DESIGN, FABRICATION AND TESTING OF A PARTICULATE MEDIUM THERMAL PROCESSOR

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by

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ABSTRACT

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Design, Fabrication and Testing of a
Particulate Medium Thermal Processor

A particulate medium thermal Processor was designed and fabricated to dry, roast, disinfest and de-germinate cereal grains. The components are: a particulate heater, medium and grain mixer, separation unit and aeration unit. Comparative tests showed that particulate medium heating was 5 times faster and 87% more efficient than convective heating. Although the drying efficiency was 95% higher in the convection system, the overall use of input energy was 28% higher in the Processor.

Drying of corn was investigated at 500kg/h. High moisture removal was achieved at initial moisture contents of 19% and 24% using salt at initial medium temperature of 250°C. The highest moisture removal achieved was 6.17% (w.b.) with a corn flow rate of 500 kg/h, initial moisture content of 19%, initial medium temperature of 250°C, and a 60 s contact time.

Soybean was roasted in the Processor at 500 kg/h. Initial medium temperatures of 175, 200 and 250°C resulted in grain temperatures of 104, 107 and 127°C, respectively, for a contact time of 60 s. An average of 4.11% (w.b.) moisture reduction was achieved from commercially dried soybean at 6.8% initial moisture content.

A preliminary study showed grain temperatures over 67°C was sufficient to achieve 100% insect mortality of *Sitophilus granarius* for a 30 s exposure. These temperature and contact time data were used for evaluating the possibility of thermal disinfestation using the Processor. Tests on wheat processed at 1000 kg/h showed that grain temperatures rose to between 69.8°C and 72.9°C for exposure times of 60s. These results were achieved at thermal efficiencies of 43% and 49% respectively. Estimated cost of disinfestation using the machine was CAN$ 0.385/t.

Seed quality wheat was processed to determine parameters leading to total thermal de-germination. Tests were conducted at 40, 60, 80 and 100°C. Total de-germination of the wheat seed was found to occur at temperatures over 80°C for an exposure time of 60 s.

RÉSUMÉ

Samson A. Sotocinal Ph.D. (Génie Agricole et des Biosystèmes)

Conception, fabrication et évaluation d'un processeur thermique à granules préchauffées

Un processeur thermique à granules préchauffées a été conçu et construit pour sécher, rôtir, désinsectiser, et stériliser des grains et céréales. L'appareil est composé d'un élément chauffant pour les granules, un mélangeur, une unité de séparation, et une unité d'aération. Des tests comparatifs ont démontré que le chauffage en milieu granulaire était cinq fois plus rapide et 87% plus efficace que le chauffage à convection. Cependant l'efficacité du séchage à convection était 95% plus élevée. Néanmoins, l'utilisation d'énergie intrant du procédé granulaire était 28% plus élevée.

Le séchage du maïs fut étudié au débit de 500 kg/h. La réduction maximale d'humidité était de 6.17% (base humide, b.h.) dans les conditions suivantes: taux initial d'humidité de 19%, température initiale de sel (médium granulaire) de 250°C, période de contact de 60 s.

Des fèves de soja ont été roties au débit de 500 kg/h. Des températures granulaires de 175, 200 et 250°C ont amené les fèves de soja à atteindre des températures de 104, 107 et 127°C, pour une période de contact de 60 s. Une réduction maximale du taux d'humidité de 4.11% (b.h.) a été atteinte pour des fèves de soja ayant un taux d'humidité initial de 6.8%.

Une étude préliminaire démontra qu'un taux de mortalité de 100% de *Sitophilus granarius* peut être atteint après 30 s d'exposition à une température de 67°C. Le potentiel du processeur pour fins de désinsectisation thermique a été évalué en déterminant la température du blé traité à 1000 kg/h. Durant ces tests, la température des grains s'est située entre 72.9°C et 69.8°C pour des périodes d'exposition de 60 s. Ces résultats ont été obtenus à des efficacités thermiques de 49% et 43% respectivement. Les coûts de la désinsectisation en milieu granulaire furent estimés à 0.385 $ CAN/t.

Des échantillons de grains de semence de blé ont été traités avec ce procédé granulaire afin d'évaluer les paramètres pouvant causer la stérilisation thermique. Les tests furent menés à 40, 60, 80 et 100°C. La stérilisation totale des grains de blé fut observée à des températures de 80°C ou plus pour une exposition de 60 s.

This work is dedicated to my parents,
Do-ong and Aniang
two hard-working farmers who,
with a very small patch of land
managed to raise and educate seven children.

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w.b.	wet basis
IR	Infrared
MC	Moisture Content
RF	Radio Frequency
MW	Microwave
h	hour
rpm	revolutions per minute
d.b.	dry basis
DC	Direct Current
AC	Alternating Current
EHD	Equal Horizontal Distribution
SCFM	Standard Cubic Feet per Minute
CvH, PMH	Convection Heating, Particulate Medium Heating
η	Efficiency
η_h	Heating efficiency (%)
m	mass flow rate (kg/h)
C_p	Specific heat (kJ/kg °C)
ΔT	Temperature gradient (°C)
E	Energy input (kW)
m_w	Mass of water removed (kg/h)
h_{fg}	Latent heat of vaporization (kJ/kg)
m_g	Mass flow rate of grain (kg/h)
C_{pg}	Specific heat of grain (kJ/kg °C)
ΔT_g	Increase in grain temperature (°C)
m_s	Mass flow rate of sand (kg/h)
C_{ps}	Specific heat of sand (kJ/kg °C)
ΔT_s	Drop in sand temperature (°C)
Δm	Ratio of water evaporated to grain flow rate
M_i	Initial moisture content (w.b.)
M_f	Final moisture content (w.b.)
m_p	Mass flow rate of propane (kg/h)
h_p	Heating value of propane (kJ/kg)
T-CT	Temperature-contact time
MGMR	Medium-to-grain mass ratio
HT-SCT	High temperature-short contact time
LT-LCT	Low temperature-long contact time
MT	Mixing temperature (°C)
DMT	Drop in medium temperature (°C)
IGT	Increase in grain temperature (°C)
MR	Moisture reduction (% w.b.)
T_{mi}	Initial medium temperature (°C)

T_{mf}	Final medium temperature (°C)
T_{gh}	Grain temperature after heating (°C)
T_{ga}	Grain temperature after aeration (°C)
T_{gi}	Initial grain temperature (°C)
RH	Relative humidity (%)
R^2	Correlation coefficient
M	Mortality (%)
a,b,c	Constants
t	Time of exposure
PID	Proportional Integral / Derivative

CHAPTER I
INTRODUCTION

1.1 Thermal Processing

Conventional thermal processing techniques use heated air. Since air has a very low heat capacity, heating is slow, thermal efficiency is low, and processing cost tends to be high. A promising alternative to heated air thermal processing is particulate medium heating. Particle-to-particle heat transfer is an efficient method of conveying heat to the grain for moisture removal, roasting, preheating, disinfestation and de-germination. A study by Holt (1960) showed the relative values of the heat transfer coefficients for different modes of heating to be 1 for convection heating, 20 for conduction heating and 200 for particulate medium heating. The two main advantages of particulate medium heating over convection heating are the high heat transfer efficiency and faster rate of transferring heat from the medium to the grain.

