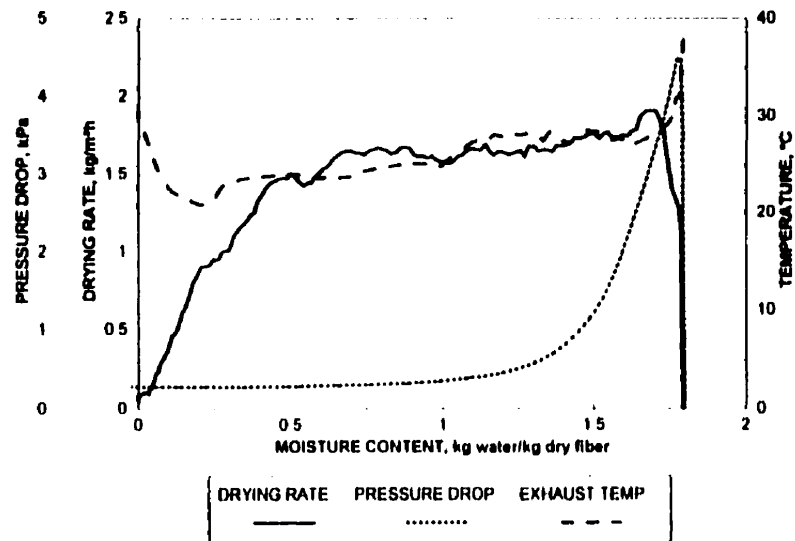
HANDSHEET FROM 25% TMP 75% KRAFT, $B=55.443\text{g/m}^3$, $T_i=40^\circ\text{C}$, $G=0.0246\text{kg/m}^3\text{s}$



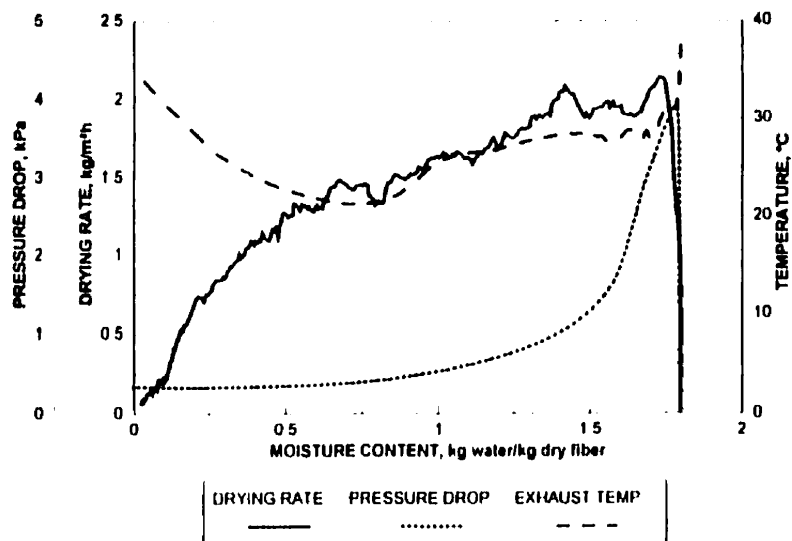
HANDSHEET FROM 25% TMP 75% KRAFT, B=65.443g/m², Tl=41.5°C, G=0.0362kg/m²s



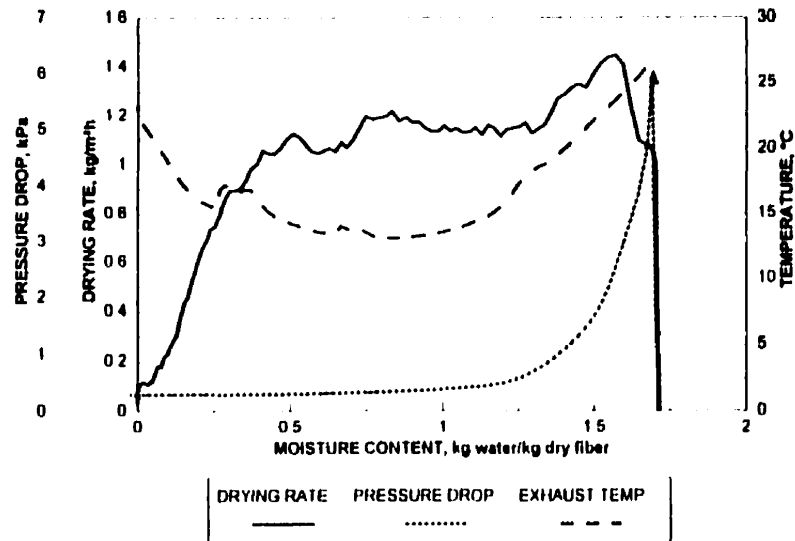
HANDSHEET FROM 25% TMP 75% KRAFT, B=65.443g/m², Tl=41.5°C, G=0.0444kg/m²s



