A CONTINUOUS FLOW PARTICULATE MEDIUM GRAIN PROCESSOR

by

Kulbir S. Pannu

A thesis submitted to the Faculty of Graduate Studies and Research, in Partial fulfillment of the requirements for the degree of Master of Science.

Departement of Agricultural Engineering
McGill University
Montreal

August 1984.

ABSTRACT

M.Sc. Kulbir S. Pannu Agr. Eng.

A CONTINUOUS FLOW PARTICULATE MEDIUM GRAIN PROCESSOR

A new machine utilizing the principle of particle-particle heat transfer to dry food grains by conduction heating was designed and a prototype constructed.

Sand was first heated and then metered into a closed annular space with a predetermined mass of high moisture corn. The two granular media were thoroughly mixed for a controlled time period and were then separated. Heated grain was dispersed into holding tanks and the particulate medium (sand) was recirculated for reheating.

The process was modeled to accomplish all the above steps in a continuous flow operation. Results indicate that the steady-state temperature conditions are easily achieved and the machine operates at a heating efficiency of 81%.

RESUME

M.Sc. Kulbir S. Pannu Génie Rural

APPAREIL DE TRAITEMENT DE GRAINS A PROCEDE CONTINU

Un nouvel appareil utilisant le principe de transfert de chaleur pour le séchage des céréales a été conçu et un prototype a été construit.

Le sable est d'abord chauffé et ensuite mesuré dans un espace cylindrique fermé avec une quantité prédéterminée de maïs à haute teneur d'humidité. Les deux produits granuleux sont mélangés pendant une période contrôlée et par la suite séparés. Les grains chauffés sont dirigés dans un réservoir d'entreposage et l'intrant approprié (sable) est recirculé pour être chauffé à nouveau.

Toutes les opérations ont été pensées pour accomplir d'après les phases d'un procédé continu. Les résultats indiquent que les conditions désirées sont facilement atteintes et que l'appareil opère à un coefficient d'efficacité de chaleur de 81%

ACKNOWLEDGEMENTS

The author/inventor is grateful to Dr. G.S.V. Raghavan (Associate Professor, Agr. Eng. Dept., Macdonald College of McGill University) for his guidance, encouragement and criticism throughout this study and in preparation of this manuscript.

Special thanks to Mr. R. Cassidy for providing experienced technical help and advice.

The contributions of Messrs. K. Khatri, M.I. Kalwar, K. Sibley, Y. Gariepy and R. Plasse, all graduate students, for their help in various phases of this study are gratefully acknowledged. Support of the Agr. Eng. staff is also deeply appreciated. Criticism and advice of Dr. Shiv Prasher (Assistant Professor, Agr. Eng. Dept.) while preparing this manuscript is appreciated.

The author is very grateful to his wife, Inderjeet, and his son, Jasbir, without whose support and patience this study would not have been possible. Also the moral support of his parents Lt. Col. (retd.) and Mrs. S.S. Pannu was instrumental in completion of this study. Special thanks to Mr. and Mrs. B.M. Boysen for accepting me as part of their family and encouraging me in my quest for education.

The financial assistance of the NSERC grant is gratefully acknowledged.

TABLE OF CONTENTS

Page

Page

LIST OF TABLES

LIST OF FIGURES

Figure | Page

Figure		Page

NOMENCLATURE

Symbol	Definition	Units
B	Volume coefficient of expansion	1/K
Cp	Specific heat	kJ/kg^oC
Cpa	-air	"
Cpg	-grain	"
Cpm	-granular medium	"
Cps	-sand	"
D	Density	kg/m^3
D	-corn	"
Da	-air	"
Dm	-granular medium	"
E	Efficiency	-
Ed	-drying	"
Ef	-fuel	"
Eh	-heating	"
Et	-total	"
Gr	Grashof number	-
H	Relative humidity decimal	-
K'	Thermal conductance	$W/m^{2o}C$
K	Thermal conductivity	W/m^oC
Ka	-air	"
Kc	-corn	"
Kd	-dispersed phase	"
Kk	-continuous phase	"
Km	-granular medium	"
Kmix	-mixture	"
Kg	-gas	"
Kp	-plate	"
L	Latent heat	kJ/kg
Lc	-condensation	"
Lp	-combustion-propane	"
Lv	-evaporation	"
Lw	-adsorption	"
M	Moisture content	
M	-wet basis	%
Md	-dry basis	kg/kg
Mw	-wet basis	"
Ml	-loss (wet basis)	"

Symbol	Definition	Units
N	Machine rotational speed	rpm
Nu	Nusselt number	-
Pr	Prandtl number	-
Pe	Pecklet number	-
Q	Heat energy	kJ/h
Qai	-grain by cold air-in	"
Qao	-loss by hot air-out	"
Qs	-sand	"
SGMR	Sand-grain mass ratio	-
T'	Temperature	K
T	Temperature	^oC
Tae	-air-exit	"
Tah	-air-hot	"
Tgc	-grain-cold	"
Tgh	-grain-hot	"
Tsh	-sand-hot	"
Tsc	-sand-cold	"
Tg	-hot gases	K
Ts	-drum surface	"
Vd	Volume (dispersed phase)	m^3
Vk	Volume (continuous phase)	"
Va	Volumetric flow-rate (air)	m^3/h
W	Mass flow-rate	kg/h
Wg	-grain	"
Wp	-propane	"
Ws	-sand	"
Ww	-water	"
X'	Constant	-
Y	Thermal diffusivity	m^2/s

Symbol	Definition	Units
a	Constant	-
b	Constant	-
d	Length	m
g	Constant	m/s^2
h	Heat transfer coefficient	$W/m^{2o}C$
h'	Heat transfer coefficient	"
h"	Volumetric heat transfer coefficient	$W/m^{3o}C$
j	gas mass velocity	kg/m^2s
l	Length	m
pi	Constant	-
t	Time	s
t_g	Time	s
t_s	Time	s
u	Kinematic viscosity	m^2/s
v	Velocity	m/s
ω	Angular velocity	rad/s
x	Length	m

I. INTRODUCTION

1.1 Background

The two factors that are part of any efficient drying process are the optimal utilization of heat and the mass transfer mechanism. Mass transfer in grain drying implies the moving out of moisture from within a solid body. As agricultural engineers, we are mostly concerned as to how this process of moisture movement can be accomplished efficiently from within cereal grains, oilseeds and other food products.

Heat in grain drying acts as a catalytic agent enhancing the moisture removal process. It is usually supplied to the product being artificially dried in one of the three ways:

a) by convection; a process where hot air is forced through a bed of high moisture grain,

b) by conduction; where a second source is first heated and then made to come in direct contact with the high moisture product being processed, and

c) by radiation; a phenomena where energy can be transfered through a transparent medium by electo-magnetic waves; e.g. solar energy as used in most of the third world countries to dry cereal grains.

The above three sources of supplying heat can be used independently or in a multitude of different combinations.

Most of the dryers available on the market use hot air, i.e. a convective drying process. This is not a very efficient way of transmitting heat to the granular product being processed. For example, in the heat transfer process there is usually a 100 fold reduction in the value of the heat transfer coefficient when hot water is replaced by hot air as the heating medium (Holman, 1976). The small value of the heat transfer coefficient, in an air drying system, is tolerated for lack of a better and proven alternative. Thus, it is desirable to find an alternative heat transfer method to replace air drying. Particle-particle heat transfer mechanism is one such option.

1.2 Objectives

The primary objective of the study is to design and build a prototype machine utilizing a particulate medium, such as sand, to dry food grains by conduction-heating. To achieve the above objective this machine should successfully handle the following situations:

- dry grain on a continuous basis
- achieve steady state conditions rapidly for a varying range of grain feed-rates
- control inlet temperature of the hot particulate medium
- control the ratio of particulate medium to grain mass
- vary contact time between the two mediums.

1.3 Scope

The present study does not endeavour to find solutions on the nature of heat and mass transfer problems encountered in a particulate medium grain drying operation. The work is centered around designing a machine that can successfully process approximately 0.5 to 1.0 t/h of high moisture grain corn in a continuous flow operation.

In trying to tackle this problem it was realized that the main parameter influencing the machine design is the particulate medium temperature. If the entrance temperature of the recirculated hot particulate medium can be maintained at a constant value, the machine should be able to achieve steady state conditions. Therefore, it was necessary to find a solution to transmit heat rapidly and efficiently to a moving sand bed.

Other machine design problems resolved are how a controlled mixing of two dissimilar granular mediums at different temperature levels can be accomplished, and after what time duration can the two be separated. A complete separation of the two mediums is essential, as contamination of the processed product is undesirable.

II. REVIEW OF LITERATURE

2.1 Grain Drying

The abundance of grain at harvest time must be preserved for consumption during the forthcoming year. Rapid and energy-efficient drying systems are prerequisites for safe long-term grain storage at low cost. Present methods of grain drying utilize a forced air drying system. A comprehensive summary of past research dealing with these aspects has been presented by Brooker et al. (1974). Thermal efficiency for such systems has been reported between 35% to 60% by various authors (Meiering et al., 1977; Morey et al., 1978; Otten et al., 1980; and Pierce and Thompson, 1981).

New systems which would enhance the heat transfer efficiency, thus improving upon the thermal efficiency could possibly provide substantial reductions in both drying costs and time. It has been shown that it is possible to obtain large heat transfer rates between grain and a flowing granular medium such as sand or salt (Akpaetok, 1973; Khan et al., 1973; Raghavan and Harper, 1974; Mayfield, 1974; Lapp and Manchur, 1974; Lapp et al., 1975, 1976a and 1976b; Savoie and Desilets , 1978; Richard, 1981; Tessier, 1982; and Mittal et al., 1982 and 1983).

2.2 Grain Processing

Grain drying is usually included in a grain processing system, however grain processing does not necessarily imply grain drying but may be associated with a process where the final product is to be used for some specific purpose. The roasting of grain in a high temperature

II. REVIEW OF LITERATURE

2.1 Grain Drying

The abundance of grain at harvest time must be preserved for consumption during the forthcoming year. Rapid and energy-efficient drying systems are prerequisites for safe long-term grain storage at low cost. Present methods of grain drying utilize a forced air drying system. A comprehensive summary of past research dealing with these aspects has been presented by Brooker et al. (1974). Thermal efficiency for such systems has been reported between 35% to 60% by various authors (Meiering et al., 1977; Morey et al., 1978; Otten et al., 1980; and Pierce and Thompson, 1981).

New systems which would enhance the heat transfer efficiency, thus improving upon the thermal efficiency could possibly provide substantial reductions in both drying costs and time. It has been shown that it is possible to obtain large heat transfer rates between grain and a flowing granular medium such as sand or salt (Akpaetok, 1973; Khan et al., 1973; Raghavan and Harper, 1974; Mayfield, 1974; Lapp and Manchur, 1974; Lapp et al., 1975, 1976a and 1976b; Savoie and Desiletes, 1978; Richard, 1981; Tessier, 1982; and Mittal et al., 1982 and 1983).

2.2 Grain Processing

Grain drying is usually included in a grain processing system, however grain processing does not necessarily imply grain drying but may be associated with a process where the final product is to be used for some specific purpose. The roasting of grain in a high temperature granular medium can be classified under such a heading.

Various researchers Clanton et al. (1960), Pickett et al. (1963) and Raghavan et al. (1974) have indicated that there is no detrimental effect on the quality of grain processed in a high temperature environment and shortly thereafter used as feed for farm animals. Mayfield (1974) has cited a few researchers as having found that heifers and yearling steers gained weight at an accelerated rate when fed roasted corn as opposed to regular corn. Walker et al. (1970) have attributed this effect to the disruption of highly organized starch granules in the endosperm which are more easily digested.

Further, Mayfield (1974) conducted tests to determine the quality of roasted corn after it had been stored for a period of eight months. It was found that the nutritional value of the stored corn had decreased.

2.3 Particulate Medium Grain Drying.

Particle-particle heat transfer is a term commonly used when a hot particulate medium, such as sand or salt, is used to heat up a granular medium such as grain. It can be described as a mechanism consisting of a contacting device where two dissimilar granular media at different temperature levels are thoroughly mixed and agitated mechanically for a controlled period of time and then separated. In a situation involving a horizontal drum, (cylindrical or conical) agitation is provided by rotation; a process that thoroughly mixes the two granular media. Both the amount and time of agitation can be precisely controlled by the drum angular velocity and by an internal helix that carries the mixture forward. After the desired heating has taken place, the two media are separated by means of a built-in sieve. The heated grain is dispersed into holding tanks and the particulate medium is recirculated for reheating.

2.3.1 <u>Drying process</u>: In a grain drying operation where large volumes have to be processed there are generally two options:

a) batch drying or

b) continous-flow operation.

Most dryers using the conventional air drying system were initially designed for batch operations. Raghavan (1984) has presented a comprehensive summary of various grain drying systems using the convection heat transfer process. Research developments have led to the development of continuous flow dryers using artifically heated air drying. These are very large machines and range in capacity from 5-27 t/h based on the drying and cooling of corn from 25% to 15% moisture and are not generally suited to small farm operations.

The prototypes to date that have been developed for drying grains utilizing a hot particulate medium such as sand or salt have all been designed to operate on a continous-flow operation. These dryers are comparatively small, simple to operate and can use either natural or propane gas to heat the particulate medium.

2.3.2 Grain drying mechanism: The mechanism involved in the drying of cereal crops such as corn, wheat, barley, rice and oil seeds can be split-up under:

a) the heat transfer and

b) the mass transfer process.

In the heat transfer process, heat is transfered from the hot particulate medium to the high moisture grain thus raising its temperature. Mass transfer is related to the movement of moisture from within the grain kernel.

2.3.3.1 Mass transfer: The two parameters of interest under this heading are the heat of adsorption and the heat of vaporization. The heat evolved when water is added to a large amount of moist material is referred to as the heat of adsorption.

Fortes and Okos (1981) describe the latent heat of condensation as composed of two parts; the heat liberated when water is condensed and the differential heat of adsorption, i.e.,

$$Lc = Lo + Lw \quad \text{.......................................} (1)$$

where,

Lc - specific heat of condensation (kJ/kg)

Lw - heat of adsorption (kJ/kg); and

$$Lo = Lv + Lw \quad \text{.......................................} (2)$$

where,

Lv - heat of vaporization (kJ/kg)

It should be noted that under drying conditions the heat of adsorption has a negative value.

The following four equations presented by Fortes and Okos (1981) can be used to evaluate the mass transfer process occurring in the drying of yellow dent corn:

$$H = 1 - \exp(-0.688*(T'-277)*Md^2) \quad \text{.................. (3)}$$

$$Lo = 3.11*10^6 - 2.38*10^3T' \quad \text{........................ (4)}$$

$$Lw = 318*T'^2*Md^2(H-1)/H \quad \text{............................ (5)}$$

$$Lv = 3.11*10^6 - 2.38*10^3T' + Lw \quad \text{................... (6)}$$

where,

H - relative humidity (decimal)

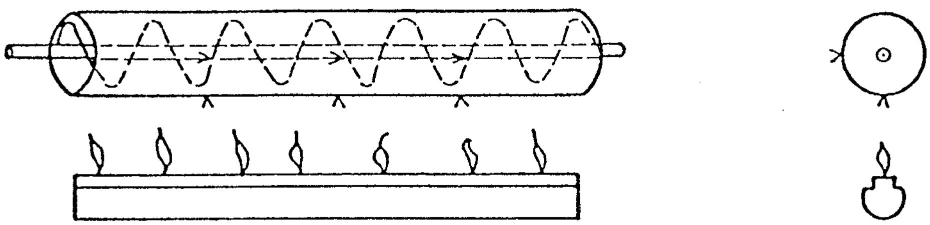
Md - moisture content, decimal dry basis (kg/kg)

T' - temperature (K)

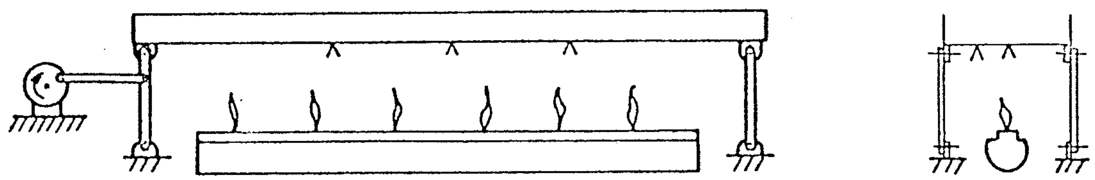
2.3.2.2 Heat transfer: In the heat transfer process as applied to the use of a particulate medium for drying there are two distinct phases. In phase one the heat is transferred from hot gases (or a flame) to the particulate medium and in phase two the hot particulate medium transfers heat to the the product being processed.

Phase 1: Not many researchers have dealt with the problem of heat transfer occurring between a heating source such as a flame or hot gas and the flowing particulate medium.

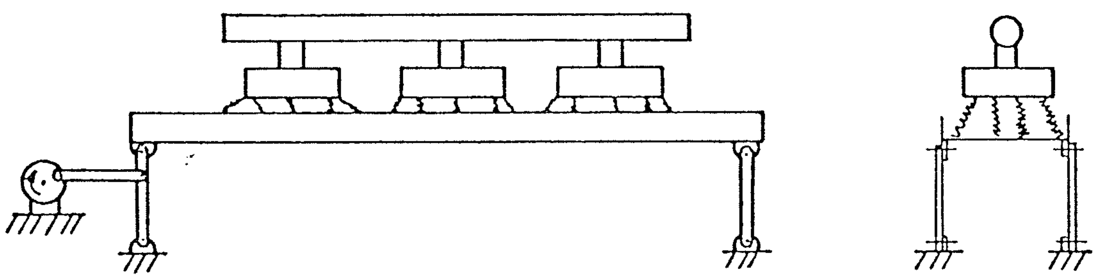
Mayfield (1974) selected four methods for transferring heat to a flowing granular medium (Figure 1). The results of his study are presented in Table 1. He indicates that for Method-a (i.e., for a line burner auger conveyor) the heat transfer coefficient can be approximated by:



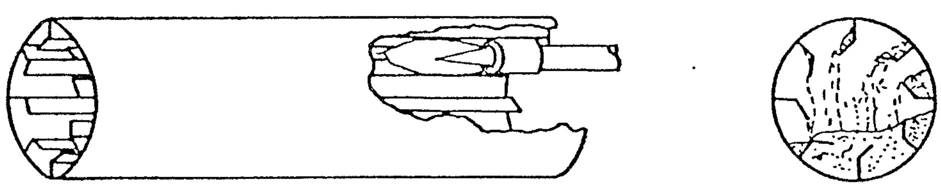
a. Line Burner-Auger Conveyor



b. Line Burner-Vibratory Conveyor



c. Radiant Burner-Vibratory Conveyor



d. Nozzle Burner Rotating Drum Conveyor

Drawings Not to Scale
^-Indicates Thermocouple Location

Figure 1. Schematic diagram of the heat transfer methods that were studied by Mayfield (1974).

Table 1. Results of the heat transfer study conducted by Mayfield (1974).

Salt Flow Rate (kg/hr)	Theoretical Heat Input (W)	Salt Temperature Rise (^oC)	Efficiency (%)	Heat Transfer Coefficient
		Line Burner-Auger Conveyor		
213	14600	104	36	70.98*
422	15652	69	43	92.55
213	23272	157	34	73.81
422	23272	94	40	89.14
		Line Burner-Vibratory Conveyor		
213	15622	102	31	47.70*
422	15065	48	32	47.70
213	23682	146	31	46.46
422	24764	88	35	51.67
		Radiant Burner-Vibratory Conveyor		
213	14919	103	34	
422	11988	51	41	
213	22686	168	37	
422	22862	111	47	
		Nozzle Burner-Rotating Drum Conveyor		
213	12545	162	64	527.19**
422	12545	86	67	517.88
213	25763	331	64	758.18
422	25763	166	63	1069.28

Note * $W/m^{2o}C$
** $W/m^{3o}C$

$$h' = 353.48*v^{0.35} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

where,

h' - heat transfer coefficient ($W/m^{2o}C$)

v - average salt velocity (m/s)

There were no analytical or empirical solutions offered for evaluating the heat transfer coefficient for Methods-b (line burner-vibratory conveyor) and Method-c (radiant burner-vibratory conveyor). For Method-d, the nozzle burner rotating drum conveyor, he suggests the use of the following equation:

$$h'' = 3116.97*j^{0.8} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

where,

h'' - volumetric heat transfer coefficient ($W/m^{3o}C$)

j - gas mass velocity (kg/m^2s)

These empirical relations indicate that the mass of the product being heated has no effect on the value of the heat transfer coefficient. For Equation 8 to be true, one has to assume that the temperature of the hot gas is constant and that the combustion process is complete. Also for Method-d, if the size of the drum is increased or decreased then the contact area between the hot gases and the flowing granular medium increases and decreases accordingly. It is to be expected that this will have an effect on the value of the heat transfer coefficient.

Pannu (1982) used a computer model to simulate the expected rise in temperature of a flowing sand bed exposed to a constant temperature hot air environment. The computer program and the results of this study are presented in Appendix I. In this study, it was assumed that during the heating phase, the sand particles are sandwiched between the hot air and the drum surface. The problem was analyzed by dividing the sand bed into finite sections or slices and assuming that each of these slices are at a different mean temperature level. Following the analysis, for a cylindrical drum each slice would have the same thickness to have constant volume, but if the drum is to be shaped like a frustrum of a cone, then each slice should have different thicknesses for obtaining the same volume.

To simplify the nature of the heat transfer problem the author further assumed that the drum surface takes on the mean temperature of the adjoining sand slice because there would be very little heat transfer occurring between the sand and the drum surface. It was later noted that once the heat transfer process had commenced, the temperature profile within the heating section gets stabilized, and this error is relatively small.

The Grashof number, for the above analysis, was calculated using the equation suggested by Holman (1976):

$$Gr = g*B*l^3*(Tg-Ts)/u^2 \quad \text{.............................} (9)$$

where,

Gr - Grashof number (-)

g - constant -acceleration due to gravity (m/s^2)

B - volume coefficient of expansion ($1/^{o}K$)

Tg - temperature of the hot gases (^{o}K)

Ts - temperature at the drum surface (^{o}K)

l - height of the sand bed (m)

u - kinematic viscosity of the hot air (m^2/s)

The Nusselt number, i.e. the dimensionless equation for the heat transfer coefficient is (Holman, 1976):

$$Nu = 0.508*Pr^{0.5}(0.952+Pr)^{-0.25}Gr^{0.25} \quad \text{.............. (10)}$$

where,

Nu - Nusselt number (-)

Pr - Prandtl number (-)

Based on the result obtained from Equation 10, the heat transfer coefficient can be evaluated by the relation:

$$h' = 4.Nu.Ka/3.x \quad \text{.................................. (11)}$$

where,

h' - heat transfer coefficient ($W/m^{2o}C$)

Ka - thermal conductivity of air at film temperature (W/m^oC)

x - thickness of the slice (m)

The heat input into each sand slice can now be evaluated and the result used to calculate its final temperature.

The three figures, A1 to A3 (Appendix I), obtained by plotting the data generated by the computer model indicate that this is a realistic approach for approximating the final temperature of a moving sand bed subjected to a convective heating source. However, no comparisons are made to a real situation in this study; therefore, before such an approach can be followed, experimental verification is required.

Phase 2: Researchers who have dealt with phase two, use the temperature of a hot particulate medium as one of the known parameters. The following is a review dealing with the heat transfer process occurring between a flowing hot particulate medium and a porous granular product.