Exhaustive investigations on basic heat transfer and drying kinetics using particle-to-particle heat transfer were conducted throughout the years. Factors affecting the rate of heat transfer were also investigated thoroughly. Uhl and Root (1967), Sullivan and Sabersky (1975), Downs et al. (1977), Richard and Raghavan (1980), Richard (1981), studied the heat transfer aspects of drying grains by immersion in heated granular media. Akpaetok (1973), Khan et al. (1973), Lapp et al. (1976), Tessier (1982), Raghavan and Langlois (1984), Pannu and Raghavan (1986), studied the drying characteristics of cereal grains immersed in heated media such as sand or salt. Sibley and Raghavan (1985) studied different variables affecting grain drying by immersion in a hot particulate medium; namely, initial grain moisture content, initial medium temperature, medium particle size, medium to grain mass ratio, and contact time. Raghavan et al.(1974) studied the effect of particle size on the heat transfer coefficient.

Comparative studies on the effectiveness of different media were also undertaken. These studies followed the findings of Pannu and Raghavan (1986) which suggested that when a hot particulate medium, such as sand, is used to dry cereal grains, most of the heat transferred by the medium goes to raise the temperature of the grain kernel instead of evaporating moisture. Finding a suitable hygroscopic medium to enhance mass transfer characteristics during mixing would overcome the inherent limitations of the process operating in a restricted airflow environment of immersed grain particles. Alikhani (1990) and McBratney (1989) compared drying kinetics of corn immersed in heated beds of sand, zeolite and molecular sieves.

Attempts to develop continuous flow particulate medium dryers were also made. Khan et al. (1973) designed a machine for drying paddy rice using sand as the heat transfer medium. Lapp et al. (1976) and Raghavan and Langlois (1984), developed a machine for particulate medium drying cereal grains. Pannu (1984) constructed a continuous flow corn dryer which could use sand or salt as the heat transfer medium.

Besides drying of agricultural products, particulate medium heat transfer can be used in other farm processing operations. Grain pre-heating prior to large capacity drying or any other subsequent application can be undertaken faster and more efficiently. A study by Montross et al. (1995) showed that pre-heating increased capacity in a concurrent-flow dryer and improved its fuel efficiency by up to 4%.

The method can also be used in the roasting of cereal grains such as soybeans to improve protein availability (Raghavan et al., 1974). McKenzie and Gottbrath (1971) evaluated five grain processing methods which apply heat to grains and found that the cost of roasting, extrusion, gelatinization, popping and steam flaking to be so expensive and said they outweighed the benefits derived from thermal treatment. Their study emphasized the need for developing cost-effective methods of thermal treatment of grain for animal feeding. Tromp (1992) studied particulate medium roasting of soybean using heated salt in the machine developed by Raghavan and Pannu (1986). His findings highlighted the potential of the method in economically roasting grains destined for animal feed.

With concerns over the entry of hazardous chemicals into the food chain particulate medium thermal processing seems to be a good alternative to chemical fumigation for controlling infestation in grain handling and processing centers and farms. Research on rapid disinfestation using physical means has centered on the use of radiant energy for heating such as infrared (IR), radio-frequency (RF) and microwaves (MW). The capital cost of these methods coupled with the difficulty of operating complex electronic equipment in the harsh environment of a grain processing facility prevented the widespread application of the technique. Convective methods were also investigated thoroughly. Studies conducted by Sutherland (1986) showed that heating grain to temperatures of 60-65°C was effective in controlling the population of *R. dominica*, the most heat tolerant insect pest in stored grains. Thorpe (1987) showed that heat treatment using air at 65°C in a continuous flow fluidized-bed disinfestor could achieve 100% mortality on the most common insect species at a cost competitive with chemical fumigation. The primary disadvantage of the convective method is the slow rate of heating and the significant amount of heat lost in the exiting air. With its high rate of heat transfer, particulate medium heating can make thermal disinfestation more economically feasible. The banning of commonly used insecticides and fumigants of stored grains for possible adverse health effects make particulate medium thermal treatment a promising immediate alternative.

The widespread use of animal manure as fertilizer supplement in farms and the importation of seeds for bird feed has spawned a problem in controlling the growth of weeds in farming communities. Weeds are a major problem especially for seed growers who need to ensure the purity of seeds they produce (Belcan, 1996). De-germination of all grains destined for animal feed will ensure that weed seeds will not be spread in the farms during the yearly manure application. This activity can be economically undertaken using particulate medium thermal treatment.

Studies conducted in the area of thermal treatment by immersion in heated granular media dealt mostly with the dynamics of particle-to-particle heat transfer. Although some media used in later experiments were hygroscopic, very little information was generated on the process of moisture exchange between the drying material and the heating medium. The development of processing equipments using particulate medium heat transfer was limited to pilot scale models and has not seen commercial application. Furthermore, the high operating temperature inherent in particulate medium thermal processes which can be used in other applications such as roasting, disinfesting, and de-germination was not exploited.

1.2 Hypotheses

The information accumulated through review of relevant literature and preliminary experiments on particulate medium thermal processing leads to the following hypotheses:

The drying of corn can be accomplished more efficiently by immersion in a heated granular media than by the conventional method of heated air drying.

Particulate medium thermal treatment can be used in the roasting of soybeans more efficiently than conventional methods.

Particulate medium heating can be used for the rapid and economical disinfestation of wheat from *Sitophilus granarius*.

High temperature thermal treatment can be used in the de-germination of wheat.

1.3 Objectives

The main objective of the proposed investigation is to develop a fast and efficient system for the thermal processing of grains using particulate medium heat transfer methods. Specific objectives of the study are:

To design and fabricate a continuous-flow particulate medium grain Processor suitable for several on-farm thermal processing applications.

To compare the Processor's performance with a conventional heated air dryer in terms of heating rate, heating efficiency, drying efficiency and overall thermal efficiency.

To dry corn in the Processor to evaluate the effect of grain moisture content and medium temperature on moisture removal, and to determine the percentage of moisture removed in the mixing section and aeration section of the machine.

To evaluate the potential of the Processor in roasting soybeans and determine the amount of moisture reduction from the grain.

To evaluate the possibility of disinfesting and de-germinating wheat using particulate medium thermal treatment.

1.4 Scope of the Study

This study will focus on the development of a particulate medium thermal Processor. Four potential applications to important field crops will be investigated. These are: drying (corn), disinfestation (wheat), de-germination (wheat), and roasting (soybeans). The particulate medium to be used is salt (NaCl). It was selected over another hygroscopic material, zeolite, because it is more resistant to attrition. A farm scale Processor will be constructed which uses sand, salt and natural zeolite as heat transfer medium. Although no actual experiments will be conducted on grain disinfestation using the dryer, information on temperature and contact time combinations obtained in an early study will be used for the evaluation.