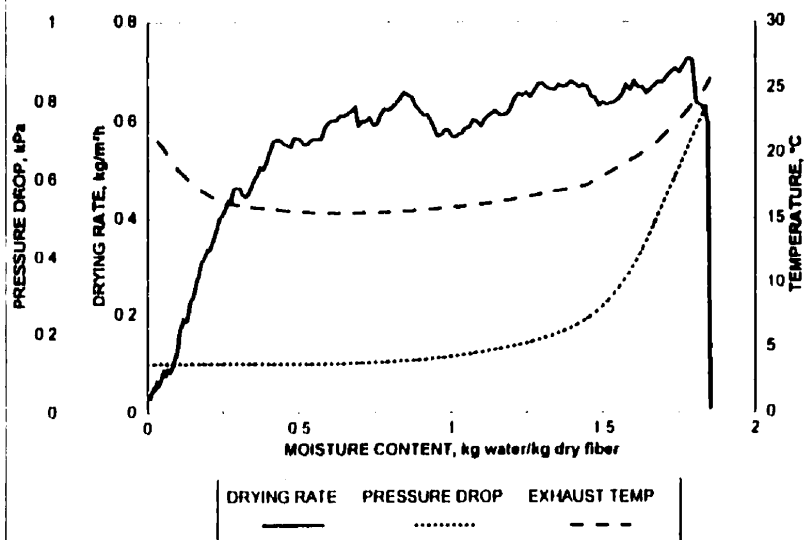
HANDSHEET FROM 25% TMP 75% KRAFT, B=65.443g/m², Tl=42.0°C, G=0.051kg/m²s



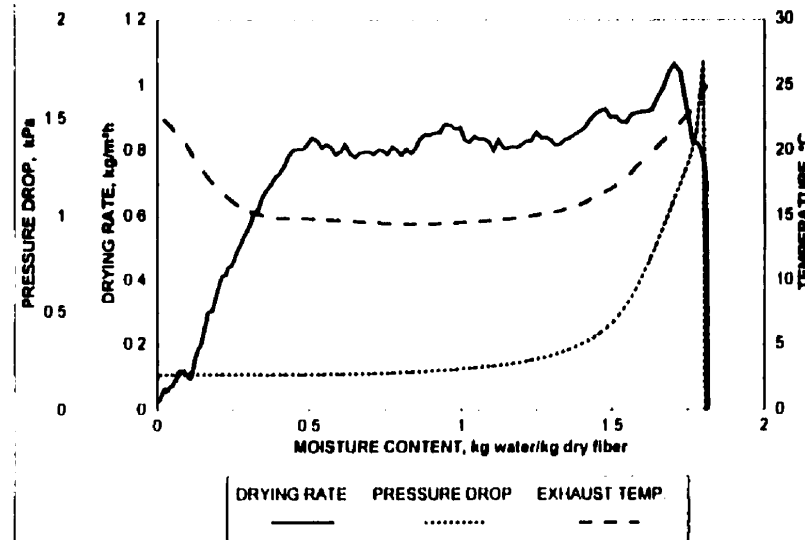
HANDSHEET FROM 25% TMP 75% KRAFT, B=65.443g/m², Tl=26.0°C, G=0.051kg/m²s