Mickley and Fairbanks (1955), Harakas and Beatty (1963), Berntsson

(1979), Sullivan and Sabersky (1975) and Richard and Raghavan (1980) have tried to approximate the heat transfer coefficient that occurs between a moving bed of granular particles and a heated surface (plate). Two of the solutions, for the heat transfer coefficient occurring in such a case, are presented here. Mickley and Fairbanks (1955) imply that the heat transfer coefficient is a function of the time the granular bed is in contact with the heating surface. It is assumed that the simple heat penetration theory is applicable because the bed is a homogeneous fluid. The following expression was obtained:

$$h = ((Km*Dm*Cpm)/(t*pi))^{0.5} \qquad \text{........................(12)}$$

where,

h - heat transfer coefficient ($W/m^{2o}C$)

Km - granular medium thermal conductivity (W/m^oC)

Dm - granular medium density (kg/m^3)

Cpm - granular medium specific heat (kJ/kg^oC)

t - contact time (s)

pi - constant

Harakas and Beatty (1963) later pointed out that the values of h, predicted by the above equation were higher than those observed for short contact time. Gabor (1970), Kubie and Broughton (1975) and Denloye and Botterill (1978) all agree that the heat penetration theory should be modified to take into account the change in porosity that occurs in agitated units and that the heat transfer resistance is mainly controlled by bed mixing. The modified equation of Mickley and Fairbanks (1955) for predicting the heat transfer coefficient takes the form:

$$h = 2*((Ke*De*Cpm)/(t*pi))^{0.5} \quad \text{.....................(13)}$$

where, bed properties are now the equivalent medium properties.

A further development of this equation took place when researchers insisted that in free flowing situations such as those encountered in a rotary kiln or in the grain dryer presented by Raghavan and Harper (1974), the granular medium neither has a packed bed behaviour nor does fluidization take place. Wunschmann and Schlunder (1974), Sullivan and Sabersky (1975) and Richard and Raghavan (1980) added another term to the above equation, and defined it as the thermal conductance K' that takes place at the heated surface. The equation now takes the form:

$$\frac{1}{h} = \frac{1}{K'} + \frac{1}{2}((t*pi)/(Km*Dm*Cpm))^{0.5} \quad \text{....................(14)}$$

where,

$$K' = Kg/(X'*d) \quad \text{.....................................(15)}$$

Kg - thermal conductivity of interstitial gases ($W/m^{o}C$)

d - charasteristic length (m)

X' - proportionality constant (-)

Furthermore, Sullivan and Sabersky (1975) point out that for geometrically similar arrangement of particles, X' does not change. If however the physical configuration of the particles changes then X' takes on a new value (e.g., particles flowing over a smooth plate will have a different X' than those moving over a rough plate).

Rearranging some of the terms in Equation 14 leads to the following expression:

$$h*d/Kg = (X'+0.5*Pe*pi^{0.5}(Kg*L/(Kp*d))^{2})^{-1} \quad \text{...........(16)}$$

where,

$$Pe = v*l/Y \qquad (17)$$

Pe - Pecklet number (-)

v - velocity of the moving bed (m/s)

l - contact length of the hot plate (m)

Y - thermal diffusivity (m^2/s)

Kp - thermal conductivity of the plate (W/m^oC)

In a grain drying operation, where the particulate medium and the grain are travelling forward together, the sand particles will have a zero velocity relative to the grain kernels. This would imply that the Pecklet number approaches zero, thus indicating that Equation 16 cannot be used for calculating the heat transfer coefficient.

Looking at Equations 12 - 14 it is seen that the term "contact time" was defined as the flow rate of the granular particles divided by the "contact length". These equations were derived by maintaining the plate at a steady temperature, a situation that cannot be assumed for the drying operation. If the particulate medium and the product to be processed travel together as a mixture for a controlled contact time, there would be transfer of energy from the fine granular particles to the product being processed. This would cause a rise in temperature of the product and a drop in final temperature of the medium. Therefore, to derive the heat transfer coefficient of this process the temperature gradient should be taken into account. Further work is required before the above equations can be used to approximate the heat transfer coefficient between two granular media, at different temperature levels, that are mixed while they are made to flow together.

2.4 Thermal Properties of Corn

In grain drying operations the varying nature of the thermal properties of grains pose many problems. As this study is centered around the designing of a machine which can dry corn by immersion in a hot particulate medium, such as sand, it is essential to know how to obtain this data. This part of the literature search is concentrated around the evaluation of the physical properties of corn.

2.4.1 Thermal conductivity : Thermal conductivity can be defined as the quantity of heat that will flow across a unit surface area in a unit time period. It has been stipulated (ASHRAE,1981) that the thermal conductivity depends on many factors including substance material, composition, structure, temperature and pressure. Thus making it very difficult to accurately measure and predict the thermal conductivity of food materials. The agricultural engineering yearbook (ASAE,1982) recommends the following expression to calculate the thermal conductivty of corn:

$$Kc = 0.1409 + 1.118*10^{-3}M \quad \text{..........................(18)}$$

where,

Kc - thermal conductivity of corn (W/m^oC)

M - moisture content, wet basis (%)

The above equation predicts the thermal conductivity of yellow dent corn for a mean temperature of 35^oC.

Fortes and Okos (1981) found that the thermal conductivity of corn can be more accurately predicted by the following equation:

$$Kc = \exp(-1.738 - 3.696*Md + 4.725*10^{-2}T + 6.843*Md^2$$

$$- 1.499*10^{-4}T^2 + 6.272*10^{-4}Md*T) \quad (19)$$

where,

Md - moisture content, dry basis (kg/kg)

T - temperature (^oC)

The above equation is limited for a corn temperature range of 30^{o}C to 80^{o}C and moisture range of 10% to 28%, dry basis. At temperatures greater than 80^{o}C and for corn moisture contents, greater than 28%, the values of thermal conductivity become very large, deviating from reality.

Euckens adaption of Maxwells equation (ASHRAE,1981) is another approach for calculating the thermal conductivity of food materials.

$$Kmix = Kk \frac{1-(1-a(Kd/Kk))b}{1+(a-1)b} \quad (20)$$

where,

$$a = 3Kk/(2Kk+Kd) \quad (21)$$

$$b = Vd/(Vk+Vd) \quad (22)$$

Kmix - thermal conductivity of the mixture (W/m^{o}C)

Kk - conductivity of the continuous phase (")

Kd - conductivity of the dispersed phase (")

Vd - volume of the dispersed phase (m^3)

Vk - volume of the continuous phase (")

The above equation (Equation 20) assumes water to be the continous phase and the non-aqueous part as the dispersed phase. Considering that the thermal conductivity and density of the non-aqueous components fall in a relatively narrow range, the Maxwell-Eucken equation should be valuable in predicting the thermal conductivity of food products such as high moisture corn.

2.4.2 Specific heat : The ratio of the total heat supplied to the corresponding rise in temperature is defined as the heat capacity of a body. Specific heat is the heat capacity of a body per unit mass of the body. In heat transfer problems of biological materials, usually constant pressure prevails. Therefore, the specific heat at constant pressure is normally used.

To estimate the specific heat value for corn, most researchers use the following equation (ASAE, 1982):

$$Cpg = 1.4654 + 3.5631*10^{-2}M \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (23)$$

where,

Cpg - specific heat of corn ($kJ/kg^{o}C$)

M - moisture content, wet basis (%)

2.4.3 Density : In heat transfer calculations, density usually appears in the form of specific gravity or mass density with units of kg/m^3. It is essential to recognize that there are actually three types of densities: bulk density, unit density and true density. Unit density is used in all calculations pertaining to a heat transfer process in the grain drying operation. It refers to the mass of each intact unit, divided by the volume of the unit (e.g., each kernel of corn represents one unit).

Fortes and Okos (1980) found out that the density of corn has a high dependence on temperature and moisture content. They propose the use of the following equation:

$$D = 1335.0 - 477.3*Md + 508.7*Md^2 - 0.01561*T^2 + 0.05818*Md*T^2 \quad \text{.......} (24)$$

where,

Md - moisture content, dry basis (kg/kg)

T - temperature (^oC)

This equation predicts density values for a temperature range of 32^oC to 150^oC and a moisture range of 18% to 28% dry-basis.

2.5 Particulate Medium Grain Dryers

Although there are a number of experimental solid medium grain drying units built and tested, none is available on the market; thus implying that more research and development work is required in this field. The market is ready for a newer machine that can accomplish the grain drying operation more efficiently, as fuel prices over the last few years have gone up rather dramatically. Some of the past work, with respect to grain drying, are reviewed here to find their advantages and disadvantages for a future machine.

Akpaetok (1973) built a small prototype dryer to study the effect of hot sand on the moisture loss and heating process involved in the drying of yellow dent corn. The main part of the dryer are a cylindrical rotating drum 0.86 m (36 in) long and 0.23 m (9 in) in diameter. Preheated sand and moist corn were metered into the elevated end of the drum, thereby allowing mixing of the two products to take place. Residence time of the mixture was contolled by the drum angular velocity and its angle of inclination. Separation was accomplished by a cylindrical screen attached to the exit end of the drum. This allowed the hot corn to roll forward into a collection bin and the sand to fall into a trough through the holes in the screen.

When the sand temperature and the contact time were varied between 150°C to 200°C and between 100 to 300 s respectively, the corn moisture content was lowered from 25% to 18.5% on a wet-basis. The main parameters affecting the drying process were, the inlet sand temperature, the grain feed rate and the contact time. The contact time was dependent upon the drum inclination angle. Further tests revealed that the initial grain moisture content was also an important dependent parameter.

Raghavan and Harper (1974) and Mayfield (1974) tested the continuous-flow prototype dryer (Figure 2) to dry corn using salt as the heat transfer medium. This was a much larger machine than that tested by Akpaetok (1973) and performs the heating, mixing and seperating operation simultaneously. The corn feed rates were in the range of 300 to 700 kg/h as opposed to a maximum 7.8 kg/h for the dryer tested by Akpaetok (1973). The perforated helix not only allows for the separation but also controls the residence time of corn in the hot salt bed depending upon the drum angular velocity. The machine was tested for a salt temperature and residence time variation between 200°C to 275°C and between 4 to 20 s respectively and resulted in corn moisture loss from 21% to 12% wet-basis. Some of the factors that influenced the drying process were, the salt temperature, the initial moisture content, the residence time, the grain feed rate and the equilibrium moisture content.

Tessier (1982) tested a newer version of the particulate medium

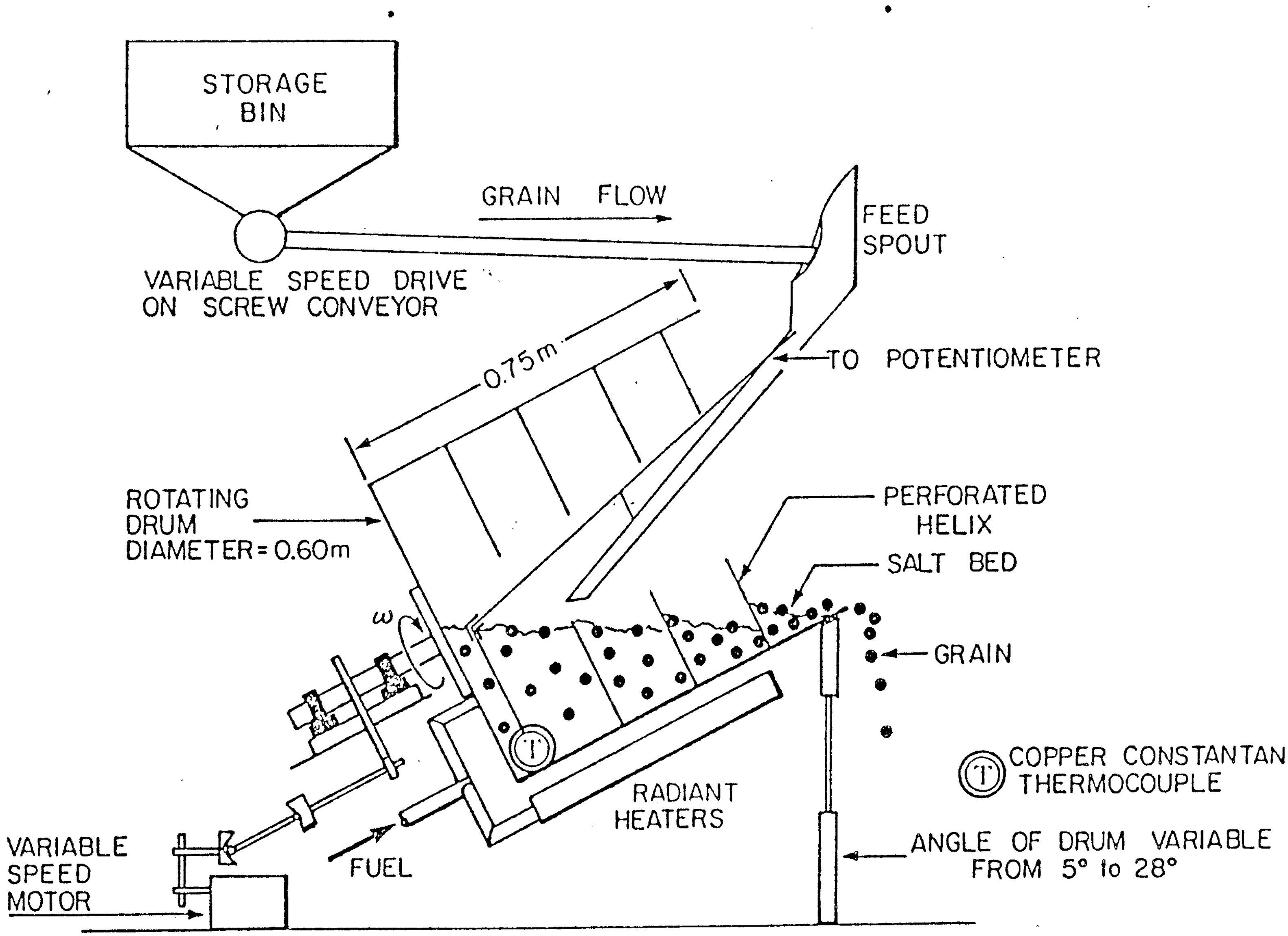


Figure 2. Schematic diagram of the experimental particulate bed dryer tested by Raghavan and Harper (1974) and Mayfield (1974).

dryer developed at Macdonald college of McGill University, and used sand as the particulate medium to dry high moisture yellow dent corn. Hot air was used to heat the sand in the outer section, ie. the annular space created by two concentric cylinders (Figure 3). Sand is carried downwards by gravity flow and exits into the inside cylinder through a sieve and allowed to mix with the raw corn fed in by an external conveying auger. The mixture was pushed forward by an internal helix towards the exit, where the seperation of the products takes place. This allowed sand to be recirculated for reheating and the processed corn was discharged out into the containers.

This machine (Figure 3) was capable of processing 300 to 700 kg/h of grain corn. However, as opposed to the maximum moisture loss of 7% and 9% reported by Akpaetok (1973) and Raghavan and Harper (1974) respectively, Tessier (1982) reported the magnitude of moisture loss to be in the range of only 4%. This could be attributed to the lower sand temperature (150^{o}) attained in the unit. Also in this work, the moisture loss occurring during the cooling phase was not included.

Another source of discrepancy between the three dryers is the duration of the contact time. Akpaetok (1973) suggests a contact time between 100 seconds to 300 seconds as opposed to the 4 to 20 s reported by Raghavan and Harper (1974) and 18 to 29 seconds reported by Tessier (1982). These researchers also do not agree upon the optimum particulate medium to corn-mass ratio, values range between 2 to 20.

There are several other researchers who have experimented with the principle of particle-particle heat transfer to dry rice, oilseeds and wheat. Khan et al. (1974) demonstrated that rice can be successfully

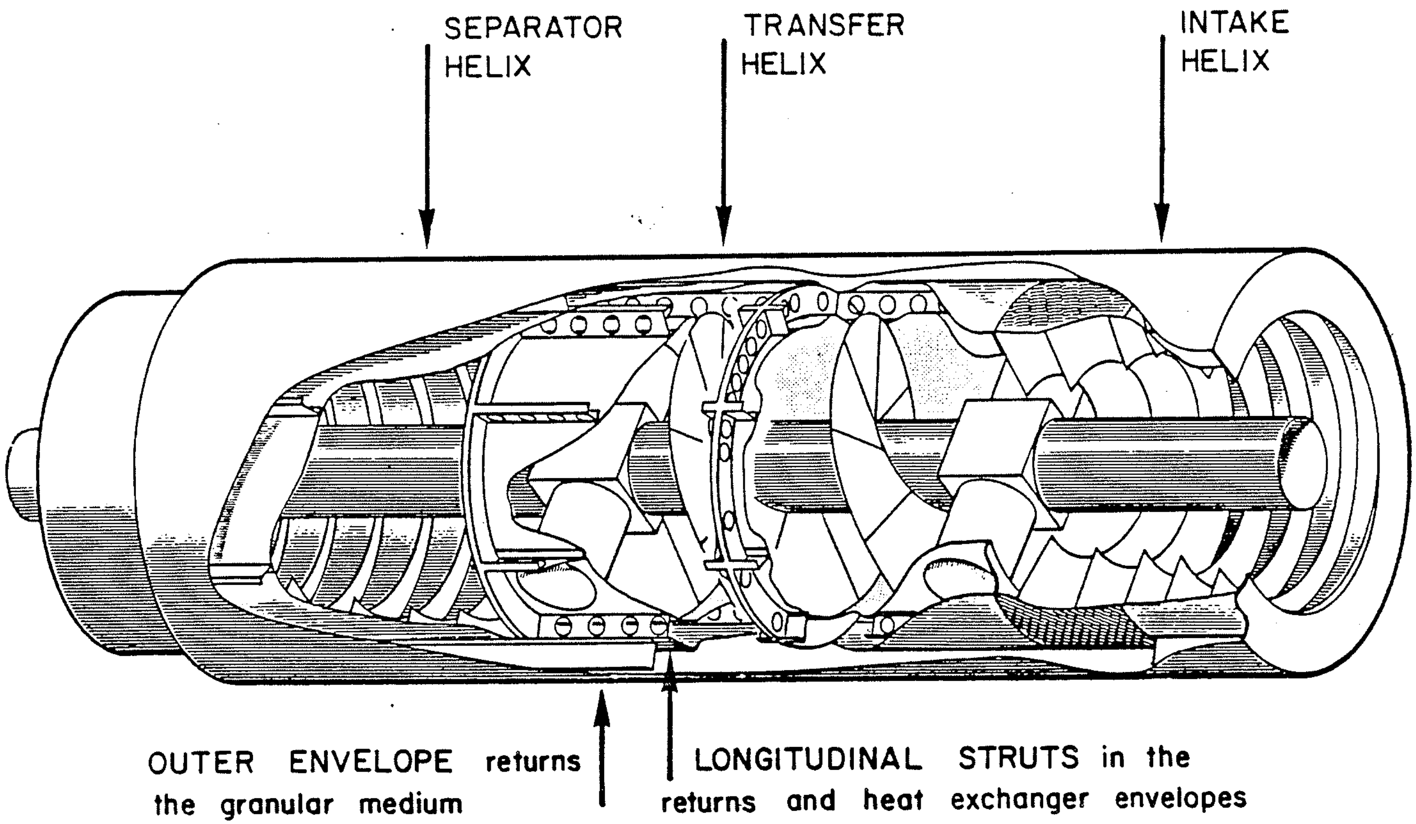


Figure 3. Schematic diagram of the experimental particulate bed dryer tested by Tessier (1982).

dried and par-boiled by using hot sand as the drying medium. Unlike corn, dried rice was reported as being of a high quality. The best rice quality was obtained with a sand temperature ranging between 150°C and 180°C and the resulting drop in moisture content was from 45% to 20% on a dry-basis.

Lapp and Manchur (1974) investigated the drying of rapeseed using a continuous-flow drying unit. It was found that for a sand-bed temperature of 221°C there was neither contamination nor decrease in the oil quality. Moisture losses in the range of 2.5% to 6.7% were reported for a contact time of 30 seconds, depending upon the initial moisture content. Lapp et al. (1975, 1976a) further found that when wheat was dried for 120 seconds at 105°C with a sand to wheat ratio of less than 6:1, there was no damage to the baking and germination quality and lost 4% moisture from an initial moisture content of 17% wet-basis.

Subsequent work done by Mittal et al. (1982) on the dryer tested by Lapp and Manchur (1974) and Lapp et al. (1975, 1976a) indicated that a sand-to-wheat mass ratio of 4.5:1 removed the most miosture (2.4%) for an initial sand temperature of 105°C and a residence time of 60 s. The authors also indicated that a maximum fuel efficiency of 41% and a maximum drying efficiency of 61% was achieved by the continuous flow particulate medium grain dryer.

All of the researchers quoted above (section 2.5) indicate that a hot particulate medium, such as sand or salt, can be used to successfully dry cereal grains. However, none seem to agree on the optimal initial temperature of the particulate medium or the residence time of the grain within the dryer. Values range from 105°C to 275°C for the medium temperature and from 4 to 300 s for the residence time.

III. MACHINE DESIGN AND CONSTRUCTION

The primary objective is to design and construct a continuous-flow particulate medium grain processor and test its ability to dry high-moisture corn. A step-by-step approach is taken whereby all parameters that can affect the design of such a machine are first analyzed and later on incorporated into the machine design. It was decided to build a machine that was capable of processing up to one tonne per hour of high moisture-corn. Emphasis was placed on the development and streamlining of the continuous-flow operation, i.e. the building a machine where steady-state conditions can be easily achieved and then maintained for a long duration.

3.1 Exploring the Problem

The flow characteristics involved in such a machine is summarized in Figure 4. Each one of these four steps will be scrutinized and compared with the existing literature so as to be able to incorporate the better features into the machine design. However, looking at the four steps jointly, it can be seen that to accomplish a drying process successfully and efficiently, the heat transfer mechanism needs to be thoroughly streamlined in order to minimize any heat losses that can occur.

3.1.1 <u>Step 1 (Heating stage)</u>: Raghavan and Harper (1974) used line-burners to heat the drum which in turn heats the particulate medium (salt). Mayfield (1974) evaluated the overall thermal efficiency of

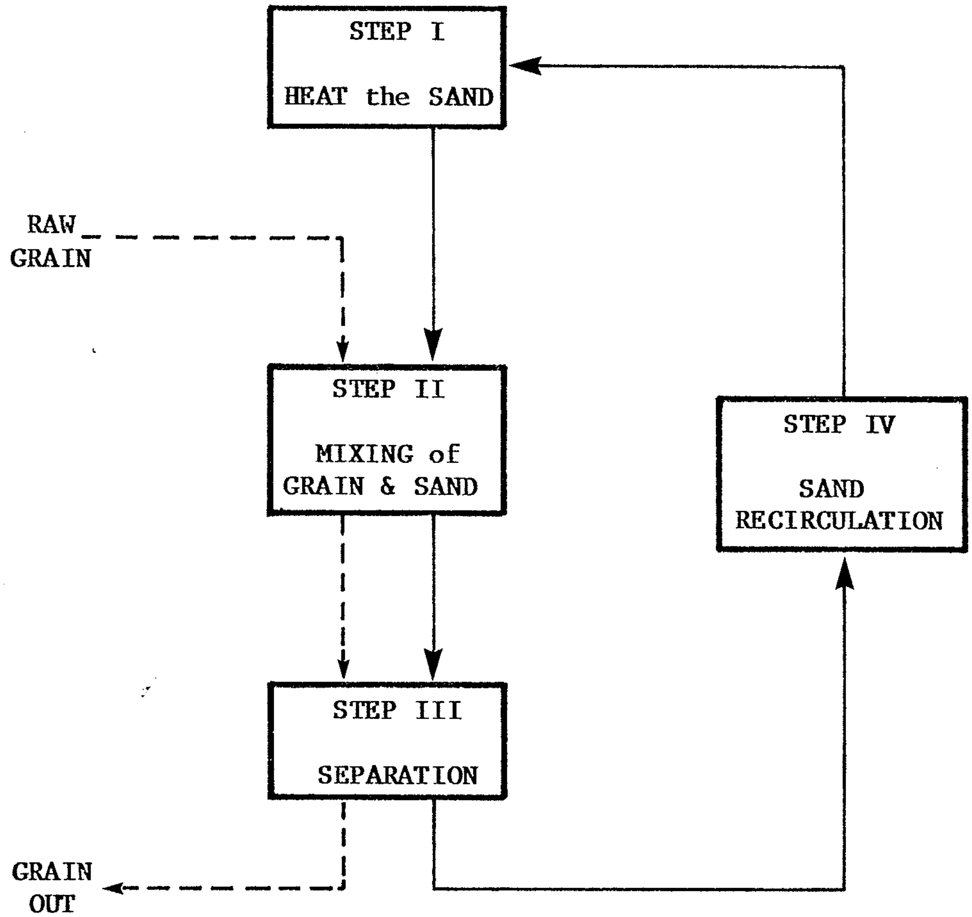


Figure 4. Schamatic diagram of the proposed particulate bed dryer.

such a system as being low due to the large radiant heat losses occurring from the drum surface. A second problem associated with such a system would be the direct contact of grain with the heated metal surface thus leading to grain damage by burning. In the design presented by Tessier (1982) hot air was used to heat the sand. Tessier (1982) was unable to achieve steady-state temperature conditions, at high temperatures, in this prototype dryer. A possible reason could be that there was an insufficient supply of hot air entering into the heat exchanger envelopes (Figure 3).