Roasting of soybeans will be undertaken in the Processor. The results will be evaluated by comparing temperature-time data with published information on roasting cereal grains for animal feed. De-germination studies will be conducted at different temperatures using wheat as test material. Results of the study will be evaluated by running germination tests on the treated samples. The evaluation of grain quality will be limited to moisture content determination and visual assessment. The evaluation of machine performance will be based partly on a comparison of power utilization with a convective crossflow dryer, and partly on the machine's ability to achieve process objectives in several applications. No attempt will be made to model the heat transfer characteristics pertaining to particulate medium heating in general or this Processor, in particular.

CHAPTER II
REVIEW OF LITERATURE

2.1 Introduction

This literature review will begin with a brief overview of commercial grain drying in order to give a basis of comparison for the sections dealing with particulate medium driers. A number of commonly used convective dryers will be described, complete with schematics and their operating and efficiency characteristics. A number of particulate medium dryers developed since 1939 will be treated in the same way in the subsequent section, leading to a partial justification of the work presented in this thesis.

2.2 Grain Drying, General

2.2.1 Grain Production

Cereal production is an important agricultural activity in most countries. Based on a Statistics Canada survey, a total of 6.9 million metric tons of corn was produced in 1992. Figure 2.1 shows the production of selected grains in Canada and in the United States for crop year 1992. While wheat and barley were widely cultivated in Canada; corn, wheat and soybeans dominate agricultural production in the US.

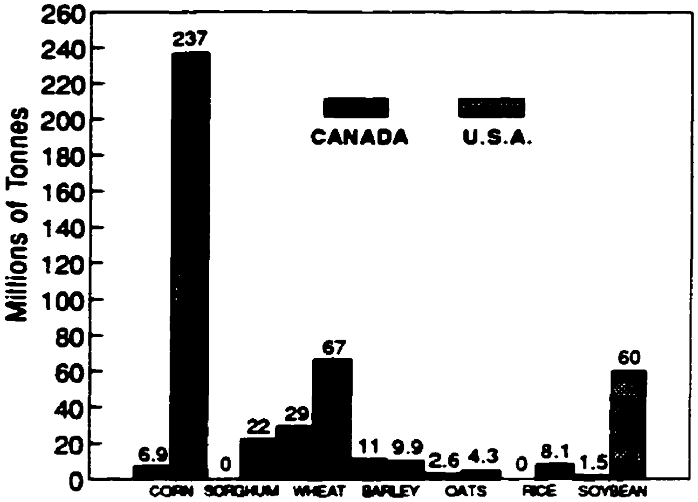

Figure 2.1 Grain production in 1992

2.2.2 Drying Requirements

The harvest moisture content for corn varies widely with location and weather conditions but normally ranges between 20% and 35% (w.b.). For safe storage, the corn has to be dried to a moisture content of 10-15%(w.b.). A large amount of moisture is evaporated from the grain in the drying process. Brooker et al. (1992) estimated that a 10% reduction in moisture content involves the removal of 100 kg of water per ton of grain which requires over 500 MJ of heat. Based on this estimate around 3.45×10^9 MJ of heat are expended annually to dry 6.9 million metric tons of corn produced in Canada.

2.2.3 Types of Dryers

Grains are either dried in the farm or in commercial grain elevators. This requires drying equipment with different capacities and operating characteristics. Grain dryers can be classified according to the means by which heat for water vaporization is transmitted to the grain, and the means for moisture removal. Based on the mode of heat transfer, grain dryers can be categorized as conductive, convective, radiative, or dielectric.

In contact dryers, heat is transferred by conduction from heated surfaces which are in direct contact with the grain and aeration is required to remove moisture from the surface of the grain.

Convective dryers, also termed "heated air dryers", use hot air as the medium for transferring heat into the grains.

In radiative dryers (IR), thermal energy is supplied to the wet material by electromagnetic radiation of wavelengths in the range 0.76-400μm. Electromagnetic waves are absorbed near the surface of the material and cause vibrations of solid and liquid molecules which result in thermal energy dissipation (Schifmann, 1987). Moisture transport in radiative drying for both vapour diffusion and evaporation follow the same principles as in convective and conductive drying.

Dielectric drying is somewhat similar in nature to radiation drying since both processes generate heat inside the material. In the latter however, a high frequency electromagnetic energy within the radio-frequency (RF) or microwave (MW) region is used. The greater penetration depth of the RF and MW results in a truly volumetric heat generation during dielectric drying in contrast to surface heating by IR radiation.

Even though heat transfer efficiency in a convective dryer is less than the other methods due to the low heat capacity of air, there is an advantage in convective drying since the heat transfer medium also serves as the mass transfer medium in removing moisture from the grain. Consequently, most commercial dryers are of the convective type using heated air as the medium.

2.2.4 Alternatives to Convection Drying

In a chronology of the early use of drying, Kroll (1980) stated that grains have been dried for storage since about 100 B.C. The scientific study of drying is considered to have begun between 1577 and 1644 A.D. (Kroll et al., 1980). Since then, many alternative heating processes for the drying of agricultural materials have been thoroughly investigated. One alternative that has shown the promise of faster rate of drying and improved thermal efficiency is conduction drying.

a. Conduction drying

Conduction drying is the term used to describe a drying process where heat is supplied to the grain using a solid medium, rather than the air surrounding the grain. The earliest work on grain drying by conduction heating was reported by Kelly (1939). He developed a rotating drum dryer with a coal burning furnace as heat source to dry wheat (Figure 2.2). Tests on the dryer showed that the quality of processed wheat was satisfactory. However, the amount of moisture removed was lower than required for safe storage of the product. Therefore, modifications were required if the technique were to be used effectively in the drying of cereal grains.

Very little work was done on the development of conduction dryers for decades. Subsequent work dealt mostly with the theoretical aspect of solid-to-solid heat transfer rather than the development of conduction drying equipment. Hall and Hall (1961) compared conduction and convection drying of corn and found that heating medium temperatures of 62 and 109°C resulted in 10.2 and 16.5% savings in drying time respectively. Finney et al., (1963) studied the

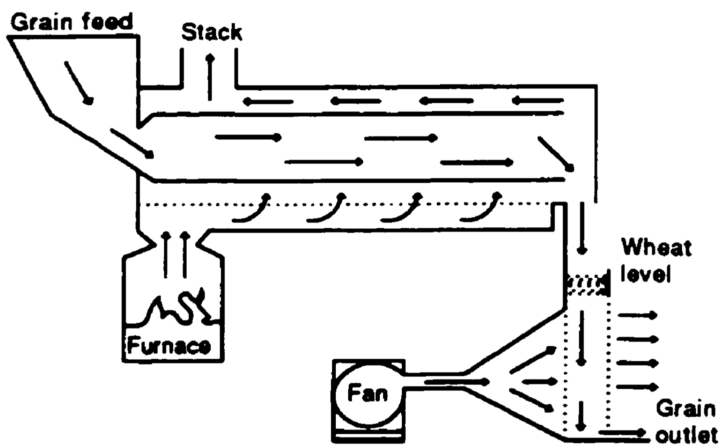

Figure 2.2 Grain dryer by Kelly (1939)

drying of shelled corn by conduction heating using heated metal plates and reported an overall thermal efficiency as high as 70%.