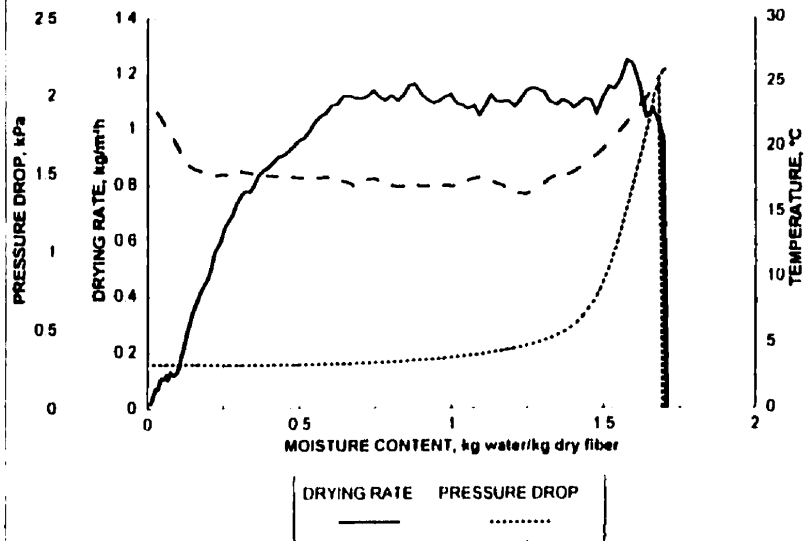
HANDSHEET FROM 25% TMP 75% KRAFT, B=55.443g/m², Tl=25.0°C, G=0.0246kg/m²s



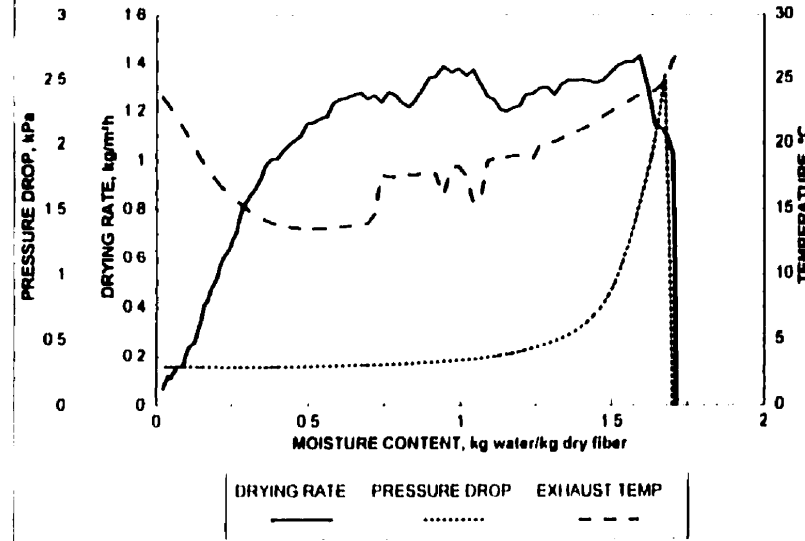
HANDSHEET FROM 25% TMP 75% KRAFT, B=55.443g/m², Tl=58.6°C, G=0.0195kg/m²s



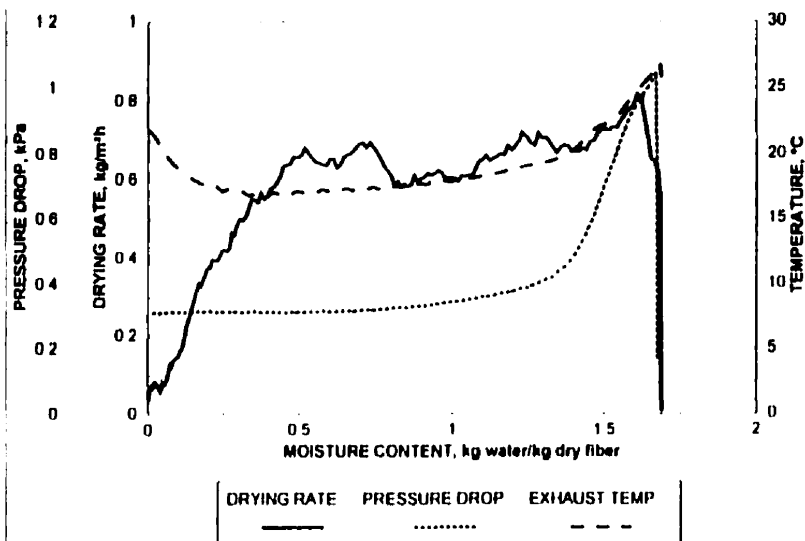
HANDSHEET FROM 25% TMP 75% KRAFT, B=55.443g/m², Tl=26.0°C, G=0.0444kg/m²s