In the study compiled by Mayfield (1974) it appears that the most efficient way of heating a particulate medium is by using a "nozzle burner rotating drum conveyor". This system has a heating efficiency of 65% as opposed to 38% for a "line burner auger conveyor". It can be seen that the particulate medium would achieve almost twice as high a temperature by the first system. Therefore, it was concluded that by placing the propane burner within the rotating drum it is possible to:

a) heat the particulate medium rapidly,

b) minimize the heat losses, and

c) achieve steady-state temperature conditions rapidly in a continuous-flow operation.

3.1.2 Step 2 (Mixing and heat transfer stage): There is not much problem associated with feeding of the grain into the dryer. This operation is relatively simple and can be accomplished by using a variable speed auger (for experimental work only) that can discharge the high moisture corn into the machine. However, the problem of mixing the two media, agitating them thoroughly to facilitate the desired heat transfer process and then leading them towards the separation-stage without any significant loss of heat would be a complicated operation. Akpaetok (1973) fed corn and sand into a rotating cylinder at the elevated-end. The two materials were mixed and carried forward by the sliding action caused by: a) the drum rotation and b) the drum inclination angle. It was found that the two materials do not have the same flow rates thus causing some problems in the heat transfer and the mixing operation.

Raghavan and Harper (1974) used a perforated helix to contain the particulate material (salt) within the rotating drum, thereby performing the heat transfer and seperation procedure in one operation. Mayfield (1974) reported that this led to a nonuniform grain quality due to a variable grain residence time. Tessier (1982) on the other hand, used an internal helix in the flighted rotating drum to carry the two materials forward. The contact time in such an operation was contolled by the drum angular velocity, thus leading to a smooth mixing and heat transfer operation.

For a better solution to the problem faced in step two i.e., the heat transfer and the mixing stage, it can be seen that it is desirable to incorporate a helix into the system. The advantages of such a system are:

a) the two materials are carried forward simultaneously,

b) the contact time is precisely controlled by the drum angular velocity,

c) the heat transfer is accomplished quite rapidly and efficiently, and

d) such a system is ideally suited for a continuous flow operation which should have precise control of the inlet temperature of the hot particulate medium.

3.1.3 <u>Step 3 (Separation)</u>: Raghavan and Harper (1974) perform this operation in a relatively simple and efficient manner. However, if the temperature of the particulate medium is to be precisely controlled the two mediums need to be separated first. Akpaetok (1973) and Tessier (1982) both recommended the use of a wire-mesh screen.

In Akpaetok's (1973) case, the two materials flow downwards freely thus permitting the fine sand particles to fall through the holes in the screen and the corn is retained within the cylinder and later discharged into a reservoir. The duration of the separation procedure in this case is governed by the inclination and the drum's angular velocity, rather than on the length of the separation-section.

Therefore, it can be seen that it is desirable in the case of a cylindrical machine to incorporate a helix in the separating section. This would force the mixture to be carried over a fixed length of the wire-mesh, a length predetermined to insure a complete separation of the two products.

3.1.4 <u>Step 4 (Sand recirculation)</u>: This is perhaps the most interesting and challenging aspect of the machine. The main problem here is not only to return the particulate medium for reheating but to ensure that it is done rapidly, efficiently and without much loss of heat energy that is still stored in the medium. The development of an effective recirculation process is mainly dependent upon the location of the heating source.

3.2 Summarizing the Design Problem

When designing a machine that can successfully process large volumes of grain, such as corn, by immersing it in a hot particulate medium, such as sand, the following parameters must be kept in mind;

1) inlet temperature of the heated medium is to be maintained at a constant level,
2) heat losses are to be minimized,
3) the mixing process is to be regulated and the time of contact should be precisely controlled,
4) the separation operation should be complete (i.e., contaminants such as sand particles left in the processed grain are undesirable),
5) the recirculation procedure should be simple but effective and finally,
6) ease of handling of the product at both the inlet and discharge stage.

3.3 Machine Construction

Instead of going through the tedious work of describing how the final design of the machine was achieved it has been decided to tackle the problem in a reverse order. An overall view and a sectional view of the machine are presented in Figures 5 and 6 respectively. All components that led towards the final design and construction of the

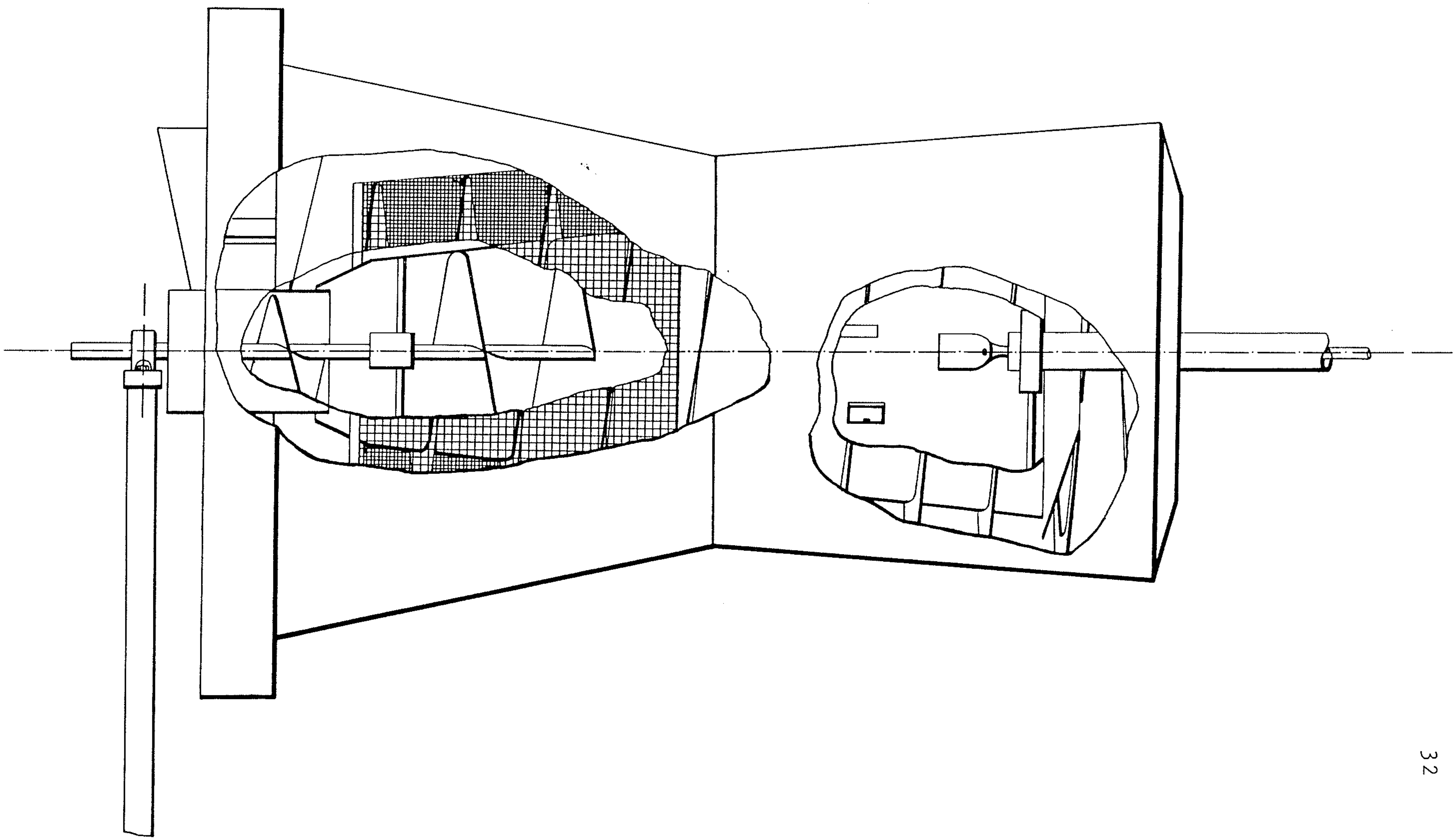


Figure 5. An overall view of the proposed processor with cut sections.

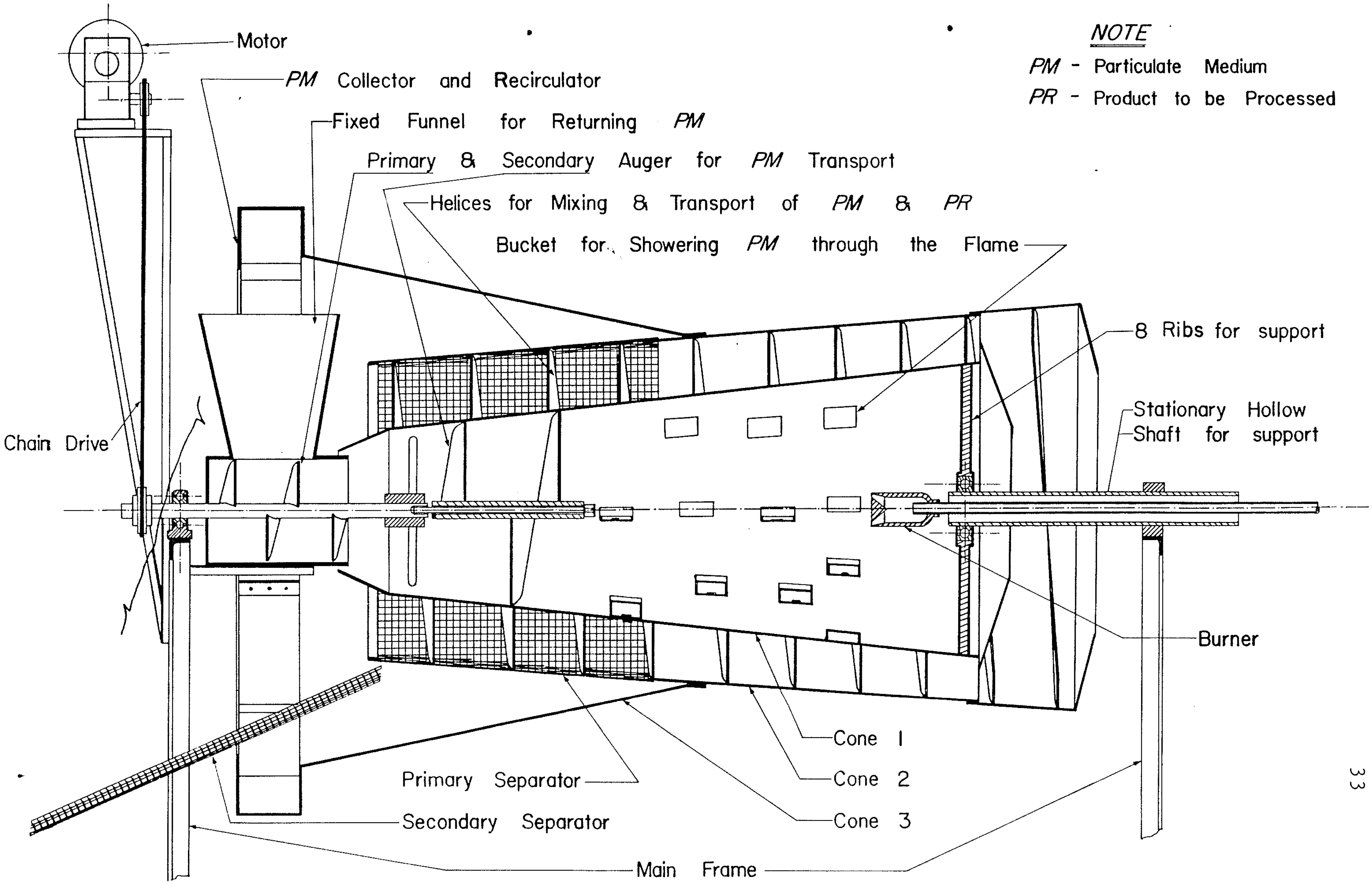


Figure 6. A sectional view of the machine showing all the components.

prototype will be discussed briefly and their incorporation into the design process will be defended in a step by step operation. The order choosen is according to the flow chart (Figure 4), i.e. commencing at Step 1 and leading towards Step 4.

It can be seen that the machine is built from three conical sections (Figure 6). Inside-conical-drum (Cone 1) represents the first stage where the particulate medium such as sand or salt is heated. Outer-conical-drum (Cone 2) deals with the second and third stage of the flow process, wherein the mixing of the two media and transport to the separation section after the heat transfer process are done. Lastly, the Last-conical-drum (Cone 3) initiates the recirculation process by collecting the discharged particulate medium and preparing for its re-entry into the heating stage.

3.3.1 Particulate medium heating stage: It was decided to use a line burner rotating drum conveyor, as defined by Mayfield (1974) to heat the particulate medium. The main components of such a system are:

a) a heating source, such as a propane burner;

b) a drum, where the particulate medium is heated; and

c) a conveying mechanism to move the heated medium to the exit point.

If the rotating drum is a cylinder the only way to move the particulate medium forward without using an internal helix, would be by tilting the cylinder about its central axis. Therefore, an obvious solution is to use a frustrum of a cone, thereby simplifying the machine design problem and eliminating the necessity of tilting the drum. The problem of rotation was solved by installing a steel-sleeve with a 25.40 mm (1.00 in) diameter hole welded in place by four 12.5 mm (0.5 in) diameter steel rods at the smaller end of the conical drum (Figure 7). At the other end, the drum was held in place by eight steel rods (ribs) fixed to a 50.80 mm (2.00 in) ballbearing assembly (Figures 7 and 8).

Thus, it is now possible to install a propane burner protruding into the central section through the hollow shaft, with the drum (Cone 1) rotating about its central axis. A 44.0 kW propane burner was choosen to heat the particulate medium and a gas-valve was installed to regulate heat input into the system.

Some further modifications to the drum (Cone 1) had to be implemented as it is likely that the high velocity of gases might force the particulate medium to exit from the medium re-entry section. By installing a one and one-quater pitch auger (secondary auger, Figure 6) at the entrance section this problem was ratified. An added advantage of this secondary auger is that the particulate medium is pushed forward at an accelerated rate with a positive displacement action, thus no clogging due to accumulation of the fine granular particles can take place in the re-entry section.

Buckets shaped from 50.8 mm (2.0 in) steel tubing were bolted to the inside wall of the drum (Cone 1) starting at the end of the secondary auger. These buckets were designed to carry the particulate medium to the top due to the rotating action of the drum (Cone 1). This permits the medium to shower through the flame, thus instantly raising the temperature of the fine sand particles.

There are twenty-two buckets attached to the inside wall of the

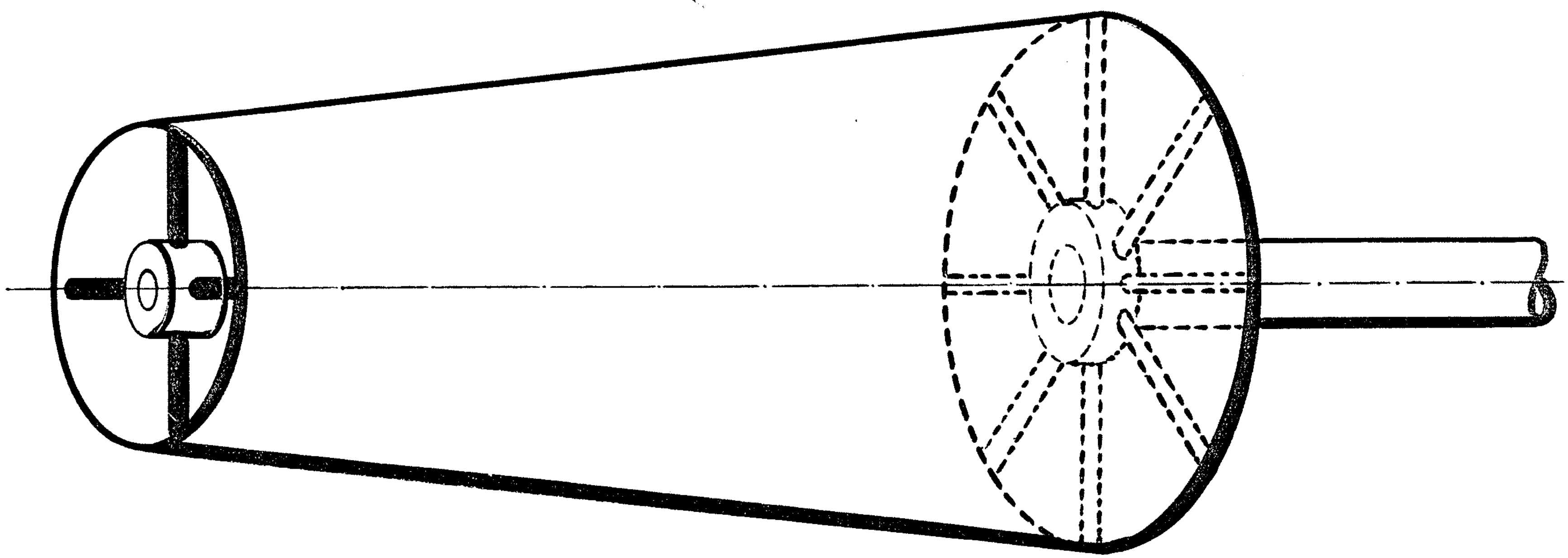


Figure 7. An oblique view of the conical drum (Cone 1).

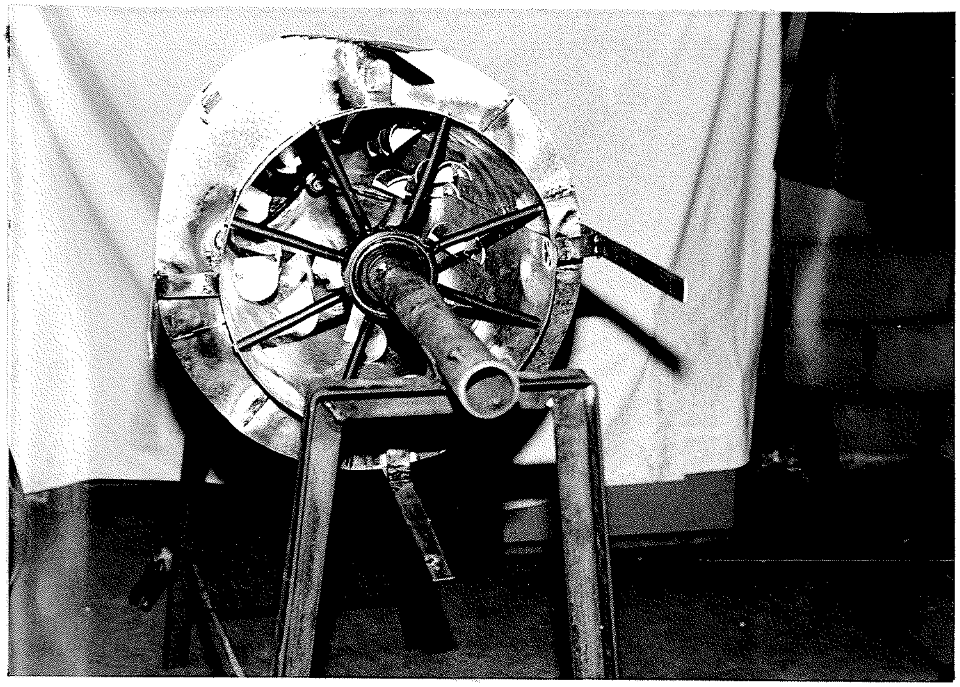


Figure 8. A view of the buckets attached to the inside wall of the drum (Cone 1).

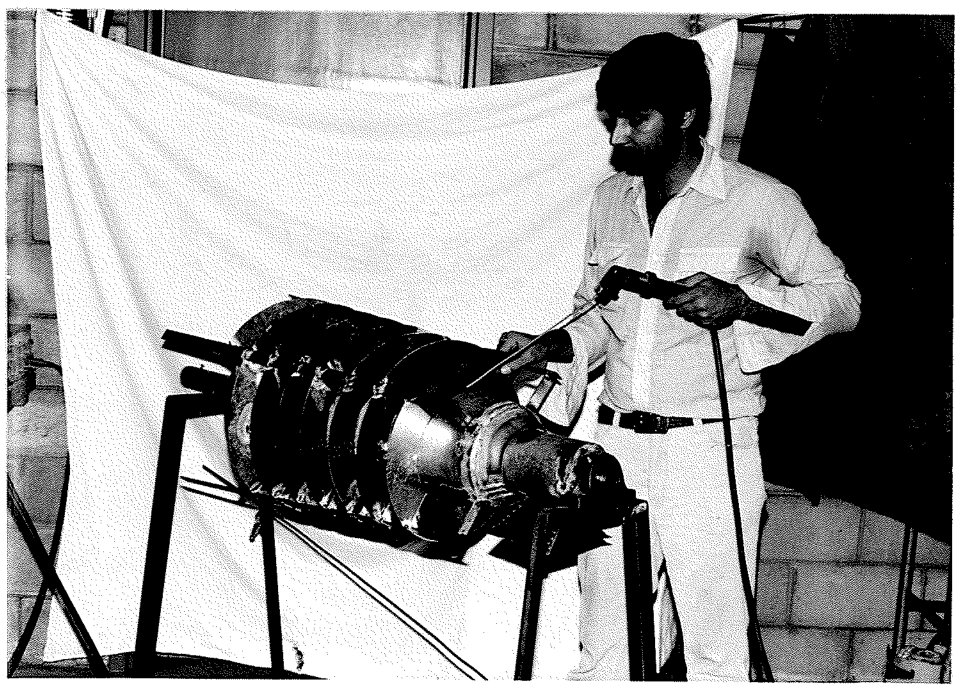


Figure 9. A view showing the constructional method of the auger around the Inside-conical-drum (Cone 1).

drum (Cone 1) (Figures 6 and 8) covering approximately one half of its length. Therefore, each particle is forced through the hot section of the flame at least three times before it is discharged out of the heating section.

3.3.2 Product inlet, mixing and heat transfer stage: After completion of the drum (Cone 1) fabrication, it was placed on a frame to facilitate in the construction of an auger around its entire length (Figure 9). The auger was constructed from 20-gauge (0.91 mm) sheet metal strips first cut to the required size and then welded onto the outside of the drum (Cone 1). Once this operation was completed, the Outer-conical-drum (Cone 2) was fabricated out of four, precut and preshaped, 24-gauge (0.64 mm) sheet metal segments. These four segments were held into place by standard 1.6*12.7 mm (1/16*1/2 in) stainless steel rivets.

The conveying auger has a total of nine complete flights (Figure 6). The first five, on the right hand side, were encased by sheet metal and the remaining four were covered by a 3.2 mm (1/8 in) hole steel wire mesh screen. The later part of the Outer-conical-drum (Cone 2), the one covered by the steel screen, acts as the primary separator.