Chancellor (1968) developed and tested a conduction rice dryer heated by straw. His study exposed one of the limitations in the use of conducted heat for grain drying. He found that grain contacting the heated surface for long periods of time were prone to overheating, so a stirring blade was added to stir and mix the grain over the heated plate. Chancellor suggested using a granular medium such as sand to reduce excessive heating of the grains.

b. Particulate medium drying

It was in the 1970's that studies on the use of solid-to-solid heat transfer appeared. Iyengar et al. (1971), Khan et al. (1973) and Arboleda et al. (1973) reported on the use of heated sand for drying paddy. Lapp (1973), Lapp and Manchur (1974) and Manchur (1975) studied the use of heated sand for drying rapeseed. The drying of corn using heated sand was reported by Akpaetok (1973), and Raghavan and Harper (1974) used a bed of heated salt. Lapp et al. (1975) reported on the feasibility of using heated sand in the drying and parching of wild rice.

These studies have shown the possible application of solid-to-solid heat transfer in drying various grains using different solid media. Further, these investigations have identified the critical variables involved in the use of heated particulate for drying. In designing a practical unit for the drying of grains at the farm level of operation, a study of the acceptable limits of variation of these operating variables is required.

2.3 Heated Air Drying

2.3.1 Batch dryers

In batch drying, the dryer is charged with a certain amount of grain which stays in the dryer until the desired final moisture content is reached. No grain enters or leaves the dryer during the entire drying process. Depending on the dryer design, the grain is either agitated in the dryer or kept stationary during the drying process. Batch dryers available on the market fall into three categories: the batch-in-bin, the column batch dryer, and the recirculating batch dryer.

a. Batch-in-bin

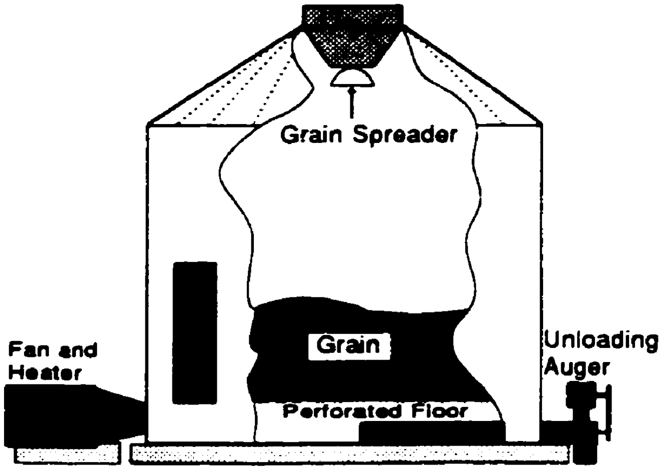

Figure 2.3 Batch-in-bin dryer

The least expensive set-up for heated-air drying is the batch-in-bin dryer. The main components of this system are a bin with perforated floor, a grain spreader, a fan with a heater unit, and an underfloor unloading auger (Figure 2.3). The operating principle of this dryer is to force large quantities of heated air through a shallow bed of grain to obtain rapid drying. The drying rate depends on variables such as grain depth, temperature of the heated air, and air flow rate.

The depth of the bed is usually 0.6-1.2 m and airflow rates of 6.4-14.4 m^3/min-air/m^3 corn at 38-71°C are commonly used (Brooker et al., 1992). When the desired moisture content is attained, the grain is either cooled by blowing unheated air through the bed or by transferring the warm grain to an aerated storage bin. Otten (1985) investigated the effect of exhaust heat recovery on a batch-in-bin dryer and found that the process is more efficient than other high temperature dryers, and has a specific energy consumption of 3.371 MJ/kg of water evaporated. The primary disadvantage of the process is the large moisture gradient between the top and bottom of the batch. Although the average moisture content of the grain batch is at the desired level, the top layers remain wet while the bottom layers are over dried. This situation is usually prevented by incorporating a mixing device into the system.

One modification carried out to overcome this problem is a design developed by Stormor Ltd. called the EZEE-DRY (Figure 2.4). The system consisted of a bin with an overhead drying floor, a fan-heater unit, and loading/unloading augers. The operating principle in this system is to dry a thin bed of grain on the overhead drying floor and dump the dried grain into the storage-cooling area below. The major advantage of this system is the recovery of heat from cooling grain. Also, the bin serves as a full capacity grain storage. Batch capacities of 19 to 74 m^3 are commercially available. This is equivalent to storage capacities of 100 to 800 m³.

b. Column batch

Another commercial batch dryer is the column batch dryer. The major components of this type of dryer (Figure 2.5) are: a holding column made of perforated steel sheet, a central heated air plenum chamber, a fan with a heater unit, and an unloading auger. The operating principle behind this dryer is to place the grain in a tall column and force heated air through the column. The system could be a stationary column batch dryer or a recirculating column batch dryer. In a stationary column batch dryer, the grain mass does not move inside the column. Typically, air temperatures are between 60 and 95°C and common dryer sizes given in a batch volume are 6.5, 9.0 and 12.7 m^3. Column batch dryers are suitable for farm use and are not used for large scale commercial operation. The primary disadvantage of column dryers is operation at high drying air temperatures which result in over dying of the grain near the heated-air plenum chamber. It is therefore necessary to supervise them more carefully to prevent severe over drying of the grain if a problem occurs.

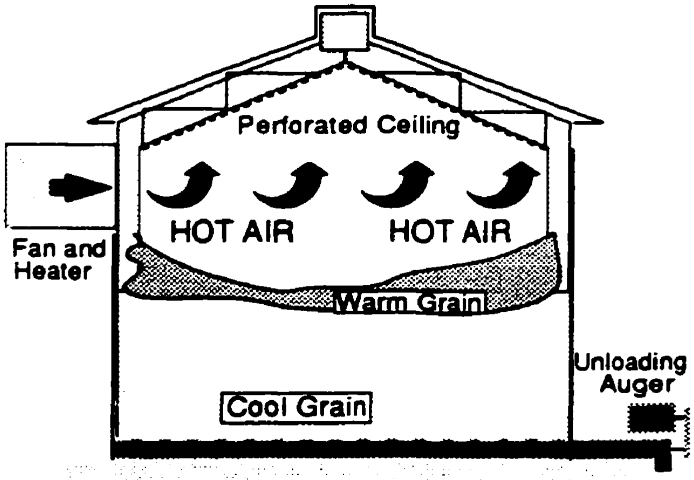

Figure 2.4 Stormor Ezee-dry dryer

This situation is corrected in a recirculating column batch dryer where the grain is constantly moved from the bottom to the top of the dryer, thus mixing the grain and resulting in a more uniformly dried product.

c. Recirculating batch

In recirculating batch dryers, the grain is constantly mixed while drying. This dryer consists of a bin with a