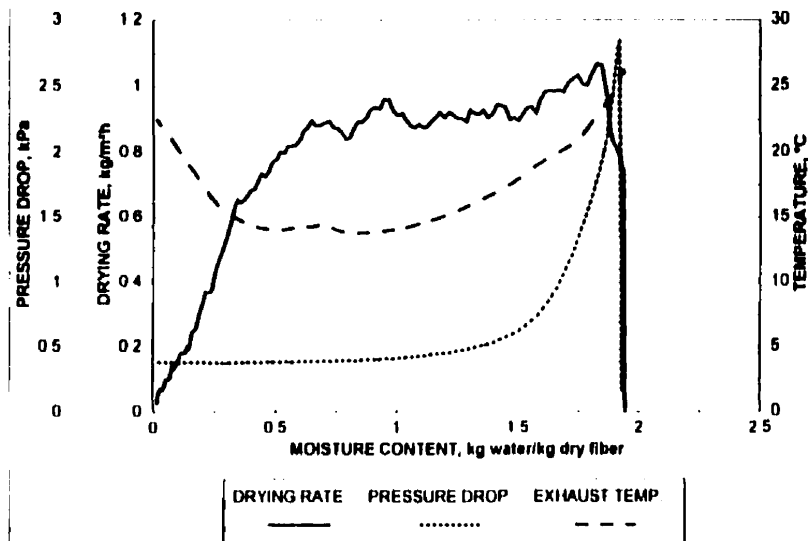
HANDSHEET FROM 25% TMP 75% KRAFT, B=55.443g/m², Tl=26.0°C, G=0.051kg/m²s



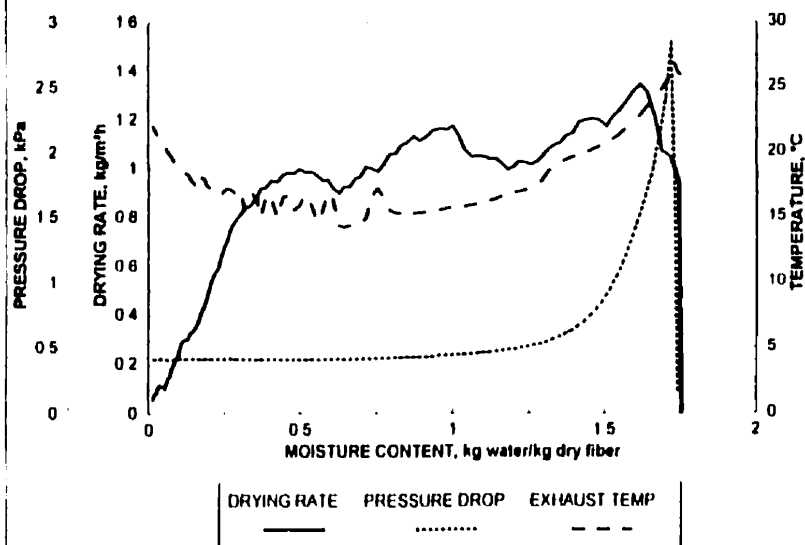
HANDSHEET FROM 25% TMP 75% KRAFT, $B=55.443\text{g/m}^2$, $T_i=25.5^\circ\text{C}$, $G=0.0246\text{kg/m}^2\text{s}$



HANDSHEET FROM 25% TMP 75% KRAFT, $B=55.443\text{g/m}^2$, $T_i=25.5^\circ\text{C}$, $G=0.0362\text{kg/m}^2\text{s}$



HANDSHEET FROM 25% TMP 75% KRAFT, $B=55.443\text{g/m}^2$, $T_i=25.5^\circ\text{C}$, $G=0.0444\text{kg/m}^2\text{s}$



HANDSHEET FROM 25% TMP 75% KRAFT, $B=55.443\text{g/m}^2$, $T_i=25.5^\circ\text{C}$, $G=0.051\text{kg/m}^2\text{s}$