Another frustrum of a cone was then fabricated and attached to the Inside-conical-drum (Cone 1) by four 6.3 mm (1/4 in) bolts (Figure 10) at the gas and grain inlet end. This component has a three fold purpose;

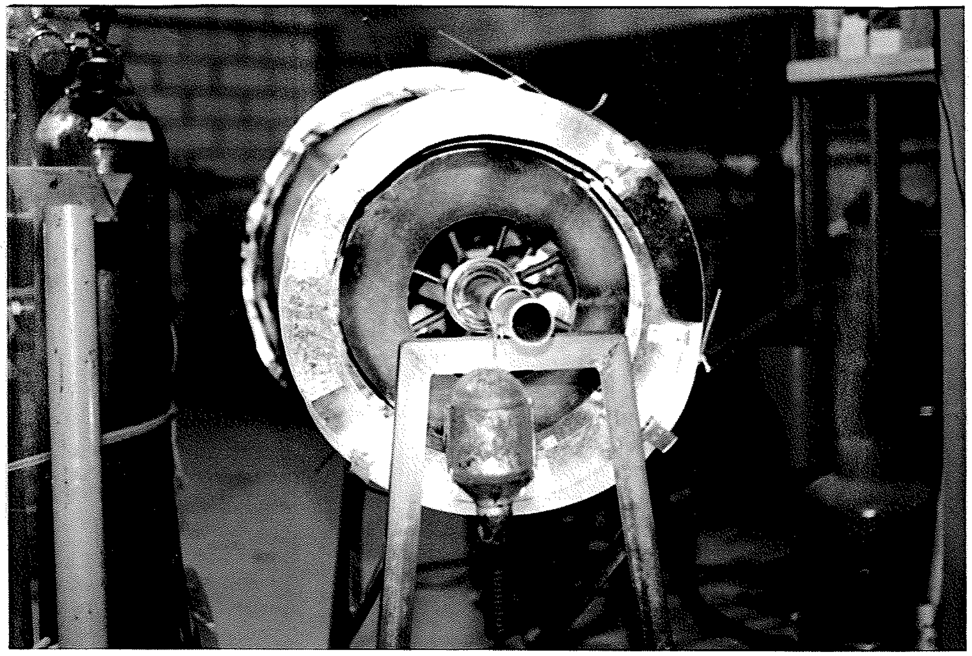


Figure 10. A view of the entrance section (at the gas and grain inlet end).

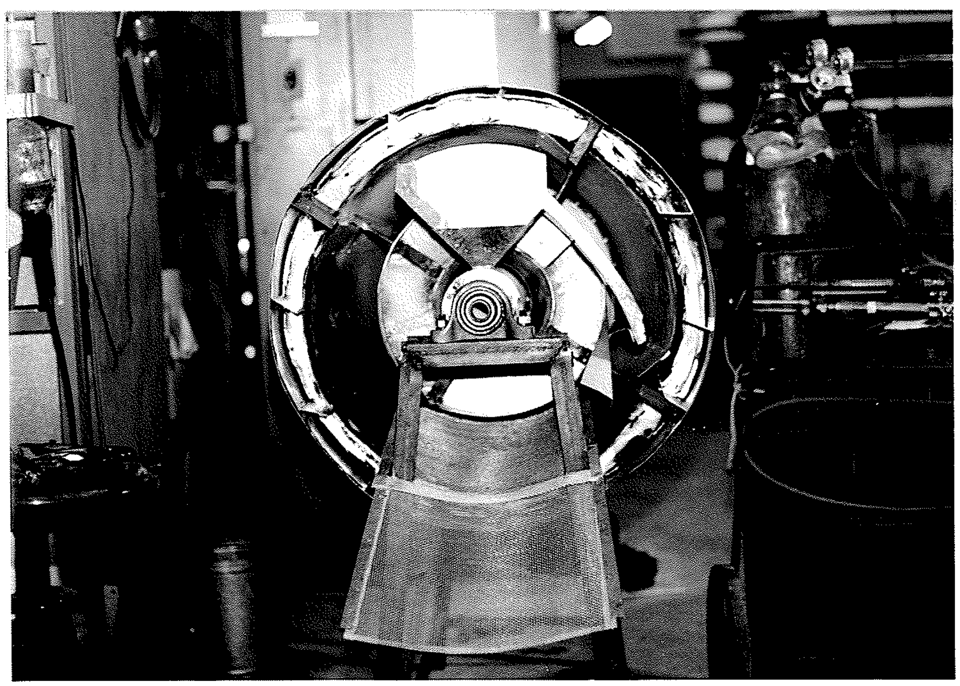


Figure 11. A view showing the secondary separator.

a) it reduces the flow of hot gases out of the Inside-conical-drum (Cone 1), thus reducing the heat loss and maintaining a steady temperature within the heating section,

b) it regulates the flow of the hot particulate medium being discharged over the material being processed; and lastly

c) it prevents the material being processed from entering into the hot section of the drum (Cone 1).

Further, the Outer-conical-drum (Cone 2) was extended to contain a two-pitch helix to allow room for the product entrance section where the product to be processed can be safely fed into the machine. It can be observed that the Outer-conical-drum (Cone 2) design significantly simplifies the complicated three step operation (product inlet; mixing; heat transfer) and also has the added advantage of allowing separation to take place in one simple step.

3.3.3 Separation and product discharge stage: As explained earlier, the four flights of the helix built around the Inside-conical-drum (Cone 1) encased by a steel wire screen facilitates the product discharge operation. The machine has to make four complete rotations before the processed product can exit from the primary separator into the secondary separator (Figure 6).

The secondary separator was fabricated from the same material as the primary separator and its location is shown in Figure 11.

This now leaves only the problem of recirculation of the particulate medium discharged by the primary separator into the machine.

3.3.4 Particulate medium recirculation stage: Perhaps the simplest solution to this problem is to install a collector at the bottom of the separating screen and then feed the discharged material by some conveying mechanism, such as a conveying auger, back into the Inside-conical-drum (Cone 1). This would require the use of an additional electric motor and before choosing this alternative it was decided to conduct a feasibility study to determine whether the recirculation of the medium can be achieved by an alternative design.

Inside the drum (Cone 1) the medium was carried upwards by a simple bucket arrangement as seen earlier. To follow such an approach at the exit end it was necessary to carry the material past the discharge section and install some kind of a collector. The problem was solved by attaching a third frustrum of a cone to the machine (i.e., Cone 3. as depicted in Figure 6). The Last-conical-drum (Cone 3) serves a dual purpose; firstly, it acts as a collector and secondly, it carries the fine granular particles to one central point of discharge.

Four U shaped ribs with the stem attached to one end were fabricated from 25.4 mm (1.0 in) angle iron and attached to the frame of the Outer-conical-drum (Cone 2). Four sheet metal strips were cut to the required size and rivetted together to form the Last-conical-drum (Cone 3). The U-shaped portion of the angle iron frame protruding beyond Cone 3 was used to construct a cylindrical bucket elevator as shown in Figure 12. Twelve buckets were spot-welded to the inside surface of the cylindrical section. These buckets carry the particulate medium to the top when the machine is subjected to an angular velocity and discharge the material at the top position as shown in the figure.

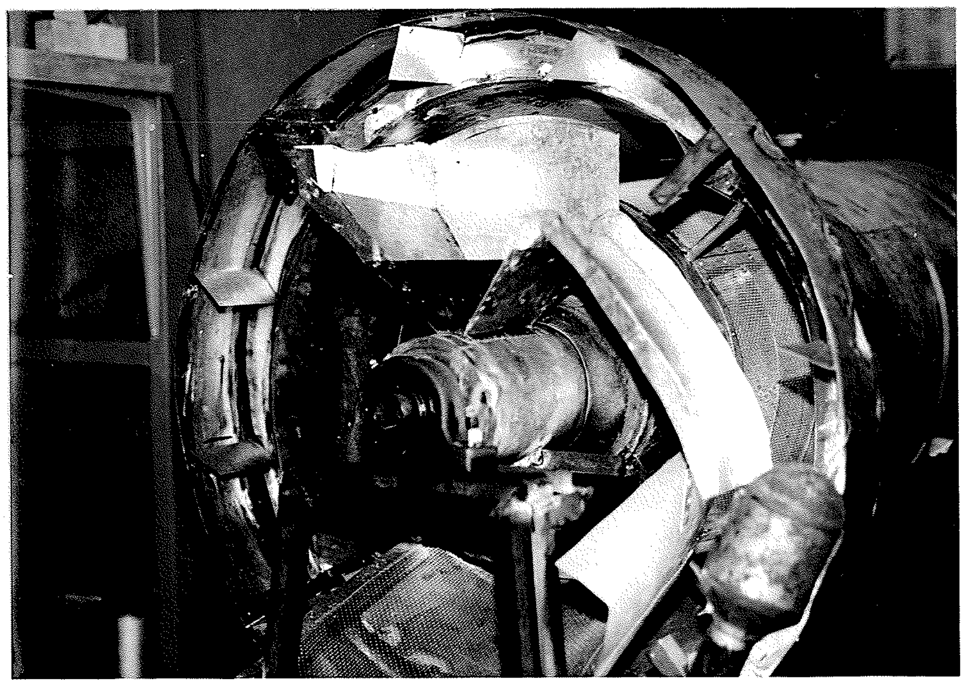


Figure 12. Product discharge and sand recirculation end of the machine.

A funnel that could receive the discharged material was then designed and fabricated out of 20-gauge (0.91 mm) sheet metal (Figures 6 and 12). The drive shaft was further modified and a two-pitch auger built around it so that it could carry the particulate medium back into the Inside-conical-drum (Cone 1).

As a final step, a stand was constructed to hold the variable speed 0.75 kW motor as shown in Figure 6. The outside of the machine was insulated with a 80 mm thick R-10 glass wool batts to minimize heat losses. Two views of the final machine are presented in Figures 13 and 14.

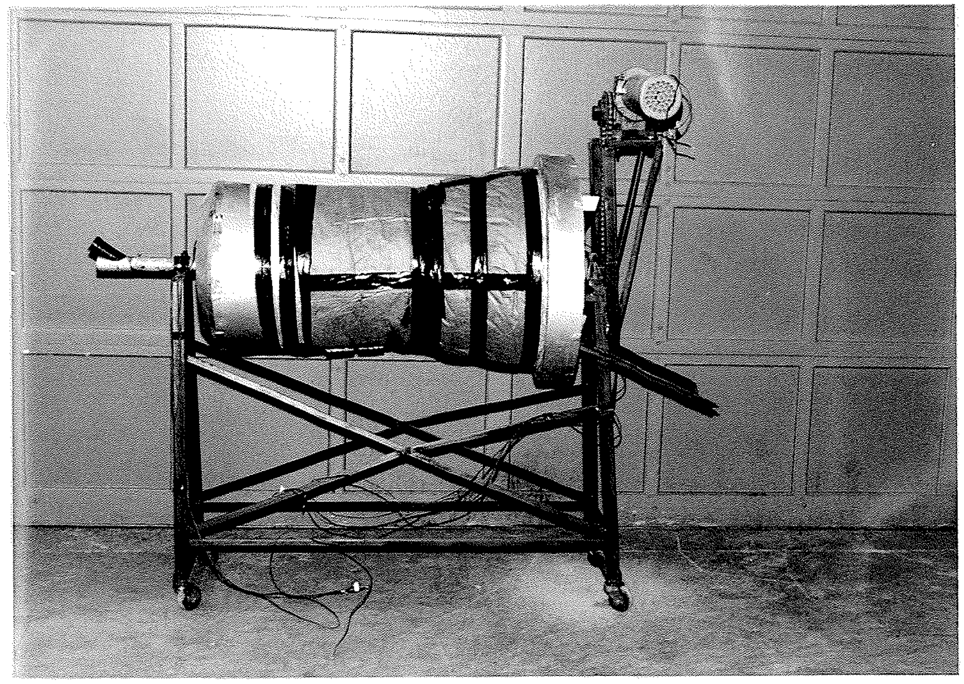


Figure 13. A frontal view of the machine.

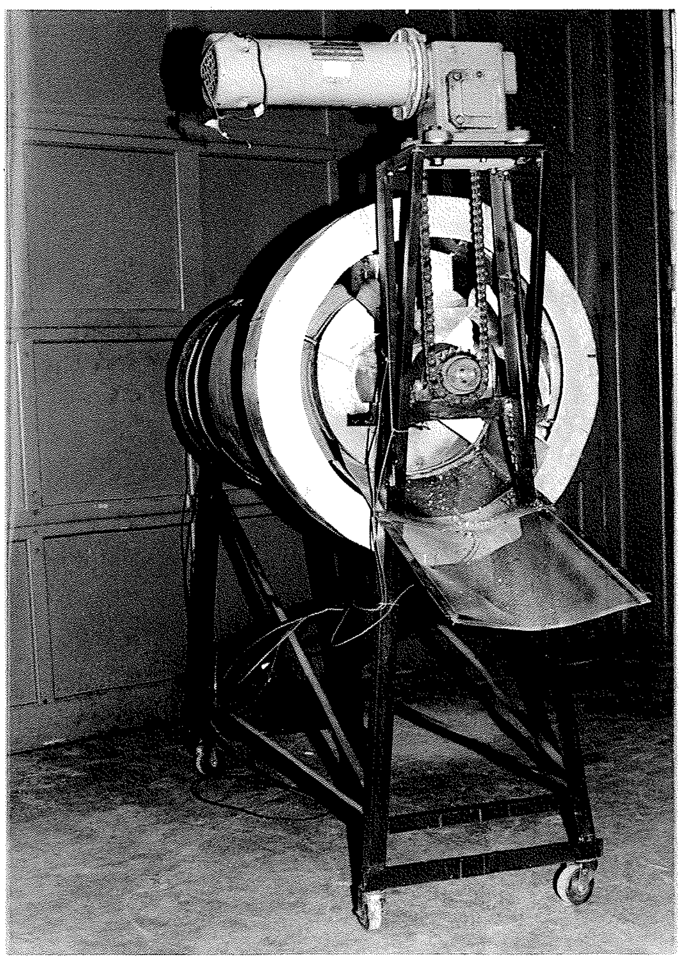


Figure 14. A perspective view of the machine showing product discharge end.

IV. DRYING POTENTIAL OF THE GRAIN PROCESSOR

In this section drying potential of the grain processor was experimently evaluated. The objective was to collect as much information as possible on the dryer performance in relation to heat input, grain feed-rate, contact time and moisture loss. This would determine whether the machine is able to achieve steady state conditions and process corn in a continuous flow operation.

4.1 Equipment and Instrumentation

Initially, when the machine was fired, the bearing got excessively hot and the flame inside the drum (Cone 1) was yellowish in color implying that the combustion process was incomplete. Therefore, a few modifications were made to the machine to insure complete combustion of the gaseous fuel. Since the burner was located in an enclosed space it was necessary to force air through the hollow support shaft;

a) to bring the fuel to complete combustion, and

b) to hold the temperature level of the main bearing to within its design limits.

The machine was provided with a 0.75 kW variable speed motor. Figure 15 illustrates the schematic of the flow path of the materials inside the processor. Grain is fed into the processor at the right end (Figure 15) by an external auger-conveyor, driven by another 0.75 kW variable speed motor. The auger-conveyor selected had a flow capacity range of 0.15 to 2.0 t/h. The two motors were controlled independently.

Eighteen iron constantan (Type J) thermocouples were connected to

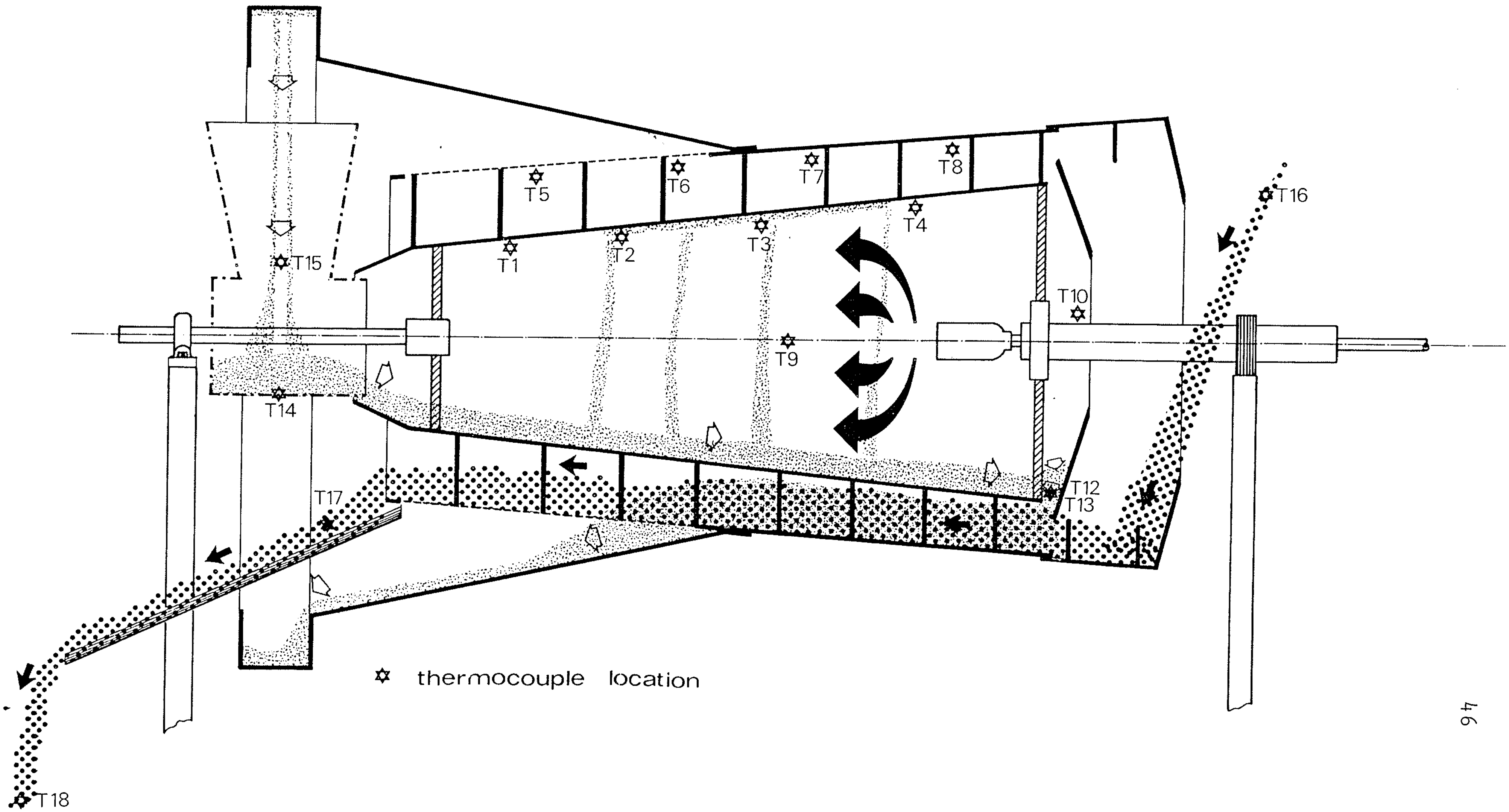


Figure 15. A schematic diagram showing the thermocouple locations and the flow-path of the particulate medium and product to be processed.

the machine (Figure 15). T1-T4 were fixed to the inside wall of the drum (Cone 1) and T5-T8 were attached to the inside wall of the outer drum (Cone 2). The wiring for these eight thermocouples was led out to eight connectors attached to the outside of the machine. Therefore, their readings can only be monitored when the machine is not rotating. These eight thermocouple readings indicate temperature profiles that exist in the heating stage of the sand particles and during the heat transfer stage where sand transfers some of its heat to raw corn. When the machine was stopped it was necessary to have thermocouple junctions located at the bottom, since all the materials are collected at the bottom.

The temperature readings from thermocouples, T9-T18, were recorded on a Doric 205 data logger, which has an accuracy of $\pm 1^{o}C$. This set has the ability to provide a continuous prinout of the temperature measurements even when the machine was operating. T9 measures the temperature of the hot gases inside the drum (Cone 1), T10 the temperature of the hot gases exiting from the drum (Cone 1) and T11 the ambient or room temperature. Thermocouples T12-T15 monitor the temperature of the particulate medium at different locations inside the machine (Figure 15). T12 and T13 provide temperature of the sand particles just before it enters the mixing zone. T14 and T15 indicate the temperature of the sand prior to its re-entry back into the heating section. Lastly, thermocouples T16-T18 record temperature variation of the grain corn along its path inside the machine.

4.2 Materials

Prewashed and pregraded medium texture sand (sieve no. 55) was used as the drying medium in this experiment. Two trials were also conducted using a coarse sand (sieve no. 30) and a fine sand (sieve no. 65). The grain used in these experimental trials was corn harvested at the Macdonald College Farm of McGill University, Quebec. Since the year 1983 had been relatively dry, the harvested corn had a final moisture content of 18% wb. Thus, it was necessary to re-wet the corn before the dryer performance could be evaluated.

4.3 Experimental Procedure

Fifteen trials were conducted in a random order involving five variable test parameters: drum speed (rpm), hot sand temperature, grain feed-rate, initial grain moisture content and initial grain temperature.

The first step was to have a minimum of 125 kg grain corn ready for processing at the desired moisture content. To conduct an experimental trial it was estimated that a minimum of 5 min were required to achieve steady state drying conditions within the processing unit.

For experiments where the grain moisture level had to be increased the following procedure was used. Corn was immersed in water for a period ranging between 5 to 45 min and allowed to soak. The water was then drained and corn was placed in closed plastic garbage containers and stored in a refrigerator at 4^{o}C for two days prior to use. It was expected that this would result in uniform moisture distribution throughout the grain sample.

The grain conveying-auger was calibrated first to achieve the varying feed-rates at different control settings. This was accomplished by measuring the mass of grain collected in a container after five minutes for each setting. The process was repeated five times at each setting and the mean value was used for the analysis.

The processor was then calibrated for grain residence time and sand flow rate. The residence time was obtained by noting the total time taken by a small sample of corn to travel from one end of the machine to the other for any one preset angular velocity. Therefore, if the angular velocity changes so does the residence time. To determine the flow rate (kg/h) of the sand particles it was necessary to approximate the time required by sand to complete one cycle. This was obtained by recording the time taken by tracer particles introduced into the funnel to return after going through one cycle. Once this was known the flow rate was obtainable by taking the ratio of total mass of the sand in the processor to the time observed to complete a cycle.

Sand to grain mass ratio (SGMR) is defined as the ratio of the flow rate of the particulate medium to the flow rate of the processed product. It should be noted that the flow rate of the product is independent of the machine angular velocity since it is fed by an independent auger, but a change in the machine angular velocity influences the medium flow rate. Varying SGMR is obtainable by either changing the feed rate or the drum speed.

After all the above information pertaining to the flow characteristics of the two media was gathered, the processor was prepared for lighting of the propane burner. The machine was stopped and a flame was introduced into the central section. As soon as the burner was lit, the machine was set to rotate so that high temperature-points would not develop and cause damage due to uneven expansion at the joints.

The sand particles attained a temperature of approximately 250°C in 5 minutes. Therefore, it was necessary to have the grain ready for processing as soon as this temperature was reached. At this point the grain feed-auger was started and the temperature of the sand at both ends of the machine was monitored. As indicated earlier it takes a few minutes before the temperature of the sand and the processed grain stabilizes. Once satisfactory conditions existed, samples of the hot and raw corn were collected from the secondary separator and the feed-bin, respectively, and were sealed in moisture cans for further tests pertinent to gravimetric moisture content determination. The aforementioned procedure was repeated for all the test runs.