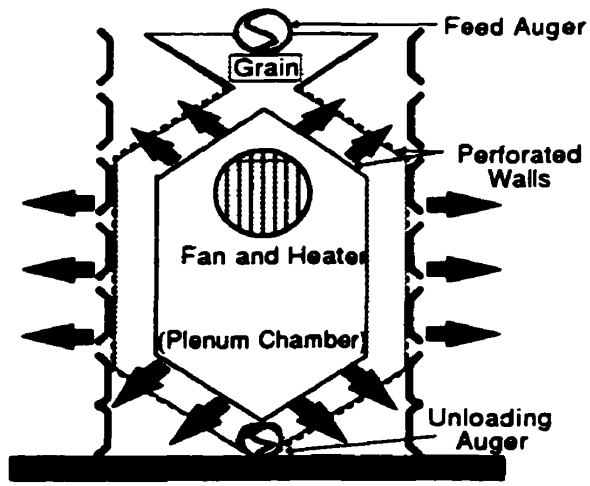

Figure 2.5 Column batch dryer

slanted perforated floor, a fan and heater unit, a grain spreader, a central recirculating auger, and an underfloor unloading auger (Figure 2.6). The slanted floor causes the grain to move toward the central recirculator which in turn lifts the grain and delivers it to the top of the grain bin. The drying process follows a crossflow pattern which, combined with permanent mixing, results in a more uniformly dried crop than that obtained using non-recirculating type of dryer. A typical recirculating grain dryer can remove 5% to 8% moisture (w.b.) per hour from 5 to 9 tons of grain, depending on the dryer size and operating conditions. Meiering et al. (1977) tested a rotating batch crossflow dryer which dried 7.5 tons of corn from an initial moisture content of 27.5% w.b. to a final moisture content of 14.2% w.b. in a total time of 3 h, amounting to a capacity of 2.5 tons/h. They found that heating of the corn to the equilibrium drying temperature and partial overheating of the grain caused a high energy consumption of the order of 5.243 MJ/kg of water evaporated. Further recirculation of the grain in several stages reduced the overall energy consumption down to 4.00 MJ/kg of water evaporated.

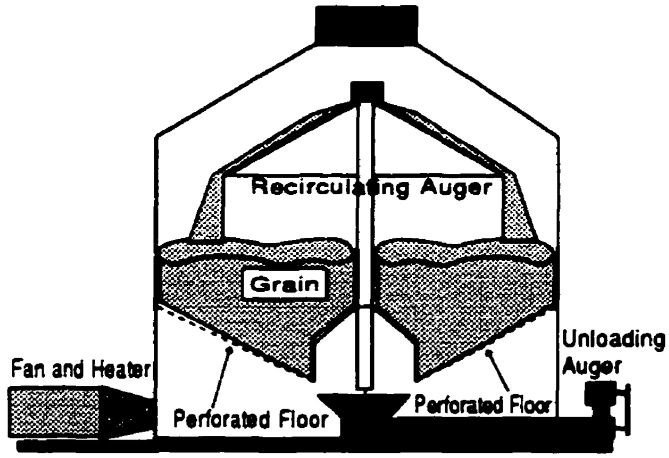

Figure 2.6 Recirculating batch dryer

2.3.2 Continuous flow dryers

a. Cross flow

The crossflow dryer is the most common continuous flow dryer design in the market. The major components of the dryer are: the wet grain holding bin, a perforated column grain bin, a hot air plenum, a cold air plenum and

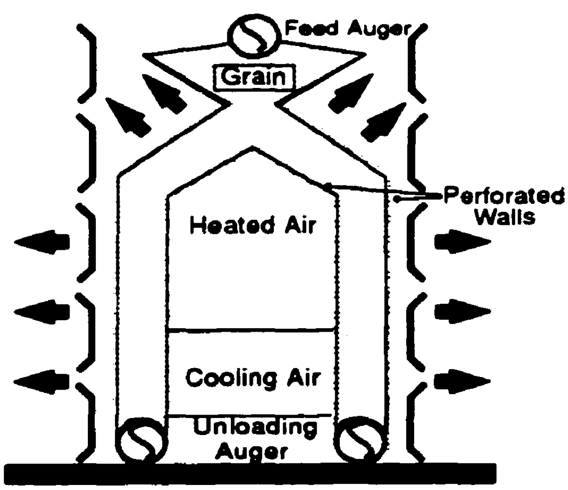

Figure 2.7 Crossflow dryer

an unloading auger (Figure 2.7).The operating principle of this process is to force heated air across (crossflow) a thin column of grain flowing downwards by gravity. The thickness of the grain column is usually 0.24-0.45 m and the height of the grain column in the heated air section varies from 1 to 10 m. Drying air temperatures vary depending on the grain to be dried and the grain quality requirements. For food grains, the air temperature ranges typically from 60°C to 75°C and for feed grains from 80 to 110°C. Air flow rates for the drying and cooling section range from 83-140 m^3/min-t maintained at a static pressure of 0.5-1.2 kPa (Brooker et al., 1992).

Meiering et al., (1977) tested a dual column continuous flow dryer which dried a total of 2.8 tons of corn from an initial moisture content of 27.5% w.b. to a final moisture content of 14.8% in one hour. The drying process required 5.063 MJ/kg of water evaporated. An acceptable specific energy consumption of 4.216 MJ/kg water evaporated was attained by recirculating the cooling air. Otten et al., (1980) tested a commercial crossflow dryer of capacity over 40 tons/h to determine the effect of using a grain inverter to improve dryer performance. The dryer showed a specific energy consumption of 4.640 MJ/kg of water evaporated.

b. Concurrent flow

The basic principle in a concurrent flow dryer is that the grain and drying air move in the same direction, while the cooling air moves in the opposite direction to the grain (Figure 2.8). Very high air temperatures are used in these dryers since air with the highest temperature is forced through wet grain. Drying capacity of the system is of the order of 0.4 t/h/m^2 of column cross sectional area and the corn is dried in a single pass. Even at a high drying air temperature of 150°C, grain

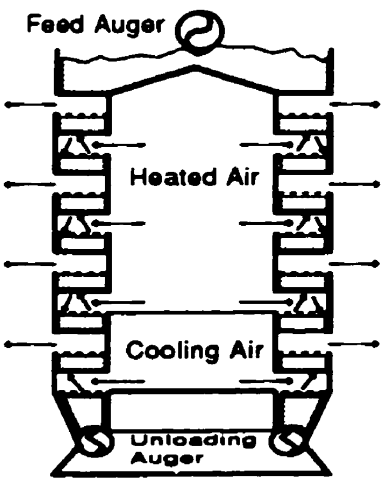

Figure 2.8 Concurrent flow dryer

temperature remains at a safe level of 41 °C due to the intense evaporation of moisture near the entrance section of the dryer. Exhaust air at the drying section reaches a relative humidity of 87% when corn is dried to 16.8% w.b. The remaining 2% moisture is removed in the counterflow cooling section of the dryer. The specific energy consumption amounts to 3.844 MJ/kg water evaporated which can be reduced to 3.466 MJ/kg if cooling air is recycled (Meiering et al., 1977).

c. Counterflow

The principle behind counterflow dryers is to make the grain travel in the opposite direction to the air flow. A bin is frequently used and the hot air enters from the bottom of the bin and moves up through the bed. The grain is removed from the bottom of the bed once it is sufficiently dried. In this type of dryer the drying zone exists only in the bottom layer of the bed. Nearly saturated air leaving the drying zone passes through incoming grain and some of its heat is used to raise the temperature of the grain. Since the drying zone containing hot grain is exposed to hot inlet air and heat in the outgoing air is recovered by the incoming grain, the system attains higher thermal efficiency. However, the grain can get over dried and grain quality suffers. It is for this reason that counterflow systems are usually used for the cooling stage in most drying installations.

d. Mixed flow

In a mixed flow dryer, the grain is cascaded over a series of staggered alternate rows of horizontal intake and outlet air ducts. Heated air enters the grain column from an open-bottomed intake duct and flows through the grain to the four surrounding exhaust ducts. The relative direction of the air and the grain in a mixed-flow dryer is a mixture of concurrent, countercurrent and crossflow. The lateral distribution ducts can be inverted V-shaped or roof shaped and have an area such that air velocity does not exceed 7.5 m/s. The length of the drying and cooling zones depends on the dryer throughput. The total dryer height can vary from 10 m to 60 m, 20-30% of which is used as the cooling section.