4.4 Method of Analysis

Determination of the moisture content of the grain samples was done according to the ASAE standard S352 (ASAE 1982) and computed using the equation:

$$Mw = \frac{\text{Mass of water}}{\text{Mass of wet material}} \qquad \text{(25)}$$

Since some of the past research on grain drying was carried out on a dry basis (db) moisture scale, the following relationship is suggested for changing Mw to Md:

$$Md = Mw \;/\; (1-Mw) \qquad \text{(26)}$$

where,

Md - moisture content, dry basis (kg/kg)

Mw - moisture content, wet basis (kg/kg)

For the remainder of the thesis all moisture contents referred to are on a wet basis unless otherwise stated.

To relate the moisture removal process to the machine operating conditions Equations 3 through 6 were used to calculate the latent heat of evaporation from which the drying efficiency, Ed, defined as the ratio of the heat used to evaporate water from the grain to the total heat input, was calculated:

$$Ed = \frac{Ww*Lv}{Ws*Cps*(Tsh-Tsc)} \quad \text{.............................} \quad (27)$$

which can be rewritten as:

$$Ed = \frac{Lv*Ml}{SGMR*Cps*(Tsh-Tsc)} \quad \text{..........................} \quad (28)$$

where,

Ed - drying efficiency (decimal)

Ww - mass-rate of water removed (kg/h)

Ws - mass-rate of hot sand (kg/h)

Ml - grain moisture loss measured, wet basis (decimal)

Lv - latent heat of evaporation (kJ/kg)

SGMR - sand grain mass ratio (-)

Cps - specific heat sand (kJ/kg^{O}C)

Tsh - temperature of the hot sand (^{O}C)

Tsc - temperature of the cold sand (^{O}C)

In evaluating the total heat input for calculating the drying efficiency, only the heat supplied by the hot sand to the raw corn was used. This assumption is true for this dryer design, since all moisture removal and temperature data used in the above calculations (Equations 27 and 28) were taken after steady state temperature conditions are reached.

Further, the heating efficiency, Eh, was calculated by the Equation 30 noted below. The heating efficiency can be defined as the ratio of the heat used to evaporate water plus the heat added to raise the temperature of the raw corn to the total heat input.

$$Eh = \frac{Ww.Lv + Wg*Cpg*(Tgh-Tgc)}{Ws*Cps*(Tsh-Tsc)} \qquad \text{(29)}$$

which can also be written as:

$$Eh = Ed + \frac{Cpg*(Tgh-Tgc)}{SGMR*Cps*(Tsh-Tsc)} \qquad \text{(30)}$$

where,

Eh - heating efficiency (decimal)

Cpg - specific heat of the grain (kJ/kg^{o}C)

Tgh - temperature of the hot grain (^{o}C)

Tgc - temperature of the cold grain (^{o}C)

A fuel efficiency, Ef, was then defined as the ratio of the heat used to raise the temperature of sand particles inside Cone 1 to the total heat input. It was calculated using the equation:

$$Ef = \frac{Qs + Qai - Qao}{Wp*Lp} \qquad \text{(31)}$$

where,

$$Qs = Ws*Cps*(Tsh-Tsc) \qquad \text{(32)}$$

$$(Qai-Qao) = Va*Da*Cpa*(Tah-Tae) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (33)$$

Wp - mass-rate of propane used (kg/h)

Lp - Latent heat of combustion for propane (kJ/kg)

Qs - heat energy used to raise the sand temperature (kJ/h)

Qai - heat energy used to raise the cold air temperature (kJ/h)

Qao - heat energy lost by the hot air leaving Cone 1 (kJ/h)

Va - volumetric flow-rate of the cold air into Cone 1 (m^3)

Tah - average temperature of the hot air in Cone 1 (^oC)

Tae - exit temperature of the hot air from Cone 1 (^oC)

Cpa - specific heat of air (kJ/kg^oC)

Da - density of air (kg/m^3)

Lastly, the total efficiency, Et, of the processor was calculated by multiplying the heating efficiency with the fuel efficiency.

$$Et = Eh*Ef \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (34)$$

It was decided not to include the energy required to drive the machine in calculating the total efficiency, because even if the energy required to drive the machine is included in the denominator of Equation 31 it was found that there was no significant effect on the result obtained, as the contribution of this term is less than 1.5 % of the total efficiency.

V. RESULTS AND DISCUSSION

The results obtained from the fifteen drying experiments carried out are summarized in Table 2. These have been presented in an ascending order for SGMR values ranging between 2.68 to 8.41. For experiment Set 1 to 14, steady-state temperature conditions were achieved for continuous flow grain processing operation. It was found that in Set 15 there was a significant loss of sand mass as it was blown out of the machine by the exiting hot air. The results of this set are questionable as SGMR could not be accurately determined. It was, therefore, decided to use the data from Sets 1 to 13 for evaluating the dryer potential as the sand particle size used, is the same for these thirteen experimental trials.

5.1 Machine Characteristics

A plot of grain residence time vs. the machine angular velocity is presented in Figure 16. It was observed that the curve is very close to a linear fit. This is true because the internal helix advances the grain forward by a distance equivalent to one pitch for every rotation. However, as the angular velocity increases it can be seen that the curve shifts upwards, indicating that the grain particles tend to prolong their stay in the dryer. The best fit line was drawn and a numerical solution found to fit the data. The following equation approximates the grain residence time for the machine drum speed ranging between 15 to 25 rpm:

Table 2 Results obtained from the 15 trial-runs conducted using the prototype machine.

No.	SGMR	m/s Speed (rpm)	GRAIN Res. Time (s)	GRAIN Flow Rate (t/h)	TEMPERATURE (°C) Sand Hot	Sand Cold	Grain Raw	Grain Hot	GRAIN Moisture (% wb) Raw	Hot	Loss
1	2.68	16.2	34.8	0.52	250	125	0	96	18.22	16.97	1.25
2	2.93	17.5	32.1	0.49	249	117	7	84	32.89	31.41	1.48
3	3.40	16.2	34.8	0.41	222	101	1	82	31.47	29.69	1.78
4	3.64	23.9	23.1	0.51	198	111	12	80	30.44	29.21	1.23
5	4.11	15.0	36.5	0.33	204	110	3	87	27.42	24.98	2.44
6	4.49	24.8	22.0	0.45	205	121	7	90	32.01	29.26	2.75
7	4.97	16.2	34.8	0.28	208	126	10	92	32.60	29.55	3.05
8	5.43	15.0	36.5	0.25	191	108	0	91	28.82	26.30	2.52
9	6.08	22.6	24.6	0.28	201	122	0	89	34.47	30.68	3.79
10	6.52	24.8	22.0	0.31	192	133	9	87	32.16	28.91	3.25
11	7.10	22.6	24.6	0.24	235	157	1	102	35.78	30.46	5.32
12	7.73	23.9	23.1	0.24	238	174	11	100	30.38	26.69	3.69
13	8.42	24.8	22.0	0.24	188	127	0	86	31.81	28.92	2.89
14	5.01	16.2	34.8	--	203	137	9	97	32.34	29.39	2.95
15	--	16.2	34.7	--	187	109	11	90	32.40	29.41	2.99

Set 1 to 13 was conducted using medium sand (sieve No. 55)
Set 14 was conducted using coarse sand (sieve No. 30)
Set 15 was conducted using fine sand (sieve No. 65)
Contact time = (Res. Time)*5/9

SGMR - calculated sand to grain mass ratio
m/c Speed - machine rotational speed
Res. Time - grain residence time in the processor

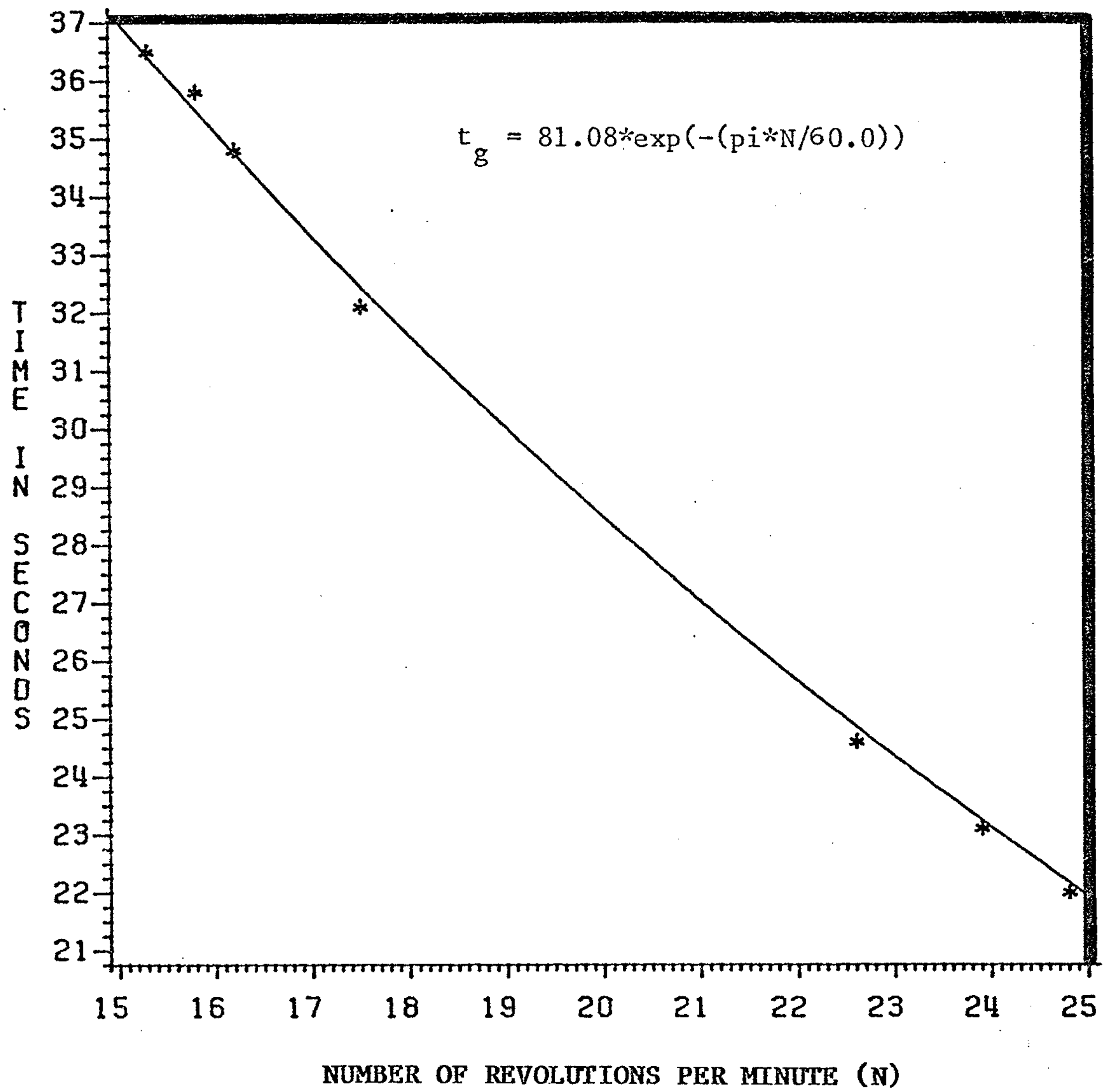


Figure 16. Grain residence time vs. machine rotational speed.

$$t_g = 81.08 \cdot \exp(-0.5 \cdot w) \quad \text{.........................} \quad (35)$$

where,

$$w = (2 \cdot pi \cdot N) / 60.0 \quad \text{..............................} \quad (36)$$

t_g - grain residence time in the dryer (s)

w - angular velocity (rad/s)

pi - constant (-)

N - machine rotational speed (rpm)

A second numerical solution was developed to calculate the recycle time of sand particles (i.e., the time required by sand particles to complete one cycle). Figure 17 is a plot of the experimentally determined values for sand recycle time vs. the machine rotational speed. Equation 37 approximates the recycle time, t_s, for a machine rotational speed between 15 to 25 rpm.

$$t_s = 53.05 + 10.56/\tan(w) \quad \text{.......................} \quad (37)$$

It is interesting to note that the two curves behave differently. As the machine angular velocity increases it is expected that the grain kernels stick to the side of the primary separation screen, thus prolonging their stay. On the other hand, it appears that the sand particles after falling through the screen are carried forward at an accelerated rate from Cone 3 into Cone 1 thereby reducing the recycling time. Further, it is expected that the slope of both Cone 1 and Cone 3 would accelerate the forward motion of the sand particles as the angular velocity increases.

Several cold trial runs were conducted to test the flow behaviour of the two media before evaluating the machine for its heat and mass transfer characteristics. It was noted that the separation process was

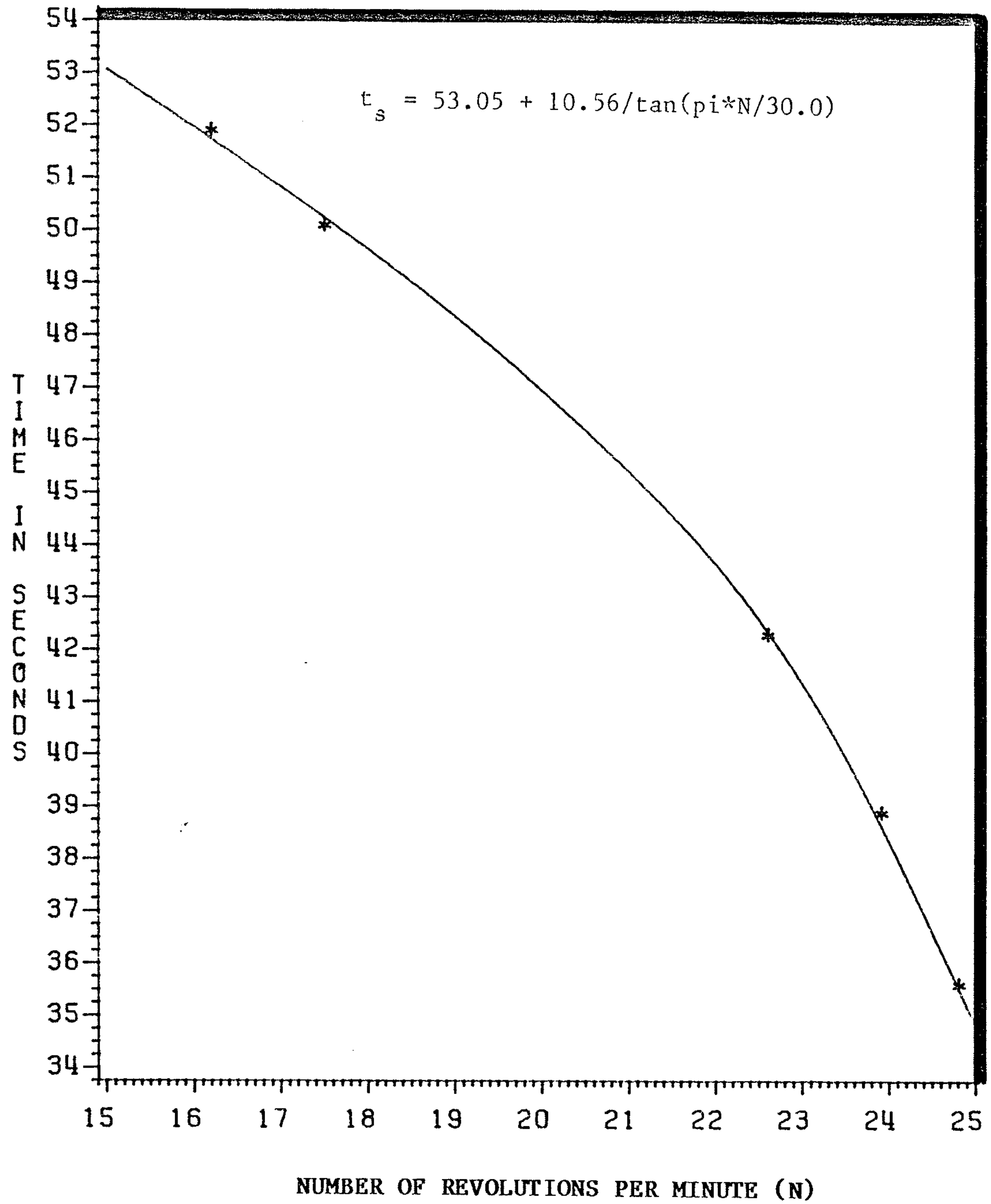


Figure 17. Sand recycle time vs. machine rotational speed.

complete and the recirculation was very effective for machine angular velocities between 15 and 25 rpm. However, outside these limits it was observed that the sand recirculation was not as effective. When the angular velocity was decreased to below 12 rpm the sand particles accumulated in the cylindrical bucket elevator and substantial sand losses were recorded. It is felt that this effect was due to the special 'V' configuration of the recirculation buckets as they were unable to successfully elevate the sand particles to the top for discharge into the fixed funnel (Figure 6).

When the machine rotational speed was increased beyond 28 rpm the sand particles were carried upwards at an accelerated rate and discharged beyond the range of the fixed funnel. This effect was probably due to the centrifugal force which tends to keep the sand particles attached to the inside surface of the drum. For a drum diameter of o.75 m centrifuging occurs at 34.5 rpm, thus indicating that the angular velocity dictates the range for which this machine can be operated.

In the preliminary heating study conducted it was found that the flow behaviour of the two media and the separation process were satisfactory. The result suggests that the secondary auger (Figure.6) performed very well in preventing the hot air from discharging the fine sand particles out of Cone 1. Because of this blockage it was also noticed that the ambient hot air temperature inside the heating section achieved a steady temperature of 385^{o}C very rapidly.

The temperatures registered by thermocouples T9 through T18 for data Sets 1 and 12 are presented in Tables 3 and 4 respectively. It

Table 3. Temperature readings of thermocouples T-9 through T-18, for experimental data-set 1.

Time	T-9	T-10	T-11	T-12	T-13	T-14	T-15	T-16	T-17	T-18
13:39:00	486	140	16	99	102	18	19	4	-	-
13:40:00	384	135	16	131	136	20	19	4	-	-
13:41:00	352	148	17	168	175	41	64	4	-	-
13:42:00	374	167	17	199	205	76	98	4	-	-
13:43:00	410	188	18	231	230	106	114	5	-	-
start										
13:43:47	384	193	18	238	241	122	141	3	-	-
13:44:00	399	194	18	248	246	126	145	2	-	-
13:45:00	376	198	19	250	253	132	135	1	103	-
13:46:00	391	202	20	252	250	125	128	0	111	-
13:47:00	391	202	20	251	250	122	125	0	109	96
13:47:51	385	203	20	246	248	120	123	-	104	96
stop										
13:49:00	109	133	20	146	153	126	128	13	-	98

Time - hour:minute:second
T-n - thermocouple number as defined in the text (Figure 15).

Table 4. Temperature readings of thermocouples T-9 through T-18, for experimental data set 12.

Time	T-9	T-10	T-11	T-12	T-13	T-14	T-15	T-16	T-17	T-18
11:33:23	414	161	18	63	67	24	49	12	-	-
11:34:00	255	121	17	63	88	30	50	12	-	-
11:35:00	302	151	16	133	130	59	83	13	-	-
11:36:00	316	176	18	162	160	94	122	13	-	-
11:37:00	331	190	19	187	188	126	150	13	-	-
11:38:00	154	127	22	165	163	147	153	13	-	-
11:39:00	738	325	-	179	178	137	126	14	-	-
11:40:00	340	202	26	198	199	145	169	14	-	-
11:41:00	367	213	23	227	226	169	192	14	-	-
start										
11:41:13	369	213	25	231	231	174	198	14	-	-
11:42:00	375	227	21	242	240	183	197	8	-	-
11:43:00	385	220	26	235	234	175	184	11	104	-
11:44:00	386	222	24	235	236	166	174	10	124	100
11:45:00	376	221	27	229	232	159	167	12	127	99
11:45:36	380	217	29	230	229	157	165	13	127	99
stop										
11:47:00	111	143	29	165	163	147	151	-	-	100

Time - hour:minute:second
T-n - thermocouple number as defined in the text (Figure 15).

can be seen that after approximately six minutes the sand particles (T12 and T13) attained a steady temperature of about 250°C (Table 3). The same trend is noticed in Table 4, except at 11:38:00 when the burner flame died out, a rapid drop in the temperature of hot air and sand resulted. In both data sets, test results indicate that once the grain processing commenced there was very little fluctuation in the inlet temperature of the sand (T12). The sand at the recirculation end (T15) registers a further increase before dropping down to a steady temperature value. This effect is probably due to: a) the time lag between the two locations and b) the heat transfer taking place between the machine and the sand particles before an equilibrium temperature condition is achieved.

Similar results were found in all the other trials conducted. Therefore, the primary objective in terms of processing the grain on a continuous flow basis was achieved. Examining the results presented in Table 2 it is observed that the grain feed-rates were between 0.24 to 0.52 t/h for a varying range of grain moisture, sand temperature and grain residence time conditions. The fifteen experiments conducted demonstrate that it is possible to successfully process large volumes of high moisture corn in this prototype machine. The maximum capacity of this machine would be approximately one tonne per hour, of high moisture grain corn, if a SGMR of 1.0 were selected.

5.2 Moisture Removal

For relatively high grain mass flow-rates and a short contact time (12.2 to 19.3 s), the moisture removal varied between 1.25 to 5.32 %. In these cases most of the heat transferred by the hot sand were used to raise the temperature of the grain kernel instead of evaporating the moisture. After the first few trials, it was decided to experiment with an aeration process to find out whether further reduction in the final grain moisture can take place.

The processed corn was collected and sealed in plastic garbage cans. Small samples (4 to 5 kg) of the heated corn were then placed on a screen and two trials were conducted by forcing air, at 40^{o}C and 20^{o}C respectively, through it. The results are presented in Figures 18 through 22. Although, substantial moisture losses were recorded in all the five cases, it is not conclusive whether air at a higher temperature removes more moisture, since only one set of result (Figure 20) indicates this trend.

There were moisture losses noted in the holding tank. For all the tests usually the time allowed in the holding tank was about five minutes for the first test and twenty minutes for the second test. Therefore, it is not too surprising to note that a moisture loss of 0.4% to 1.0% was recorded between the two tests (Figures 18 to 22). Based on these results no conclusion can be drawn whether the processed corn should undergo tempering before it is aerated. However, it can be argued that the aeration process successfully used the heat stored in the processed grain to increase the moisture loss substantially.