Drying air temperatures ranging from 65 °C to 85 °C are recommended for food grains, while temperatures between 95 °C and 130 °C are employed for feed grains. Air flow rates of 45-78 m^3/min-ton grain at 0.25-0.50 kPa are common in mixed-flow dryers (Brooker et al., 1992). These dryers range in capacity from 22 to 200 tons/hr.

2.3.3 Rotary dryers

Rotary dryers are presently employed in the grain industry to a limited extent. The major components of the system are a long inclined cylindrical shell, a fan and heater unit, loading and unloading augers, and a variable speed drive. The operating principle of this type of dryer is to repeatedly lift the grain using a set of flights along the perimeter of the cylindrical shell and drop them into a stream of heated air. Most rotary grain dryers are of the concurrent flow type where grain and heated air are introduced at one end of the shell and dried grain and moist air exit at the other end. The grain is moved through the entire length of the shell by cascading a certain distance along the periphery of the inclined shell such that in each fall, the grain is moved closer to the exit.

A typical commercial rotary dryer has a shell diameter of 1-2 m, a length of 15-30 m, and a slope 2-4° from the horizontal. The shell usually rotates at 4-8 rpm and drying air temperature is 121-288°C (Brooker et al., 1992). The rotary drying process is finding more application in the parboiling of rice. Its ability to dry high moisture grain kernels that have a tendency to stick together is suited to the parboiling process where the kernels are initially too sticky to allow drying in a bin or column dryer. The specific energy consumption of the system can not be fairly compared with other dryers since the parboiled rice is at a much higher moisture content than the materials dried in other types of unit.

2.3.4 Dryeration

The dryeration process was developed by researchers at Purdue University in the mid 60's based on their findings that most damage by cracking occurs at moisture contents less than 18% and that stress cracking is related to drying temperature, drying rate and cooling rate. It is a two-stage process in which grain is dried in a heated air dryer to within 2% of the desired moisture content and then transferred to an aerating bin for 4 to 10 hours of tempering. The tempering stage allows for the redistribution of moisture within the kernel which serves to relieve stresses caused by rapid drying. Tempering also improves moisture removal during the aeration process as it enhances moisture migration towards the surface as internal kernel moisture equilibrate.

Aside from the quality effects, several advantages of the process over conventional drying methods can be seen. The use of higher drying air temperature is possible since the grain does not remain in the high temperature dryer until it is completely dry. An increase in capacity for high temperature dryers is possible with the removal of the cooling stage since cooling is accomplished in the aeration stage external to the dryer. Removal of the remaining 2% moisture in the grain, which is the most difficult to remove, is accomplished in a bin using the heat already contained within the grain. This results in fuel savings of 20% or more. One disadvantage of the process is the possibility of excessive condensation during the cooling stage which could eventually damage the grain. The amount of condensation can be reduced by pulling the air down through the grain or by cooling the grain immediately after it comes out of the dryer (Raghavan, 1987).

2.3.5 Conclusions

Batch dryers can be considered to be an on-farm systems and have capacities below 10 t/h. Batch volumes from 3.5 to 70 m^3 are available and operate on a stationary or recirculating batch mode. The most recent tests by the Prairie Agricultural Machineries Institute (PAMI) on several batch dryers showed that they have specific energy consumption of 3.6 to 5.4 MJ/kg of water evaporated.

Continuous flow dryers are usually considered to be off-farm systems and are available in capacities ranging from 2 to over 200 t/h. Tests conducted on continuous flow corn dryers showed that at optimum performance a mixed flow dryer operating at 15 to 45 t/h will yield a specific energy consumption of 3.2 to 4.5 MJ/kg of water evaporated.

Aside from their high specific energy consumption, the primary disadvantage of these systems is that they are idle during most of the grain production season. Bin-type batch dryers are sometimes used as grain storage during off-season while column or recirculating dryers and most continuous flow dryers are idle. This situation lowers the use factor of the unit and increases overall operating cost. Furthermore, in both batch and continuous dryers, a minimum amount of grain is needed to operate the system in a reasonable drying condition. Drying of grains below the hourly throughput of the dryer will be inefficient and in some systems, not possible. Table 2.1 summarizes some of the characteristics of heated-air dryers.

Table 2.1 Summary of characteristics of heated-air dryers.

Dryer type	Capacity, t/h or m^3/batch	Reduction in MC, %	Air temperature, °C	Air Flow, m^3/min-m^3 corn	Bed depth or thickness, m	Spec. energy con., MJ/kg
Batch dryers						
Batch-in-bin	19-74 m^3	no data	38-71	6.4-14.4	2-4	3.37
Column batch	6.5-12.7 m^3	no data	60-95	no data	no data	no data
Recirc. Batch	5-9 t/h	5-8	no data	no data	no data	no data
Continuous flow dryers		**%**	**°C**	**m^3/min-ton**	**m**	**MJ/kg of water evap**
Cross Flow	〉40 t/h	13	60--110	83-140	0.24-0.45	5.0
Counter Flow	0.4 t/h/m^2	no data	150	no data	no data	4.0
Mixed Flow	22-200 t/h	25	65-130	45-78	no data	3.0-5.0

2.4 Particulate Medium Processes

Particulate medium thermal treatment can be categorized as conduction heating because heat is transmitted to the wet material by conduction from hot granular particles. Superior heat transfer rates result from a much higher heat capacity of solids compared to air. Since solids retain more heat than air, excess energy after the heat transfer process can be reclaimed when the medium is recirculated. Recirculation of the media reduces heat loss thereby improving overall system efficiency. Thorough mixing of the heated media and the grain results in uniformity of heating which is attainable in a very short time.

Five processes in sequence are involved in the thermal processing of grains using heated particulate medium: heating the medium, mixing the medium and grain, separating the medium from the grain, recirculating the medium, and cooling/aerating the grain before storage. A brief description of these processes follows.

2.4.1 Heating

Heating the medium is the first step in particulate medium thermal processing of agricultural materials. This process is the most critical in terms of heat utilization. Transfer of heat usually involves products of combustion transferring heat into an inert solid conducted at very high heat transfer rates. The main objective in heating the medium is to attain a high medium temperature at the least fuel consumption. Degree of heating sets the initial medium temperature for thermal processing. It is here that there is direct coupling of the external energy source and the thermal treatment process. At this point, the first efficiency limitation is encountered. Furthermore, the attained medium temperature influences the other operating parameters subject to the set of constraints imposed by the machine and the processing objectives.