From the results of the present study it would seem that the two

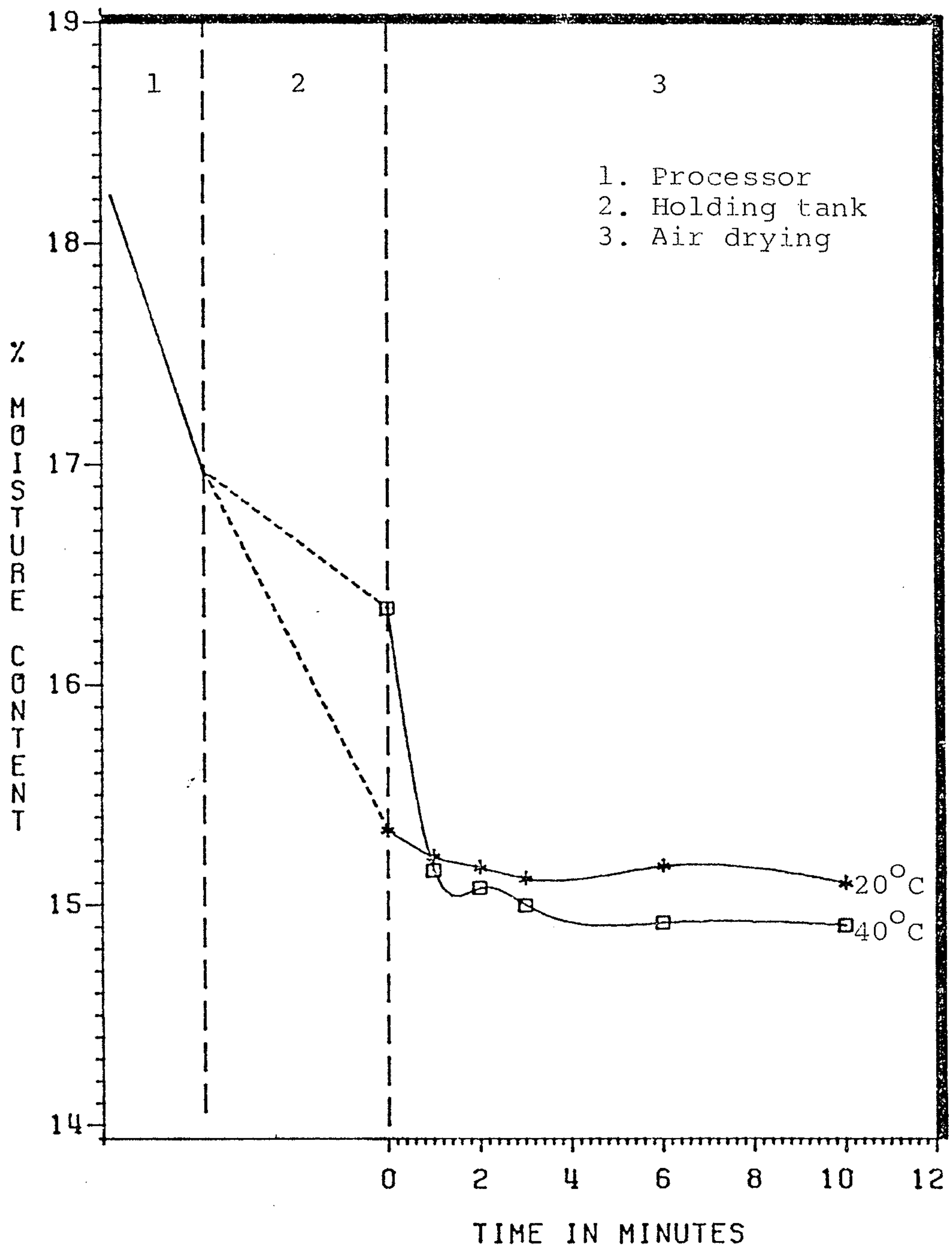


Figure 18. Three step moisture loss for data set 1.

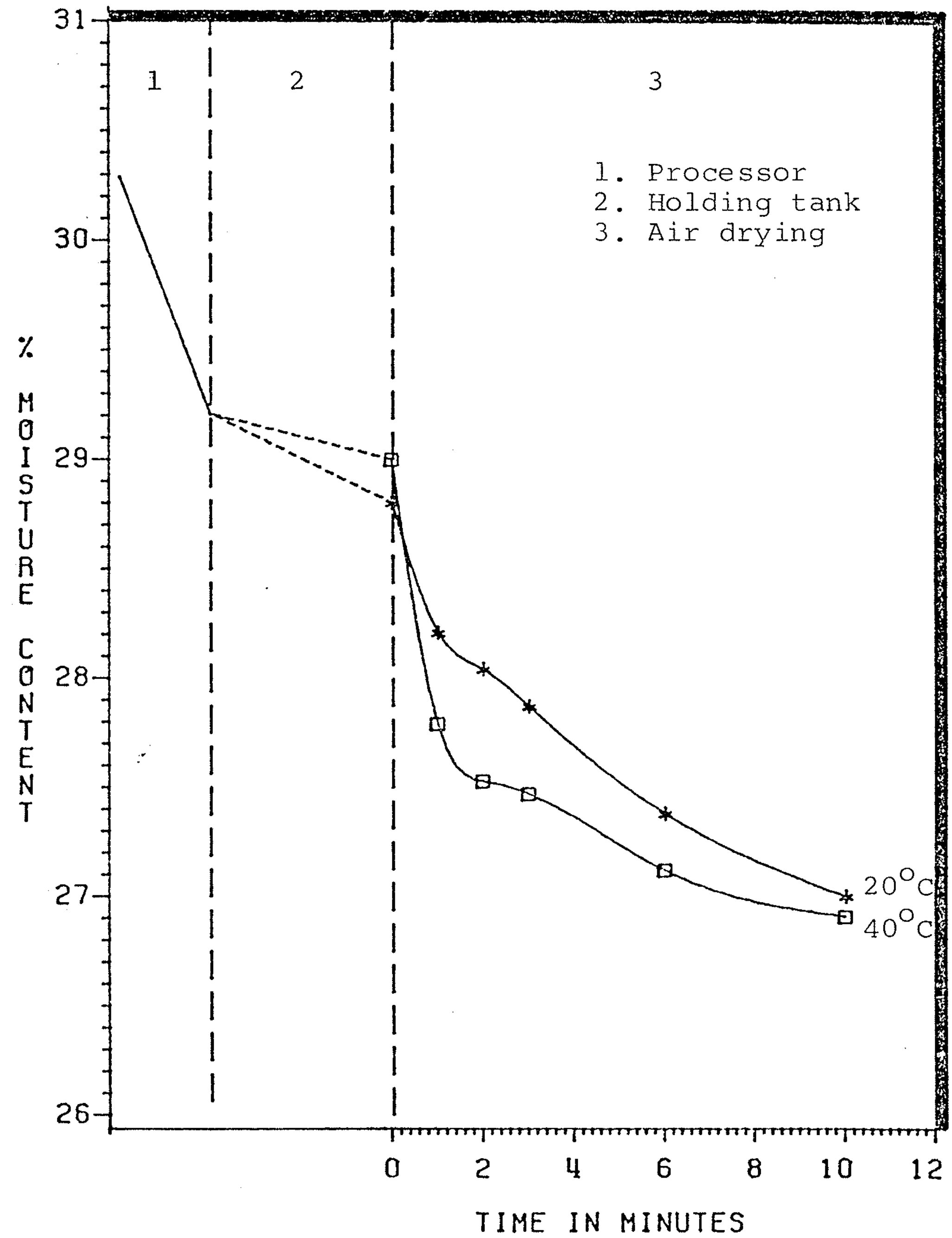


Figure 19. Three step moisture loss for data set 4.

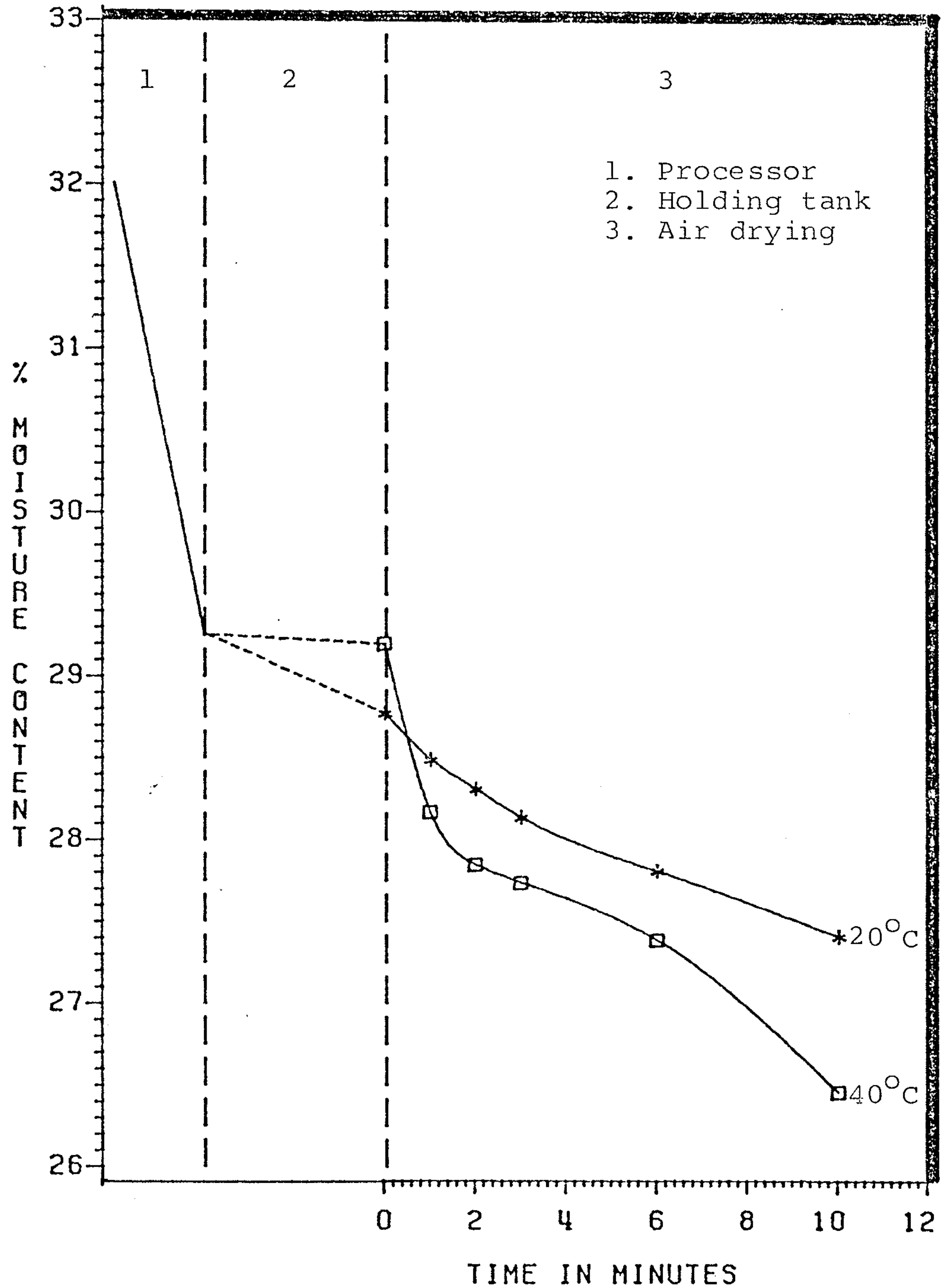


Figure 20. Three step moisture loss for data set 6.

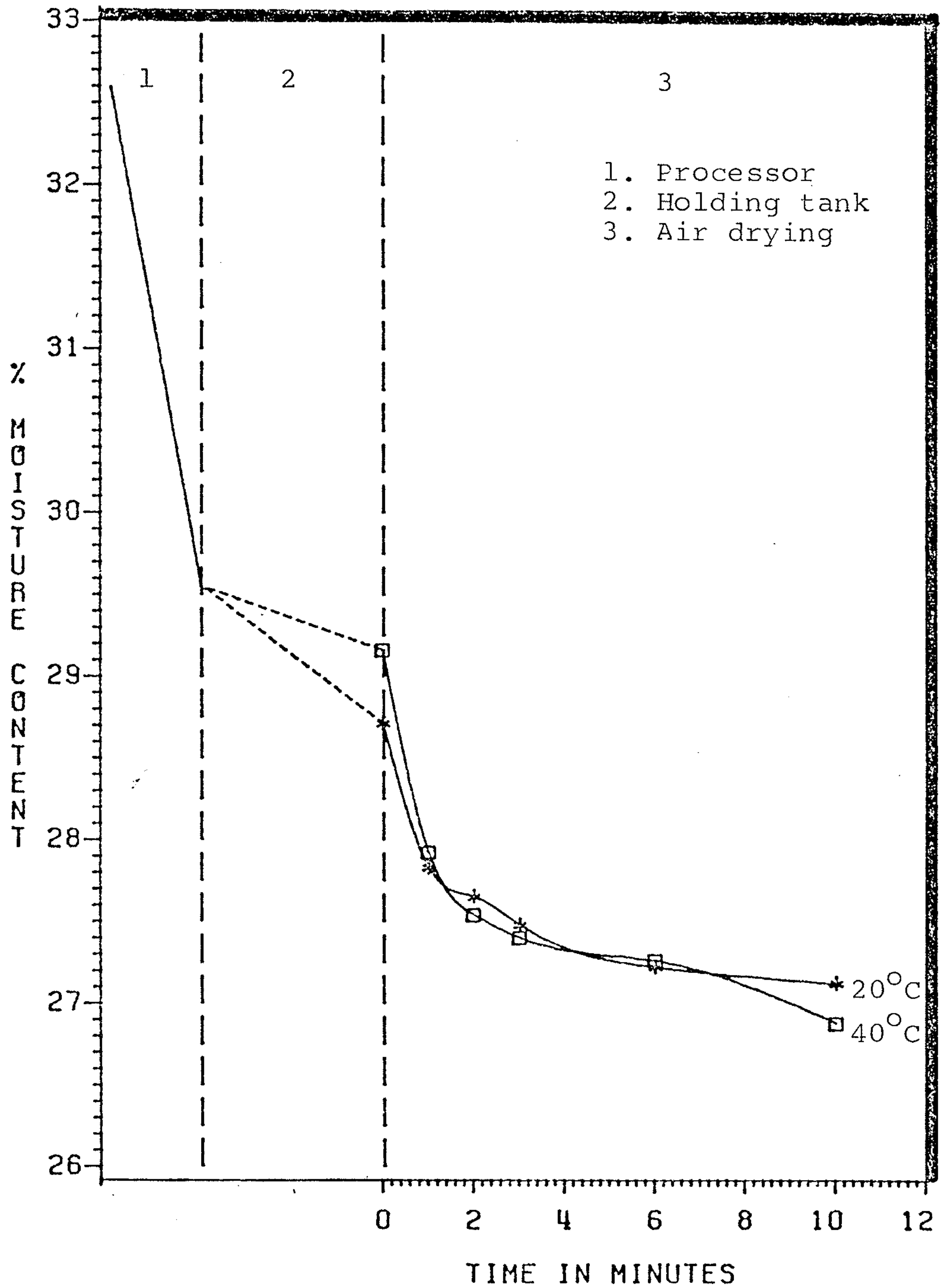


Figure 21. Three step moisture loss for data set 7.

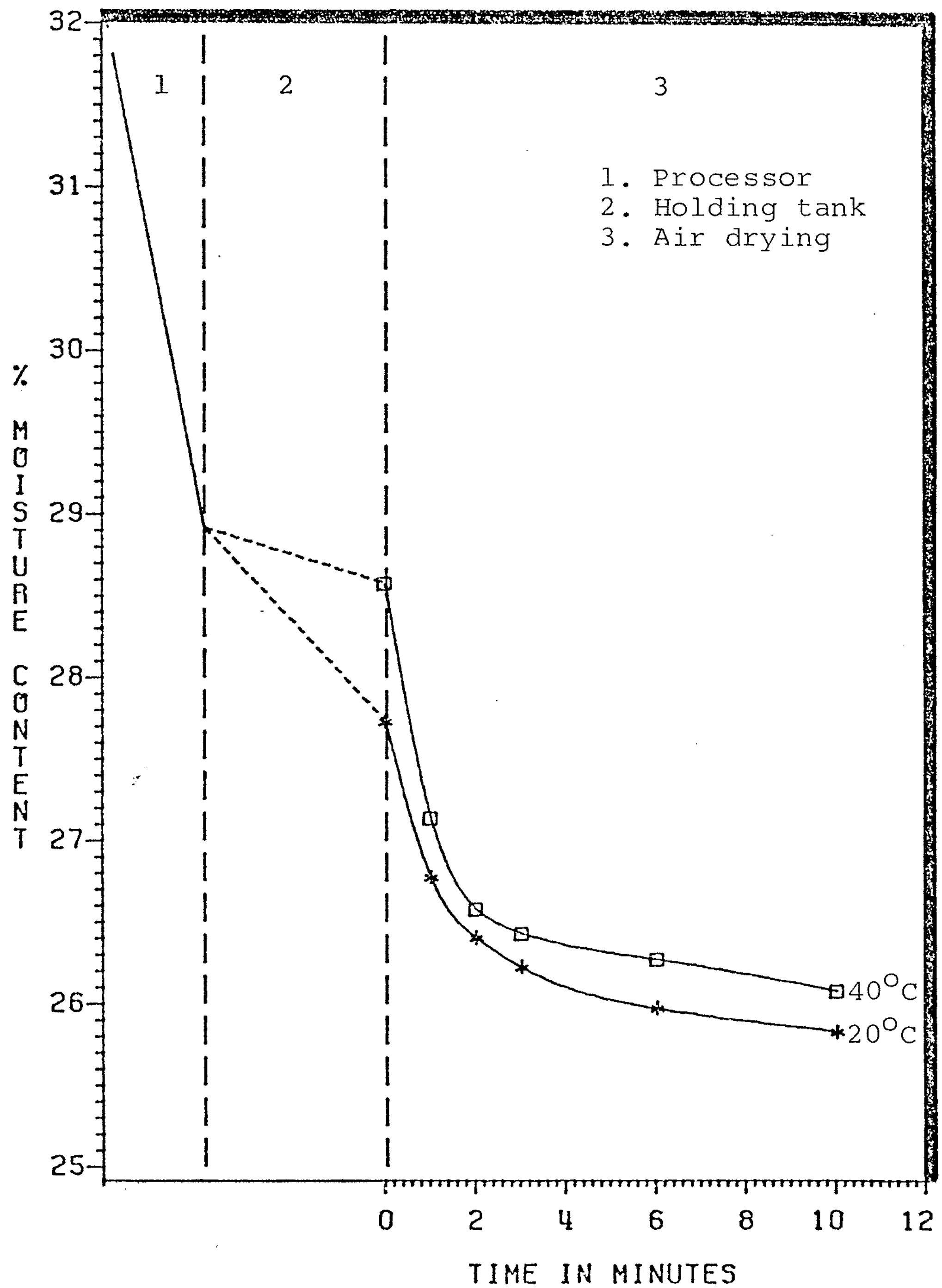


Figure 22. Three step moisture loss for data set 13.

systems, i.e. a grain processing unit and an aeration unit, would have to be somehow integrated for optimizing the moisture removal process. More work is required to establish this fact.

5.3 Efficiency of the Grain Processor

For calculating the drying and heating efficiencies, the physical properties of the corn were ascertained. These were done by following the approach presented by Fortes and Okos (1980, 1981) and the results are presented in Table 5. The latent heat of evaporation was found to vary between 2.22 to 2.35 MJ/kg, which is lower than the suggested value of 2.56 MJ/kg taken by other researchers (Lapp et al., 1976a, 1976b; Meiering et al., 1977). This difference is due to the very high relative humidity found to exist at the kernel surface, thus contribution of the last term in Equation 6 is negligible.

The experimental drying efficiency ranged from 10.61% to 26.14%, whereas the heating efficiency varied between 68.97% and 90.46% (Table 6). The latter is very close to the values reported by Tessier (1982).

In testing the dryer potential grain feed-rates and/or machine angular velocity had to be varied in order to test for different SGMR. For the range of values tested, there was no noticeable effect of either the contact time or SGMR on the heating efficiency. This indicates that the hot sand particles have a surplus of heat energy stored and approximately 81% (average value for Ed) of this is picked up by the raw corn when the two media are mixed together. Perhaps it is not the contact time that is responsible for the heat transfer but rather the

Table 5. Calculated values of the physical properties of the corn kernel obtained from the data presented in Table 2.

No.	Moisture Content (kg/kg)		RH. at grain surface (decimal)	Specific Heat (kJ/kg^oC)	Latent Heat of Evaporation $(kJ/kg)*10^3$
	wb.	db.			
1	0.176	0.214	0.944	2.115	2.35
2	0.321	0.474	1.000	2.637	2.26
3	0.306	0.441	1.000	2.587	2.27
4	0.298	0.425	1.000	2.550	2.27
5	0.262	0.355	0.999	2.442	2.26
6	0.306	0.442	1.000	2.606	2.25
7	0.311	0.451	1.000	2.627	2.24
8	0.276	0.380	1.000	2.492	2.24
9	0.326	0.483	1.000	2.694	2.25
10	0.305	0.440	1.000	2.611	2.25
11	0.331	0.495	1.000	2.740	2.22
12	0.285	0.399	1.000	2.548	2.22
13	0.304	0.436	1.000	2.599	2.26

wb. - wet basis
db. - dry basis
RH. - relative humidity

Table 6. Calculated efficiencies for the thirteen experimental drying tests.

No.	Drum Speed (rpm)	Grain Feed-rate (t/h)	Efficiency (decimal)			
			Drying	Heating	Fuel	Total
1	16.2	0.52	0.1075	0.8510	0.8015	0.6821
2	17.5	0.49	0.1061	0.7504	0.8639	0.6483
3	16.2	0.41	0.1203	0.7452	0.7790	0.5805
4	23.9	0.51	0.1082	0.7801	0.7498	0.5849
5	15.0	0.33	0.1749	0.8265	0.6112	0.5052
6	24.8	0.45	0.2009	0.9046	0.7833	0.7086
7	16.2	0.28	0.2058	0.8544	0.5567	0.4756
8	15.0	0.25	0.1540	0.7715	0.5508	0.4249
9	22.6	0.28	0.2177	0.8301	0.6397	0.5310
10	24.8	0.31	0.2336	0.8833	0.5776	0.5102
11	22.6	0.24	0.2614	0.8746	0.6333	0.5539
12	23.9	0.24	0.2034	0.7658	0.5755	0.4407
13	24.8	0.24	0.1557	0.6897	0.5940	0.4097

unique mixing process. All data sets have one common denominator, i.e., the same contact process and contact length. In scrutinizing the heating process it is seen that a fixed volume of hot sand and raw corn are measured and then sealed into the annular space provided by the internal helix (Figure 7). Once enclosed within this space no heat is added or lost assuming that steady-state temperature conditions exist. Therefore, it was felt that the amount of agitation provided is the main parameter influencing the heating efficiency.

Based on the above analysis it is believed that the machine operating conditions do not influence the heating efficiency for the range tested. Since the contact time is relatively small (12.2 to 20.2 s) it is possible that very little moisture loss takes place during the heat transfer process. Most likely, all the moisture loss recorded occurs once the separation commences and is carried on till the grain is discharged into the collection bin. This has to be true, because energy in the form of moisture loss is equivalent to the heat energy lost by the grain kernel and is accounted in heating efficiency calculations. It can, therefore, be reasoned that drying efficiency is dependent on initial grain moisture, SGMR and grain feed-rate.

SGMR and grain feed-rate are related because the former is dependent on the later coupled with the machine drum speed. There is a distinct trend of increasing moisture loss with increasing SGMR as seen in Tables 2 and 6. However,it is not possible to decide the optimal SGMR with the present data.

The fuel efficiency and the total efficiency of the processor ranged between 55% to 86% and 41% to 71% respectively. It should be noted that the calculated values of the fuel efficiency are only rough estimates, as a complete heat and mass balance on the drying process was not performed. However, there is a marked trend that the fuel efficiency decreases (Table 6) as the SGMR is increased. At the present stage it is not possible to draw any conclusions as to why this trend exists.

VI SUMMARY AND CONCLUSIONS

6.1 Summary

A continuous flow particulate medium grain processor was designed and a prototype was constructed. Prewashed and pregraded foundry sand was used to act as the heat transfer medium between a propane burner and the product being processed. High moisture corn was used to test the drying capability of the machine.

The primary objective was to ascertain the ability of the machine to maintain steady state temperature conditions processing a large volume of high moisture grain corn. Fifteen trial runs were conducted to determine whether the machine was successful in meeting the objectives.

In undertaking this problem it was felt that the two heat transfer processes, namely gas to sand and sand to grain, had to be thoroughly streamlined and the heat losses minimized. After reviewing the previous prototypes it was decided to place the heat source within the dryer so that a substantial reducton in heat loss can be achieved.

This concept performed very well and can best be demonstrated by noting the high heating efficiency obtained.

6.2 Conclusions

Several conclusions can be drawn from the present study. These are:

1) Steady state temperature conditions can be easily achieved and maintained for continuous flow processing operations in the prototype dryer. Temperature can be easily regulated to suit the requirements by varying the propane feed-rate.

2) The heat transfer process (sand to grain) was proved to be very efficient and the average value of the heating efficiency was 81%. The heat transfer process mainly occured in the closed system established by the unique machine design which not only enhanced the heat transfer process but also minimized the heat loss.