Several methods of heating the particulate material have been employed. Lapp et al. (1976) used an electrically heated sand hopper containing ten-2 kW Calrod heaters to heat sand up to 105°C. A similar heating arrangement was used by Savoie and Desilets (1978) in heating sand for their fluidized corn drying device. Simonton and Stone (1986b) used 2.2 kW strip and cartridge heaters controlled by a computer to heat salt or Interprop to 65°C. Khan et al. (1973), Raghavan and Harper (1974), Noomhorm et al. (1994) and Iqbal et al. (1996)

used external in-line burners using propane or liquefied petroleum gas as fuel for heating sand. Subsequent work by Pannu and Raghavan (1986) was done with an internal single-nozzle 44 kW propane burner. Direct contact of the medium with the flame resulted in an increase in temperature well above 250°C.

2.4.2 Mixing

Once the medium attains the specified initial temperature it is conveyed into a chamber where it is mixed with the material to be processed. Three variables influence the rate and the amount of heat transmitted into the grain by the medium. The initial medium temperature influences the rate of heat transfer and the maximum temperature to which the material can be heated. The contact time and the mass ratio between the material and the medium determine the total amount of heat transmitted. In mixing the material and the medium, two parameters of importance are thermal conductivity and the heat transfer coefficient. Extensive investigations showed that aside from the inherent thermal characteristics of the materials the relative size, shape and orientation of the particulates were the physical attributes that affect the heat transfer coefficient.

Several researchers have developed different mechanisms to accomplish the task of mixing the material and medium efficiently. Raghavan and Harper (1974) employed a rotating bed of heated salt in an inclined cylinder to mix corn and medium. The corn is loaded in the lower end of the cylinder and a perforated helix moves the grain upwards across the heated salt bed consequently mixing the two materials. Lapp et al. (1976) used a tilted horizontal cylinder for mixing the heated medium with wheat. Both materials are introduced in the inlet end and get separated in the screened section of the cylinder. Khan et al. (1973), Tessier and Raghavan (1984), Pannu and Raghavan (1986), Noomhorm et al. (1994) and Iqbal et al. (1996) used a horizontal cylinder provided with spirals to mix the medium with the grain and provide a means of transporting the materials inside the cylinder.

2.4.3 Separation

After a specified time of contact between the medium and the grain, the grain is separated from the medium and the medium is subsequently returned to the heating section for reheating. In most of the earlier designs screening by a wire mesh or perforated metal plate was the most common method of separation. Tessier and Raghavan (1984) used a #8 sieve while Lapp et al. (1976), Simonton and Stone (1986b), and Pannu and Raghavan (1986) used a wire mesh for separation. The machines developed by Khan et al. (1973), Noomhorm et al. (1994) and Raghavan and Harper (1974) used perforated metal sheets for separation, although in the machine of Raghavan and Harper (1974) the perforated sheet was used both for material transport and for separation. Iqbal et al. (1996) used a vibratory sieve to separate grain from heated sand after mixing in a horizontal drum.

2.4.4 Recirculation

After the medium is separated from the grain, its temperature normally drops by as much as 30°C and it needs reheating. This requires recirculation of the medium into the heating section of the machine by paddles, bucket elevators or rotating buckets. Lapp et al. (1976) utilized a bucket elevator to move sand from the separation section to the sand hopper. Paddles were used in the machine of Khan et al. (1973) and Noomhorm et al. (1994), while Pannu and Raghavan (1986) and Tessier and Raghavan (1984) used a rotating bucket attached to the mixing cylinder for recirculating the medium. Only Iqbal et al. (1996) used an insulated screw conveyor to move sand from the external heater to the inlet of the mixing drum.

2.4.5 Cooling / Aeration

Heated grain continuos to release moisture to its surrounding environment and when kept within a limited space may saturate the air leading to condensation of moisture. Therefore, the grain has to be cooled before storage to avoid condensation which could result in eventual spoilage. To accomplish this function, a cooling section is normally integrated into the heating unit. On all the machines developed so far, only the machine designed by Lapp et al. (1976) incorporated a cooling section. It consisted of a 1.22 m long perforated cylinder provided with an exhaust fan for cooling and moisture removal from the grain.

2.4.6 Conclusions

The processes involved in particulate medium thermal treatment of grains seemingly require five machine components to accomplish the tasks of heating, mixing, separation, recirculation and aeration. When components are designed to perform each function individually, a more complicated piece of equipment will be constructed. However, when the functions are analysed and the parameter limits properly set, individual components can be designed as parts of a single major machine component.

This situation is illustrated in the machines developed by Lapp et al. (1976) and Pannu and Raghavan (1986). In the former, each function was accomplished using individual components resulting in a very complicated machine. An attempt to consolidate these functions into a single machine was made in the latter. Although the machine by Lapp et al. (1976) was complex, it has the advantage of giving a high level of control over the operating parameters involved in particulate medium thermal treatment. The machine developed by Pannu and Raghavan simplified the process by concentrating all functions, except aeration, into a single multi-cylinder Processor. The main disadvantage of the Processor is that if any one parameter is altered, all the other operating parameters must be adjusted. In order to fully appreciate the limiting conditions of these processes and develop a simple machine, a comprehensive review of the thermal treatment operating parameters is required. The following section discusses these parameters as evaluated by other researchers.

2.5 Particulate Medium Heating Parameters

2.5.1 Control variables

Several parameters determine the rate and amount of heat transmitted by the medium to the grain. The rate at which heat is transferred to the material is important for thermal processing applications such as pre-heating and disinfestation. It is influenced by: 1) the initial temperature of the medium, which determines the initial thermal gradient (ΔT) between medium and grain, 2) the heat transfer coefficient, which is a function of both the thermal and physical properties of both materials, and 3) the thermal conductivity of the grain which absorbs available heat from the medium.

The amount of heat transmitted determines the final temperature that can be attained by the material. It is important in thermal processing applications such as drying, roasting and de-germination of seed grains. The amount of heat transferred to the material is influenced by the heat capacity of the medium, the rate of heat transfer, and the contact time.

Sibley and Raghavan (1985) evaluated the effects of initial grain moisture content, initial medium temperature, medium particle size, medium to grain mass ratio, and contact time on the drying of shelled corn immersed in heated sand. They found that initial moisture content, initial sand temperature, sand-to-grain mass ratio, and contact time were the main variables affecting the process.

A review of the work undertaken by various researchers shows that initial medium temperature used in the different machines tested ranged from a low of 70°C (Noomhorm et al., 1994) to a high of 274°C (Raghavan and Harper, 1974), resulting in material temperatures ranging from 35 to 102°C. In the processing of grain destined for animal feed (roasting, popping, gelatinizing), temperatures ranging from 100-150°C are normally used. Grains with moisture content as low as 8% and as high as 38% have been used with mass ratios of from 1:1 to 1:25 and contact times ranging from 4-210 seconds.