3) The moisture losses (dryer) ranged between 1.25% to 5.32%, lending credibility to the theory that a hot particulate medium can, rapidly and efficiently, dry high moisture agricultural grains.

4) Aeration of the heated grain substantially increased the moisture loss. Steps should be taken to implement this into the drying process.

5) SGMR, contact time and initial grain moisture had very little effect on the heating efficiency. The effect was more noticable on the drying efficiency, where a SGMR between 4 and 8 gave better results.

6) Separation of the two media was complete except for some overflow encountered in the recirculation stage. Some improvements in the design are required at this exit end.

6.3 Recommendations for further research

Recommendations in the form of some unanswered questions are presented, in most cases a hypothesis was drawn and is also outlined.

1) In an artificial drying system, does corn loose any or all of its moisture through the seed-coat? A few experiments were conducted to check this but no conclusions were possible.

Three sets of 25 corn kernels at two moisture levels (rewetted to 25% and 18% wet basis) were selected. The stem was sealed using an epoxy glue for Set 1; Set 2 was the control sample (unchanged) and a 0.79 mm hole was drilled into the seed-coat for Set 3. The first experiment was carried out by placing the six samples in a convective drying oven (forced hot air) at 105^{o}C. After 0.25 h the samples were removed and weighed, results indicated that Set 1 lost the least moisture and Set 3 the most. At 0.5 h Set 1 and 2 registered the same mosture loss but Set 3 was still losing moisture at an accelerated rate. Next day (24.0 h) all three sets registered the same moisture loss. This result corresponded for both moisture levels.

A similar experiment was carried out next day using hot sand at 200^{o}C instead of heated air. A measured volume (same for all six samples) of heated sand was added into the moisture can containing raw corn. The can was sealed and agitated for 30.0 s. The lid was then removed and after another 30.0 s elapsed moisture loss was recorded. Corn samples, at 18%, registered moisture losses of 5.01%, 3.60% and 4.85% for Sets 1, 2 and 3 respectively. 32% of the kernels in Set 1 had popped (burst), no damage was noticed on the other two sets. Losses recorded for corn samples at 25% were 5.64%, 4.39% and 7.11% for Sets 1, 2 and 3 respectively. 40% of the kernels from Set 1 and 8% of the kernels from Set 2 suffered damage due to popping. An increase in volume (balooning effect) for most of the kernels in Set 1 and 2 was noticed for the two trials.

Looking at these results it is felt that some moisture does move out of the seed-coat but perhaps the stem of the corn kernel should also be a large contributor. It is hypothesized that when corn is harvested a wound is inflicted to the stem of the kernel, thus an opening similar to a drilled hole (Set 3) should exist. If the harvested corn is allowed to sit for a few days before it is artifically dried the stem begins to shrink and the seed-coat hardens. Therefore, assuming the above were true, freshly harvested corn should be immediately dried. It is recommended that a study on this subject should be carried out.

2) The author tried to simulate the heating process between hot gases and sand (Appendix 1). A mean value for the hot gases was assumed.

   Results indicated that sand picks up heat more rapidly than what the model predicts. It was felt that this effect was due to showering of sand particles through the hot flame. Further work in this field would answer some questions as to how this problem can be analytically solved.

3) The problem associated with the transfering of heat energy from hot sand particles to the granular medium being processed should also

merit some consideration. This topic was dealt with in the literature review but it is felt that the approach used to evaluate the heat transfer process should be different for this dryer design.

LITERATURE CITED

ASAE, 1982. Agricultural Engineering Yearbook. ASAE Pub., St. Joseph, Michigan.

ASHRAE, 1981. ASHRAE Handbook 1981 Fundamentals. ASHRAE Pub., Atlanta, Georgia.

Akpaetok, O.I., 1973. Shelled corn drying with heated sand. Unpub. M.Sc. Thesis, University of Wisconsin.

Berntsson, T., 1979. Heat transfer in a new type of heat exchanger for divided solids. Powder Techn., 22:101-111.

Brooker, D.B., F.W. Bakker-Arkema and C.W. Hall, 1974. Drying cereal grains. AVI Pub. Co., West Port, Connecticut, 265 pp.

Clanton, D.C., M.L. Hemstrom and J. Matsushima, 1960. Nutritive value of beef cattle ration containing artifically dried corn. J. Animal Sci., 19(2):376-380.

Denloye, A.O.O. and J.S.M. Botterill, 1978. Bed to surface heat transfer in a fluidized bed of large particles. Powder Techn., 19:197-203.

Fortes, M. and M.R. Okos, 1980. Changes in physical properties of corn during drying. Trans. of the ASAE, 23(3):1004-1008.

Fortes, M. and M.R. Okos, 1981. Non-Equilibrium thermodynamic approach to heat and mass transfer in corn kernels. Trans. of the ASAE, 24(3):761-769.

Gabor, J.D., 1970. Wall to bed heat transfer in fluidized and packed beds. Chem. Eng. Prog. Symp. Ser., 66:76-86.

Harakas, N.K. and K.O. Beatty, Jr., 1963. Moving bed heat transfer: effect of interstitial gas with fine particles. Chem. Eng. Prog. Symp. Ser., 59:122-128.

Holman, J., 1976. Heat Transfer, 4th ed., McGraw-Hill Inc., New York, 530 pp.

Khan, A.U., A. Amilhussin, J.R. Arboleda, A.S. Manola, and W.J. Chancellor, 1973. Accelerated drying of rice using heat conduction media. ASAE paper No. 73-321.

Kubie, J. and J. Broughton, 1975. A model of heat transfer in gas fluidized beds. Int. J. Heat Mass Transfer, 18:289-299.

Lapp, H.M. and L.R. Manchur, 1974. Drying oilseeds with a solid heat transfer medium. Can. Agr. Eng., 16:57-59.

Lapp, H.M., R.S.K. Leung and J.R. Townsend, 1975. Solid heat transfer medium for processing grains and oilseeds. ASAE paper No. 75-302-NCR.

Lapp, H.M., G.S. Mittal and J.S. Townsend, 1976a. Cereal grain drying and processing with a solid heat transfer media. ASAE paper No. 76-3524.

Lapp, H.M., G.S. Mittal and J.S. Townsend, 1976b. Drying and processing small grains using solid heat transfer media. CSAE paper No. 76-108.

Mayfield, R.L., 1974. High temperature grain treatment with a particulate bed. Unpub. M.Sc. Thesis, Colorado State University.

Meiering, A.G., T.B. Daynard, R. Brown and L. Otten, 1977. Dryer performance and energy use in corn drying. Can. Agr. Eng., 19(1):49-54.

Mickley, H.S. and D.F. Fairbanks, 1955. Mechanism of heat transfer to fluidized beds. AIChE J., 2:374-384.

Mittal, G.S., H.M. Lapp and J.S. Townsend, 1982. Continuous drying of wheat with hot sand. Can. Agr. Eng., 24:119-122.

Mittal, G.S., H.M. Lapp and J.S. Townsend, 1983. Drying wheat using solid heat transfer medium. J. Sci. Food Agric., 34:773-779.

Morey, R.V., R.J. Gustafson, H.A. Cloud and K.L. Walters, 1978. Energy requirements for high-low temperature drying. Trans. of the ASAE, 21(3):562-567.

Otten, L., R. Brown and K. Anderson, 1980. A study of a commercial crossflow grain dryer. Can. Agr. Eng., 22(2):163-170.

Pannu, K., 1982. The temperature time history of a moving sand bed. Unpub. Simulation and Modelling project, Agr. Eng. Dept., Macdonald College of McGill University, Que. H9X-1C0.

Pierce, R.O. and T.L. Thompson, 1981. Energy use and performance related to crossflow dryer design. Trans. of the ASAE, 24(1):216-220.

Pickett, L.K., J.W. Pinkerton, R.R. Yoerger and A.H. Jansen, 1963. Accelerated drying of corn. Trans. of the ASAE, 6(2):151-157.

Raghavan, G.S.V., 1984. Drying of agricultural products. Ind. Drying Handbook, Marcel and Decker Pub. (press).

Raghavan, G.S.V. and J.M. Harper, 1974. High temperature drying using a heated bed of granular salt. Trans. of the ASAE, 17(2):108-111.

Raghavan, G.S.V., J.M. Harper and E.W. Kienholz, 1974. Nutritive value of salt-bed roasted soybeans for broiler chicks. Poultry Sci., 53:547-553.

Richard, P., 1981. Drying and processing by immersion in a particulate medium. Unpub. M.Sc. Thesis, McGill University.

Richard, P. and G.S.V. Raghavan, 1980. Heat transfer between flowing granular materials and immersed objects. Trans. of the ASAE, 23(6):1564-1568.

Savoie, P. and D. Desilets, 1978. Corn drying in a fluidized corn-sand mixture. ASAE paper No. NA-78-304.

Sullivan, W.N. and R.H. Sabersky, 1975. Heat transfer to flowing granular media. Int. J. Heat & Mass Transfer, 18:97-107.

Tessier, S., 1982. Heat transfer predictions and drying potential in a solid medium with a flighted rotating drum. Unpub. M.Sc. Thesis, McGill University.

Walker, H.G. Jr., B. Lai, W.C. Rockwell and G.O. Kohler, 1970. Preperation and evaluation of popped grain for feed use. Cereal Chemistry, 47(5):513-521.

Wunschmann, J. and E.U. Schlunder, 1974. Heat transfer from heated plate to stagnant and agitated bed of spherical shaped granules under normal pressure and vacum. Proc. fifth Int. Heat Transfer Conf., Vol. 5:49-53.

APPENDIX I

```
REQUESTED OPTIONS:
OPTIONS IN EFFECT: NAME(MAIN) OPTIMIZE(2) LINECOUNT(60) SIZE(MAX) AUTODBL(NONE)
                   SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT GOSTMT NOXREF NOALC NOANSF NOTERM IBM FLAG(I)

C
C ************************************************************************
C
C  SIMULATION AND MODELLING PROJECT
C
C ************************************************************************
C
C  THIS PROGRAM CALCULATES THE TEMPERATURE TIME HISTORY OF A MOVING SAND
C  BED. FOR MORE CLARITY LOOK AT ATTACHED SKETCH.
C  THE SAND BED IS SPLIT UP INTO 'N' EQUAL PARTS , EACH OF WHICH HAS THE
C  SAME CROSS-SECTIONAL AREA. THE SAND ENTERS THE CONICAL DRUM AT THE
C  RIGHT HAND SIDE. AT THE SAME TIME AN EQUAL AMOUNT OF SAND EXITS FROM
C  THE LEFT END OF THE DRUM. THE AIR INSIDE THE DRUM IS KEPT AT A CONST-
C  ANT TEMPERATURE (AN APPROXIMATE VALID ASSUMPTION IN THIS INITIAL PRO-
C  GRAM). THE TWO MAIN ASSUMPTIONS MADE HERE :-
C      1) HOT AIR TEMPERATURE IS CONSTANT AT ALL TIMES = TAIR
C      2) HEAT IS TRANSFERED TO THE SAND BY FREE-CONVECTION
C
C  FOR EACH ELEMENTAL AREA SAY  'XN-2' AIR AT TEMPERATURE TAIR IMPARTS
C  SOME ENERGY PER UNIT TIME. BY USING ELEMENTRY HEAT-TRANSFER EQUATIONS
C  THE ENERGY IMPARTED TO THIS ELEMENT PER UNIT TIME CAN BE CALCULATED.
C  THEN USING THE MASS BALANCE EQUATION THE NEW AVERAGE TEMPERATURE OF
C  THE SAND CAN BE CALCULATED FOR THIS PARTICULAR ELEMENTAL-VOLUME OF
C  SAND.
C
C
C  CONSTANTS AND SYMBOLS USED
C
C     N           = NUMBER OF ELEMENTS
C     NN          =     "    OF RUNS
C     XL          = SAND BED LENGTH
C  *  X(I)        = SAND ELEMENT LENGTH
C  *  Y(I)        =  "       "     WIDTH
C  *  R(I)        =  "       "     HEIGHT
C     RM          = RADIUS OF DRUM AT LEFT END(LARGER DIA.)
C     ZZL         = RADIAL HEIGHT OF SAND AT EXIT END
C     SLOPE       = DRUM SLOPE
C     SSAN        = ANGLE OF RECLINE / SAND
C  *  ANGLE       = ANGLE USED FOR CALCULATIONS (DIFF. OF ABOVE TWO)
C     TAIR        = HOT AIR TEMPERATURE
C     TSAN        = INITIAL TEMPERATURE OF SAND BED
C  *  SEC         = HEATING TIME PER UNIT SEGMENT (VARIABLE WITH N)
C     TIM         = TIME OF RESIDENCE PER CYCLE
C     TEMP(I,J)=    MATRIX HOLDING AIR PROPERTIES VARYING WITH TEMPERATURE
C  *  NHU         = KINEMATIC VISCOSITY
C  *  ALPHA       = THERMAL DIFFUSIVITY
C  *  KAIR        = THERMAL CONDUCTIVITY AIR
C  *  BETA        = VOLUME COEFFICIENT OF EXPANSION
C  *  HX          = AVERAGE HEAT TRANSFER COEFFICIENT
C  *  GR          = GRASHOF NUMBER
C  *  PR          = PRANDTL NUMBER
C  *  NU          = NUSSELT NUMBER
C  *  TFILM       = AVERAGE TEMPERATURE OF AIR FILM, USED IN CALCULATING OF
C                   ABOVE 8 VARIABLES.
C     G           = CONSTANT ACCELERATION DUE TO GRAVITY
```

```
C         PHI        = CONSTANT
C         KSAND      = CONSTANT THERMAL CONDUCTIVITY SAND
C         CSAND      =    "      SPECIFIC HEAT SAND
C         DSAND      =    "      DENSITY SAND
C  *      TSAND(I)   = TEMPERATURE OF PARTICULAR ELEMENT
C  *      MASS       = MASS OF THE ELEMENT
C  *      Q(I)       = HEAT IN PARTICULAR ELEMENT
C  *      ENERGY     = HEAT ENERGY
C
C  *      THESE VALUES ARE CALCULATED
C
C  *********************************************************************
C
          DIMENSION TEMP(10,10),X(50),Y(50),R(50),TSAND(50),ENERGY(1000),
         *Q(50),XX(50),T(10,10,150),TIMEX(150),YTEMP(150),STORE(10)
          REAL KAIR,KSAND,NHU,NU,MSAND,MASS
          INTEGER M1,M2
C
          NN=51
          XL=1.5
          RM=0.45
          SLOPE=6.50
          SSAN=2.50
          ANGLE=SLOPE-SSAN
          TSAN=0.0
          KSAND=0.33
          CSAND=800.0
          DSAND=1520.0
C
          G=9.81
          PHI=3.14159
C
C  **        READING & PRINTING THERMAL PROPERTIES OF AIR USED
C
          READ(5,100) ((TEMP(I,J),J=1,4),I=2,8)
    100   FORMAT(5X,F5.1,5X,F6.2,5X,F7.5,5X,F7.4)
          WRITE(6,21)
     21   FORMAT(1H1)
          WRITE(6,22)
     22   FORMAT(5X,'THERMAL PROPERTIES OF AIR USED IN PROGRAM',/)
          WRITE(6,23)
     23   FORMAT(5X,41('*'),//)
          WRITE(6,24)
     24   FORMAT(7X,'T',6X,'NHU(E-06)',4X,'K AIR',3X,'ALPHA(E-04)')
          WRITE(6,25)
     25   FORMAT(4X,'(DEG.K)',3X,'(M**2/S)',2X,'(W/M/DEG.C)',2X,'(M**2/S)',
         *//)
          WRITE(6,23)
          WRITE(6,100) ((TEMP(I,J),J=1,4),I=2,8)
C
C  *********************************************************************
C  **            SETTING UP LOOPS TO DO CALCULATIONS FOR SAND TEMPERATURE
C  **   UNDER DIFFERENT SETTINGS
C
C       KSEG      = VARIES SEGMENT SIZE
C       KHT       = VARIES SAND VOLUME AND MASS IN DRIER
C       KTIME     = VARIES SAND RESIDENSE TIME
C       KTEMP     = VARIES INITIAL HEATING TEMPERATURE
C
```

```
              C   ******** INITIALIZING AGAIN ***************************************
              C
ISN 0031             N=20
ISN 0032             ZZL=0.175
ISN 0033             TIM=20.0
ISN 0034             TAIR=350.0
ISN 0035             KSEG=1
ISN 0036             KHI=1
ISN 0037             KTIME=5
ISN 0038             KTEMP=5
              C
              C
ISN 0039             DO 200 K=1,KSEG
ISN 0040             N=N+5
              C
              C            DO 210 KK=1,KHI
              C            ZZL=ZZL + 0.05
              C            IF(KK.EQ.1) ZZL=0.07
              C
              C                      DO 220 KK=1,KTIME
              C                      TIM= TIM - 5.0
              C                      IF(KK.EQ.1) TIM=30.0
              C                      IF(KK.GT.1) GO TO 201
              C
ISN 0041                                       DO 230 KK=1,KTEMP
ISN 0042                                       TAIR=TAIR - 50.0
ISN 0043                                       IF(KK.EQ.1) TAIR=500.0
ISN 0045                                       IF(KK.GT.1) GO TO 201
              C
              C      INITIALIZING FOR CALCULATING SEGMENT DIMENTIONS****************
              C
ISN 0047             ZL=ZZL
ISN 0048             VOL=0.0
ISN 0049             SEC=TIM/N
ISN 0050             THETA=PHI*ANGLE/180.0
ISN 0051             AREA=(2.0*ZL-XL*TAN(THETA))*XL
ISN 0052                A=TAN(THETA)
ISN 0053                B=2.0*ZL
ISN 0054                C=AREA/N
ISN 0055             DUMX=0.0
              C
              C      CALCULATING SEGMENT DIMENTIONS
              C
ISN 0056               DUMY=0.0
ISN 0057               DO 10 I=1,N
ISN 0058               X(I)=(B-SQRT(B**2.0-4.0*A*C))/2.0/A
ISN 0059               DUMR=ZL-X(I)*A
ISN 0060               R(I)=(ZL+DUMR)/2.0
ISN 0061               ZL=DUMR
ISN 0062               B=2.0*ZL
ISN 0063               DUMX1=X(I)/2.0
ISN 0064               DUMX2=DUMX+DUMX1
ISN 0065               DUMR1=RM-DUMX2*TAN(PHI*SLOPE/180.0)
ISN 0066               Y(I)=2.0*SQRT(DUMR1**2.0-(DUMR1-R(I))**2.0)
ISN 0067               DUMX=DUMX+X(I)
ISN 0068               DUMY=DUMY+Y(I)
ISN 0069               VOL=VOL+X(I)*Y(I)*R(I)
ISN 0070      10       CONTINUE
ISN 0071             MSAND=2.0*VOL*DSAND
```

```
C
C ****************************************************************************
C OUTPUT OF RESULTS              (SEGMENT DIMENSIONS)
C ****************************************************************************
C
          IF(KHT.NE.1) GO TO 11
          WRITE(6,12)
   12     FORMAT('1',5X,'SAND VOLUME IS NOT A VARIABLE IN THIS CASE',//)
          GO TO 112
   11     WRITE(6,13) KK
   13     FORMAT('1',5X,'VARIABLE SAND VOLUME :    CASE #',I2,//)
  112     WRITE(6,15) XL
   15     FORMAT(5X,'LENGTH OF HEATED SAND BED=',F5.2,//)
          WRITE(6,16) N
   16     FORMAT(5X,'NUMBER OF SEGMENTS =',I5,//)
          WRITE(6,26) MSAND,ZZL
   26     FORMAT(5X,'MASS OF SAND IN SYSTEM =   ',F8.4,2X,'K.GM',///,5X,
         *'HEIGHT OF SAND BED AT EXIT END =   ',F6.4,///)
          WRITE(6,17)
   17     FORMAT(5X,'X , Y & Z DIMENTIONS FOR EACH SEGMENT.',//)
          WRITE(6,14)
          WRITE(6,18)
   18     FORMAT(6X,'#',6X,'X',9X,'Y',9X,'Z',9X,'XX',/)
          WRITE(6,14)
   14     FORMAT(5X,42('*'),//)
          DO 19 I=1,N
          XX(I)=X(I)*Y(I)/DUMY*N
   19     WRITE(6,20) I,X(I),Y(I),R(I),XX(I)
   20     FORMAT(5X,I2,4(3X,F7.5))
C
C ############################################################################
C **************** MAIN CALCULATIONS START HERE ***********************
C ############################################################################
C
C ******** NOTE (N+1) IS A DUMMY FILE TO STORE VALUE AT END OF EACH RUN.
C ******* THIS IS THE AVERAGE BULK TEMPERATURE OF THE SAND AT THE END
C ******* OF THAT PARTICULAR RUN. NOTE THIS VALUE IS COMPUTED AT THE END
C ******* OF LOOP (DO 40) ,VALUE IS LABELED 'DUMTS'.
C ############################################################################
C
  201     SEC=TIM/N
          TSAND(N+1)=TSAN
          TENERG=0.0
          T(K,KK,1)=0.0
          TIMEX(1)=0.0
C
          DO 30 JJ=2,NN
C
          DO 35 J1=1,60
C
          DUMTS=0.0
          DO 40 J=1,N
          M=N+1-J
          MM=M+1
          TFILM=(TSAND(MM)+TAIR)/2.0+273.0
          TEST=(TFILM+50.0)/100.0
          M1=IFIX(TEST)
          M2=M1-1
C
```

```
              C ************************************************************************
              C    **       THE FILM TEMPERATURE IS CALCULATED AND THEN THAT IS USED TO
              C    **   CALCULATE THERMAL PROPERTIES OF AIR.
              C ************************************************************************
              C
ISN 0111               DUMT=(TFILM-TEMP(M2,1))/100.0
ISN 0112               NHU=(DUMT*(TEMP(M1,2)-TEMP(M2,2))+TEMP(M2,2))*1.0 E-6
ISN 0113               KAIR=DUMT*(TEMP(M1,3)-TEMP(M2,3))+TEMP(M2,3)
ISN 0114               ALPHA=(DUMT*(TEMP(M1,4)-TEMP(M2,4))+TEMP(M2,4))*1.0 E-4
ISN 0115               BETA=1.0/TFILM
ISN 0116               PR=NHU/ALPHA
ISN 0117               GR=G*BETA*(TAIR-TSAND(MM))*XX(M)**3.0/NHU**2.0
ISN 0118               NU=0.508*SQRT(PR)/((0.952+PR)**0.25)*GR**0.25
ISN 0119               HX=4.0/3.0*NU*KAIR/X(M)
              C
ISN 0120               TAREA=X(M)*Y(M)
ISN 0121               Q(M)=HX*TAREA*(TAIR-TSAND(MM))*SEC
              C
ISN 0122               MASS=X(M)*Y(M)*R(M)*DSAND
ISN 0123               TSAND(M)=Q(M)/MASS/CSAND+TSAND(MM)
ISN 0124               DUMTS=DUMTS+TSAND(M)
ISN 0125        40     CONTINUE
ISN 0126               TSAND(N+1)=DUMTS/N
ISN 0127        35     CONTINUE
ISN 0128               BULKT=TSAND(N+1)
              C
ISN 0129               TIMEX(JJ)=JJ-1
ISN 0130               T(K,KK,JJ)=BULKT
              C            WRITE(6,42)  JJ,(TSAND(I),I=1,N)
              C     42     FORMAT(I4,/,10(6X,F7.2))
              C            ENERG=0.0
              C            DO 43  I=1,N
              C     43     ENERG=ENERG+Q(I)
              C            ENERGY(JJ)=ENERG
              C            TENERG=TENERG+ENERG
              C            WRITE(6,44)  ENERG
              C     44     FORMAT(5X,'ENERGY INPUT IN THIS RUN =',F10.2,/)
ISN 0131        30     CONTINUE
              C      ------------------------------------------------------------------
              C                        STORE(KK)=MSAND
              C       210              CONTINUE
              C                        KK=KHI
              C      ------------------------------------------------------------------
              C                                     STORE(KK)=TIM
              C        220                          CONTINUE
              C                                     KK=KTIME
              C      ------------------------------------------------------------------
ISN 0132                                             STORE(KK)=TAIR
ISN 0133       230                                   CONTINUE
ISN 0134                                             KK=KTEMP
              C      ------------------------------------------------------------------
              C
ISN 0135                WRITE(6,301) K
ISN 0136       301      FORMAT('1',//,15X,'TEMPERATUTRE TIME HISTORY    :  GROUP #',I2,//)
ISN 0137                WRITE(6,300)
ISN 0138                WRITE(6,302)
ISN 0139       302      FORMAT(5X,'TIME (MIN.)',25X,'TEMPERATURE  (DEG.C)')
ISN 0140                WRITE(6,303) (I,I=1,KK)
ISN 0141       303      FORMAT(14X,5(10X,I2),/)
```

```
  ISN 0142                WRITE(6,300)
  ISN 0143         300    FORMAT(5X,72('*'),/)
  ISN 0144                   DO 310 I=1,NN
  ISN 0145                   WRITE(6,305) TIMEX(I),(T(K,II,I),II=1,KK)
  ISN 0146         305       FORMAT(8X,F5.2,3X,5(5X,F7.2))
  ISN 0147         310       CONTINUE
                   C
  ISN 0148         200    CONTINUE
                   C
                   C      ***************************************************************************
                   C      PLOTTING RESULTS
                   C      ***************************************************************************
                   C
  ISN 0149                A1=0.0
  ISN 0150                CALL PLOTON
  ISN 0151                CALL SCALE(TIMEX,5.0,NN,1)
  ISN 0152                DO 400 M=1,KSEG
  ISN 0153                A1= A1+0.2
  ISN 0154                A2= A1/0.2
                   C
  ISN 0155                CALL RECT(0.3,0.3,10.4,7.0,0.0,3)
  ISN 0156                CALL NEWPEN(3)
  ISN 0157                CALL SYMBOL(1.0,10.3,0.2,'FREE-CONVECTION HEAT TRANSFER',0.0,29)
                   C      CALL SYMBOL(2.0,9.95,0.15,'FOR VARIABLE SAND VOLUME',0.0,24)
                   C      CALL SYMBOL(1.55,9.95,0.15,'FOR VARIABLE SAND HEATING TIME',0.,30)
  ISN 0158                CALL SYMBOL(1.33,9.95,0.15,'FOR VARIABLE HOT AIR TEMPERATURE',0.0,
                         *33)
                   C      CALL SYMBOL(4.3,4.5,0.1,'HOT AIR TEMP.= 350.0 DEG.C',0.0,27)
  ISN 0159                CALL SYMBOL(4.3,4.3,0.1,'SAND MASS     = 318.0 KG.',0.0,24)
  ISN 0160                CALL SYMBOL(4.3,4.1,0.1,'HEATING TIME = 20.0 SEC/RUN',0.0,28)
  ISN 0161                CALL NEWPEN(1)
  ISN 0162                CALL PLOT(7.3,1.8,3)
  ISN 0163                CALL PLOT(4.8,1.8,2)
  ISN 0164                CALL PLOT(4.8,0.3,2)
  ISN 0165                CALL PLOT(4.8,0.6,3)
  ISN 0166                CALL PLOT(7.3,0.6,2)
  ISN 0167                CALL SYMBOL(5.0,0.38,0.14,'AGR. ENGG. DEPT.',0.0,16)
  ISN 0168                CALL SYMBOL(5.15,1.15,0.12,'PROJECT',0.0,7)
  ISN 0169                CALL NEWPEN(4)
  ISN 0170                CALL SYMBOL(4.9,1.5,0.14,'S.& M.  336-612A',0.0,16)
  ISN 0171                CALL SYMBOL(5.15,0.8,0.12,'BY :   K.PANNU.',0.0,15)
                   C
  ISN 0172                CALL NEWPEN(1)
  ISN 0173                CALL SYMBOL(0.5,1.3,0.13,'LEGEND :-',0.0,9)
  ISN 0174                CALL NEWPEN(3)
  ISN 0175                CALL SYMBOL(1.4,2.0,0.12,'FIG # 3  TIME VS. TEMPERATURE (5 CASES)'
                         *,0.0,39)
                   C      CALL NUMBER(2.12,2.0,0.12,A2,0.0,-1)
  ISN 0176                CALL NEWPEN(4)
  ISN 0177                CALL SYMBOL(1.0,0.6,0.1,'VAR = HOT AIR TEMPERATURE  (DEG.C.)',
                         *0.0,35)
  ISN 0178                CALL NEWPEN(2)
  ISN 0179                CALL SYMBOL(1.0,0.9,0.1,'__  SAND TEMPERATURE IN DRYER',0.0,29)
                   C
  ISN 0180                CALL PLOT(1.3,3.1,-3)
  ISN 0181                DO 401 MM=1,KK
  ISN 0182                   DO 402 MMM=1,NN
  ISN 0183         402       YTEMP(MMM)=T(M,MM,MMM)
  ISN 0184                   IF(MM.GT.1) GO TO 403
```

```
   ISN 0186              CALL SCALE(YTEMP,6.0,NN,1)
   ISN 0187              DUMMY1=YTEMP(NN+1)
   ISN 0188              DUMMY2=YTEMP(NN+2)
   ISN 0189              GO TO 404
   ISN 0190      403     YTEMP(NN+1)=DUMMY1
   ISN 0191              YTEMP(NN+2)=DUMMY2
                 C
                 C       START PLOTTING RESULTS
                 C
   ISN 0192      404     CALL FLINE(TIMEX,YTEMP,-NN,1,0,0)
                 C
   ISN 0193              XP=TIMEX(NN)/TIMEX(NN+2)+0.01
   ISN 0194              YP=YTEMP(NN)/YTEMP(NN+2)-0.04
   ISN 0195              CALL NEWPEN(4)
   ISN 0196              CALL SYMBOL(XP,YP,0.08,'VAR=',0.0,4)
   ISN 0197              DUMMY3=STORE(MM)
   ISN 0198              XP=XP+0.35
   ISN 0199              CALL NUMBER(XP,YP,0.08,DUMMY3,0.,1)
   ISN 0200              CALL NEWPEN(2)
   ISN 0201      401     CONTINUE
                 C
   ISN 0202              CALL AXIS(0.,0.,'TEMPERATURE (DEG.C)',19,6.0,90.0,YTEMP(NN+1),
                        *YTEMP(NN+2))
   ISN 0203              CALL NEWPEN(1)
   ISN 0204              CALL AXIS(0.,0.,'TIME (MIN)',-10,5.0,0.,TIMEX(NN+1),TIMEX(NN+2))
                 C
   ISN 0205              CALL PLOT(8.0,-3.1,-3)
   ISN 0206      400     CONTINUE
   ISN 0207              CALL ENDPLT
   ISN 0208              STOP
   ISN 0209              END
*OPTIONS IN EFFECT*NAME(MAIN) OPTIMIZE(2) LINECOUNT(60) SIZE(MAX) AUTODBL(NONE)
*OPTIONS IN EFFECT*SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT GOSTMT NOXREF NOALC NOANSF NOTERM IBM FLAG(I)
*STATISTICS*     SOURCE STATEMENTS =      208, PROGRAM SIZE =     68866, SUBPROGRAM NAME =  MAIN
*STATISTICS*  NO  DIAGNOSTICS GENERATED

****** END OF COMPILATION ******                                          92K BYTES OF CORE NOT USED
```

THERMAL PROPERTIES OF AIR USED IN PRUGRAM

****

T (DEG.K)	NHU(E-06) (M**2/S)	K AIR (W/M/DEG.C)	ALPHA(E-04) (M**2/S)
250.0	9.49	0.02227	0.1316
350.0	20.76	0.03003	0.2983
450.0	31.71	0.03707	0.4222
550.0	44.34	0.04360	0.6532
650.0	58.51	0.04953	0.8578
750.0	73.91	0.05509	1.0774
850.0	90.75	0.06028	1.3097

VARIABLE SAND VOLUME : CASE # 1

LENGTH OF HEATED SAND BED= 1.50

NUMBER OF SEGMENTS = 25

MASS OF SAND IN SYSTEM = 33.1855 K.GM

HEIGHT OF SAND BED AT EXIT END = 0.0700

X , Y & Z DIMENTIONS FOR EACH SEGMENT.

****

I	X	Y	Z	XX
1	0.01516	0.47990	0.06947	0.01755
2	0.01540	0.47550	0.06840	0.01766
3	0.01565	0.47102	0.06732	0.01778
4	0.01591	0.46643	0.06621	0.01790
5	0.01618	0.46175	0.06509	0.01802
6	0.01647	0.45696	0.06395	0.01816
7	0.01678	0.45206	0.06279	0.01829
8	0.01710	0.44704	0.06160	0.01844
9	0.01744	0.44189	0.06039	0.01859
10	0.01780	0.43661	0.05916	0.01875
11	0.01819	0.43118	0.05790	0.01892
12	0.01860	0.42559	0.05662	0.01910
13	0.01905	0.41983	0.05530	0.01929
14	0.01952	0.41389	0.05395	0.01949
15	0.02004	0.40774	0.05257	0.01971
16	0.02059	0.40138	0.05115	0.01994
17	0.02120	0.39477	0.04969	0.02019
18	0.02186	0.38790	0.04818	0.02046
19	0.02259	0.38074	0.04663	0.02075
20	0.02340	0.37324	0.04502	0.02106
21	0.02430	0.36537	0.04335	0.02141
22	0.02531	0.35707	0.04162	0.02180
23	0.02646	0.34829	0.03981	0.02223
24	0.02778	0.33894	0.03791	0.02271
25	0.02933	0.32891	0.03592	0.02327

TEMPERATUIRE TIME HISTURY : GROUP # 1

****

TIME (MIN.)	TEMPERATURE (DEG.C) 1	2	3	4	5
0.0	0.0	0.0	0.0	0.0	0.0
1.00	46.91	27.63	16.67	11.80	9.10
2.00	85.34	52.21	32.20	23.02	17.85
3.00	117.35	74.21	46.70	33.70	26.27
4.00	144.33	94.00	60.28	43.89	34.38
5.00	167.29	111.90	73.01	53.61	42.21
6.00	186.98	128.14	84.98	62.90	49.76
7.00	203.98	142.92	96.24	71.78	57.04
8.00	218.73	156.42	106.86	80.29	64.08
9.00	231.61	168.77	116.88	88.44	70.89
10.00	242.89	180.10	126.35	96.25	77.47
11.00	252.83	190.51	135.31	103.75	83.83
12.00	261.55	200.09	143.79	110.94	89.99
13.00	269.25	208.94	151.83	117.86	95.96
14.00	276.11	217.11	159.46	124.50	101.74
15.00	282.22	224.68	166.71	130.89	107.34
16.00	287.70	231.69	173.59	137.04	112.77
17.00	292.61	238.20	180.13	142.96	118.04
18.00	297.02	244.26	186.35	148.67	123.14
19.00	301.00	249.89	192.27	154.16	128.10
20.00	304.60	255.14	197.91	159.46	132.92
21.00	307.85	259.97	203.29	164.57	137.59
22.00	310.81	264.47	208.42	169.49	142.13
23.00	313.49	268.67	213.32	174.24	146.54
24.00	315.93	272.61	217.99	178.83	150.83
25.00	318.16	276.29	222.46	183.25	154.99
26.00	320.19	279.75	226.73	187.53	159.05
27.00	322.05	282.99	230.82	191.66	162.99
28.00	323.76	286.04	234.73	195.65	166.82
29.00	325.32	288.91	238.47	199.50	170.54
30.00	326.76	291.60	242.06	203.24	174.17
31.00	328.08	294.14	245.49	206.85	177.69
32.00	329.30	296.53	248.79	210.34	181.12
33.00	330.43	298.79	251.95	213.72	184.46
34.00	331.46	300.92	254.98	216.99	187.71
35.00	332.42	302.92	257.83	220.16	190.88
36.00	333.32	304.83	260.54	223.22	193.96
37.00	334.14	306.62	263.14	226.20	196.97
38.00	334.90	308.33	265.64	229.08	199.90
39.00	335.61	309.93	268.04	231.88	202.75
40.00	336.28	311.45	270.36	234.59	205.53
41.00	336.89	312.90	272.58	237.22	208.24
42.00	337.45	314.27	274.72	239.77	210.88
43.00	337.97	315.57	276.78	242.24	213.46
44.00	338.48	316.80	278.76	244.64	215.98
45.00	338.96	317.97	280.67	246.97	218.43
46.00	339.41	319.08	282.51	249.23	220.82
47.00	339.80	320.12	284.28	251.43	223.16
48.00	340.15	321.13	285.99	253.57	225.44
49.00	340.47	322.10	287.64	255.64	227.66
50.00	340.78	323.00	289.23	257.57	229.84

FREE-CONVECTION HEAT TRANSFER
FOR VARIABLE SAND VOLUME

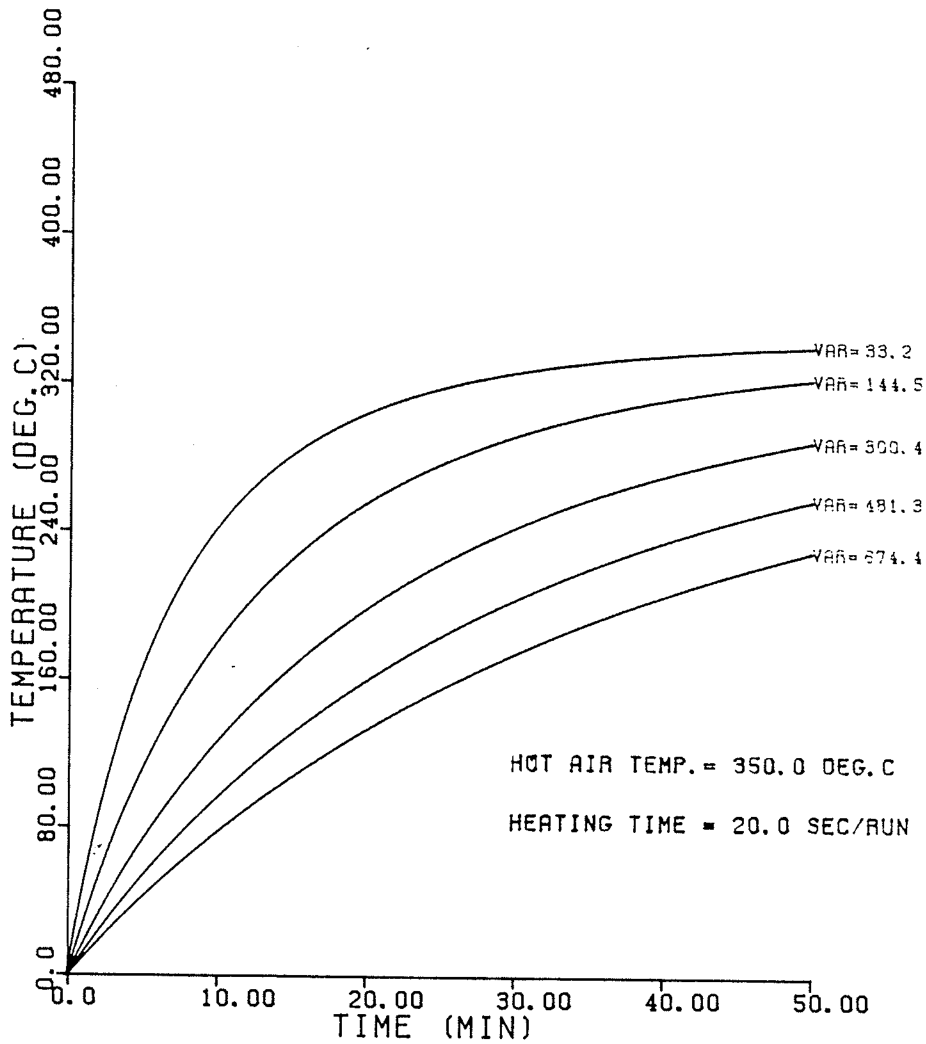


FIG #A1 TIME VS. TEMPERATURE (5 CASES)

LEGEND :-

— SAND TEMPERATURE IN DRYER

VAR = SAND MASS BEING HEATED (KG.)

S. & M. 336-612A

PROJECT

BY : K. PANNU.

AGR. ENGG. DEPT.

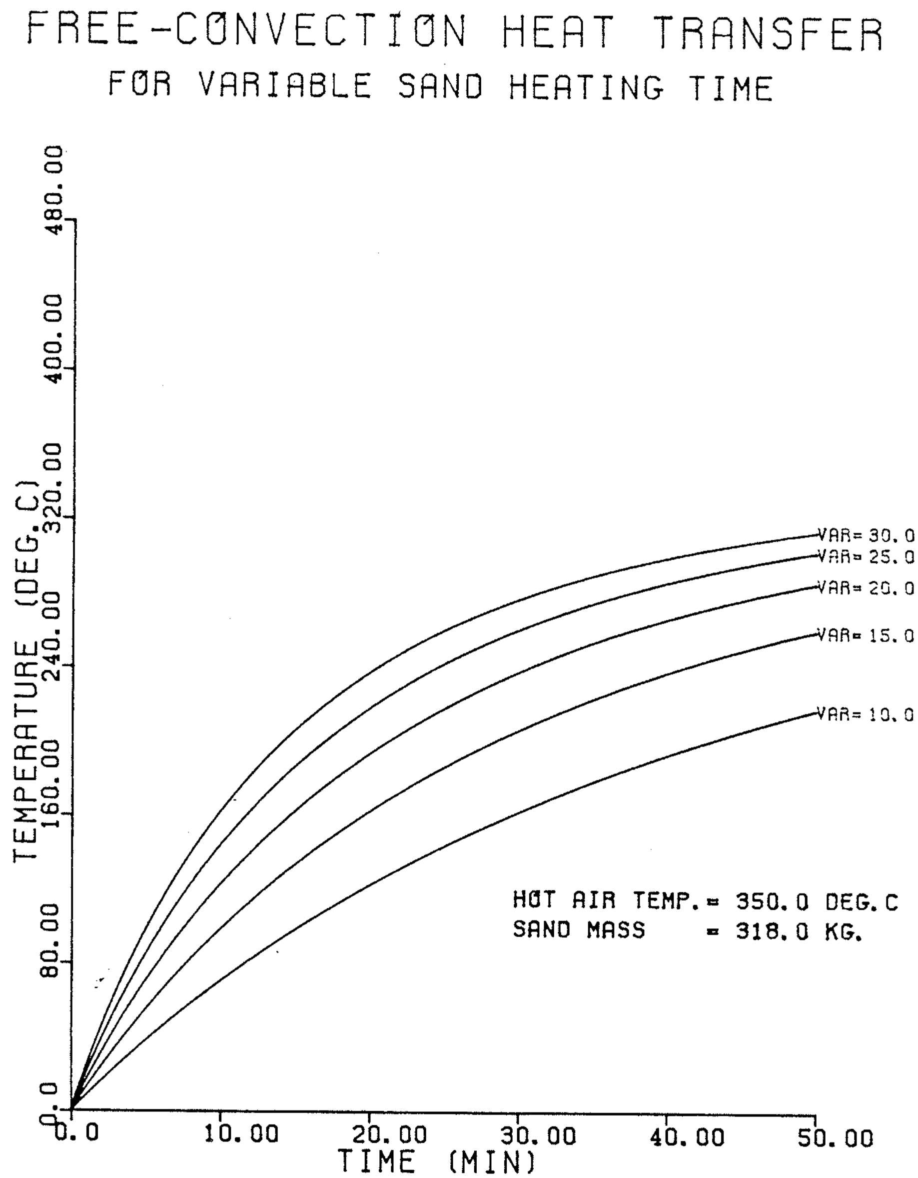


FIG #A2 TIME VS. TEMPERATURE (5 CASES)

LEGEND :-

— SAND TEMPERATURE IN DRYER

VAR = SAND RESIDENCE TIME/RUN (SEC)

S. & M. 336-612A

PROJECT

BY : K. PANNU.

AGR. ENGG. DEPT.

FREE-CONVECTION HEAT TRANSFER
FOR VARIMBLE HOT AIR TEMPERATURE

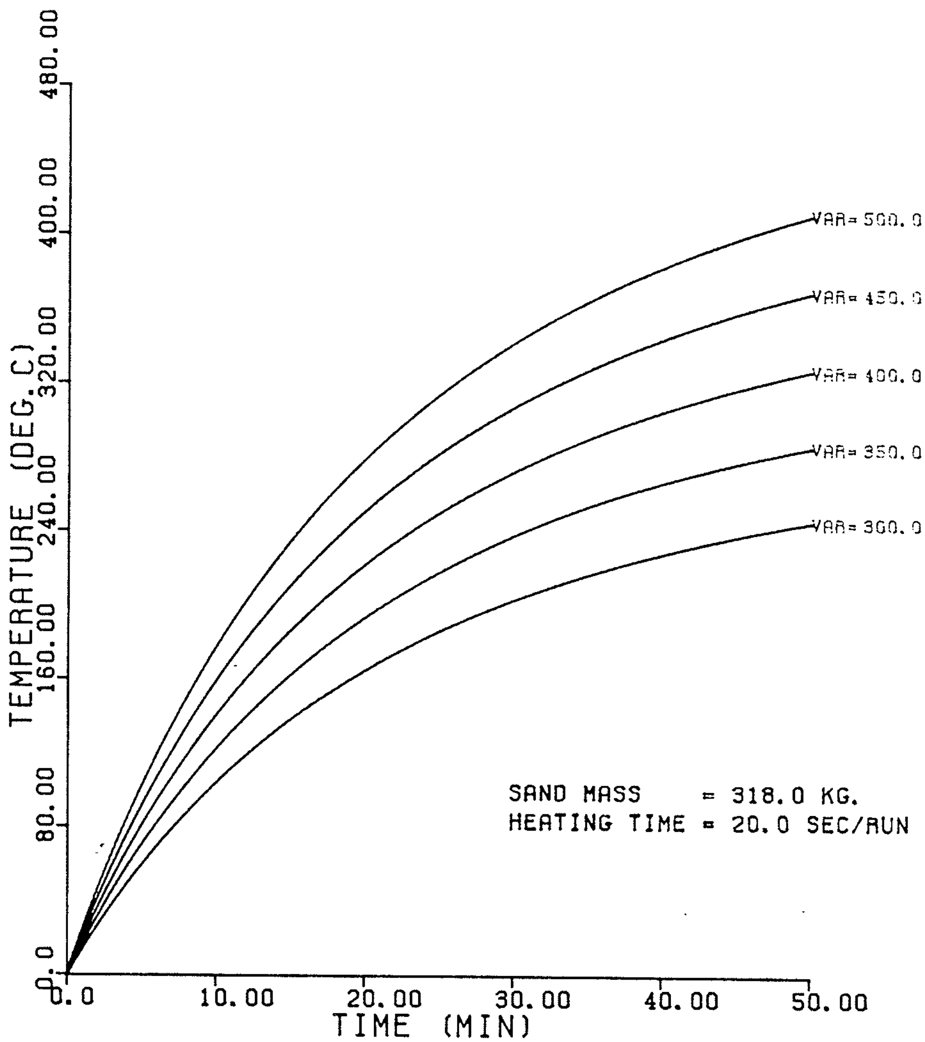


FIG #A3 TIME VS. TEMPERATURE (5 CASES)

LEGEND :-

— SAND TEMPERATURE IN DRYER

VAR = HOT AIR TEMPERATURE (DEG. C.)

S. & M. 336-612A

PROJECT

BY : K. PANNU.

AGR. ENGG. DEPT.