2.5.2 Characteristics of Heating Media

Aside from these processing parameters, one factor that has shown a big effect on the performance of particulate medium thermal processors is the type of medium being used. The media that were used were either hygroscopic or non-hygroscopic. The most common materials used were sand, salt, silica, natural zeolite and molecular sieves. Sand, which is non-hygroscopic, has been used as heat transfer medium because of its availability and low cost. Salt has been used because of its good heat transfer characteristics as well as its non-toxic effects. The use of silica, natural zeolite and molecular sieve has been studied lately and reports have been encouraging. These three particulates are considered hygroscopic since they absorb moisture during the mixing and help overcome the mass transfer limitations inherent in the restricted airflow environment of immersed particles.

Several studies on the enhancement of heat transfer using different granular media were undertaken. Alikhani (1990) compared sand and zeolite in drying of corn and found that zeolite performed better than sand. He found that higher grain temperatures can be attained with zeolite showing that the material has a higher heat capacity than sand. These studies support the findings of McBratney (1989) and Raghavan et al. (1988) that zeolite is superior to sand as a heat transfer medium for particulate medium thermal processing. McBratney (1989) studied the use of a natural zeolite (chabazite) as a drying medium for yellow dent corn. Alikhani (1990) conducted a similar study using molecular sieves. He found that over three levels of initial medium temperature, medium-to-grain mass ratio and contact time, molecular sieves were far better than sand in removing moisture. Also, he found that there was a much higher heat transfer coefficient between molecular sieves and grain than between sand and grain. Furthermore, the relative humidity of the air inside the dryer approached saturation rapidly when using sand, while when using molecular sieves, the relative humidity dropped with contact time to reach a steady state value of 10 to 20%.

2.5.3 Conclusions

Particulate medium thermal processing requires the control of the rate and amount of heat transferred to the material to be heated. It involves the manipulation of several variables that influence the flow of heat from the external heat source to the medium and from the medium into the material being processed. Factors such as initial grain moisture content, initial medium temperature, medium particle size, medium-to-grain mass ratio, and contact time each influence the transfer of heat from the medium to the material to be heated. Process variables such as initial medium temperature, medium-to-grain mass ratio and contact time have been found to be the main control variables affecting the process. Hence, these parameters should be targeted when designing components of particulate medium thermal processors. Although many of the parameters affecting particulate medium thermal processes have been studied, specific relationships between them have not been determined adequately for purposes of designing practical equipments to accomplish most processing applications.

2.6 Particulate Medium Dryers

The findings of Kelly (1939) indicated that grain quality after conduction drying was satisfactory and thus demonstrated the feasibility of drying grains using solid medium heat transfer. However, the use of solid heat transfer media resulted in lower reduction of moisture content than expected. This presented a challenge to researchers.

For decades after the publication of Kelly's report, very little work had been done on the development of dryers using solid-to-solid heat transfer. Work in the subject area dealt more with the theoretical aspect of the process rather than the development of drying equipments. It was only in the early 70's that work on prototype particulate medium dryers were undertaken. The following is a brief description of these machines, their operating characteristics, and their performance.

2.6.1 Khan et al. (1973)

The continuous flow dryer is composed of a rotary drying cylinder 45 cm in diameter and 60 cm long. The cylinder is mounted over a sand pan which is heated by two 15 kW heaters fuelled by liquefied petroleum gas. The unit is fitted with an auger feeder to obtain positive, uniform metering of wet grain into the machine. Provisions for the feeding, mixing and removal of heated sand and grain were designed into the drying cylinder (Figure 2.9).

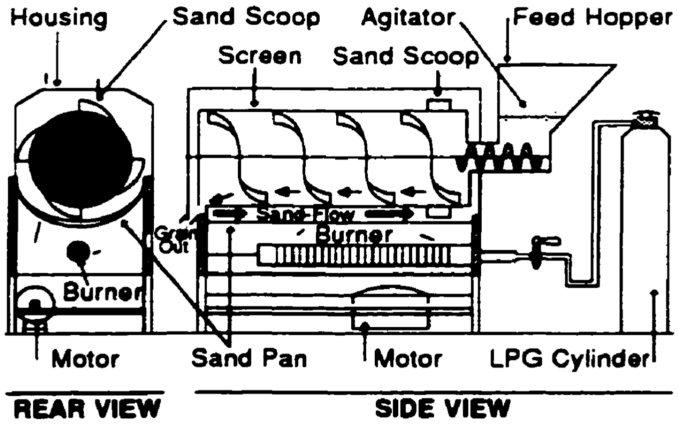

Figure 2.9 Particulate medium dryer by Khan et al. (1973)

Tests were conducted on the machine using paddy with an initial moisture content of 32%. A paddy-to-sand mass ratio of 1:25 was used for a contact time of 15 sec. A final grain temperature of 93 °C was attained and a dryer thermal efficiency of 35% was calculated based on 3.256 MJ/kg water evaporated.

2.6.2 Raghavan and Harper (1974)

The dryer consists of a rotary drum 0.6 m in diameter and 0.76 m long. A perforated helix located inside the drum conveyed the product through the drum's length toward the open end. The relatively small particles of salt mix with the product and fall back through the helix perforations due to the inclination of the drum. The perforated helix serves both as a conveying device and a primary separator of the salt and grain particles. Secondary separation of salt from the grain was accomplished using the perforated spout at the exit of the drum. The angle of inclination of the drum can be varied from 5 to 28° above horizontal. The drum is driven by a 3/4 hp variable speed motor through a chain drive. The salt within the drum is heated by natural gas fired radiant heaters located below and to the side of the drum. Salt temperature within the drum is controlled by varying the flow rate of the air-gas mixture to the radiant heaters (Figure 2.10).

A screw conveyor driven by a variable speed motor moves grain from the hopper to the dryer feed spout at a manually controlled feed rate. The feed spout within the drum directs the grain to the closed end of the inclined drum and into the heated salt bed. The product emerging from the drum is dropped into a forced air cooling unit. The cooling unit consists of a drum made of wire mesh driven by a variable speed motor and a blower which forces air through the drum's perforations.

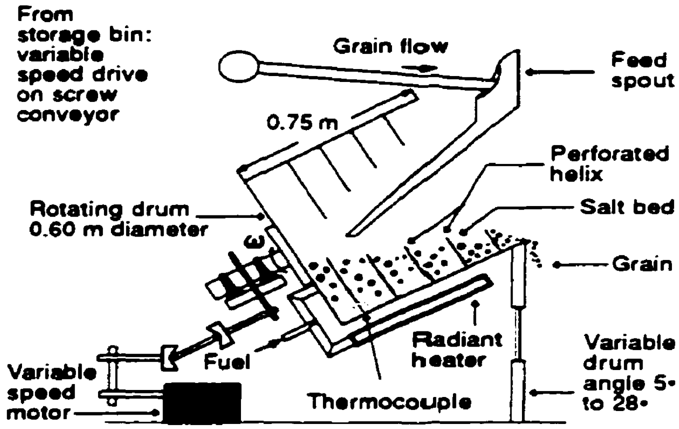

Figure 2.10 Particulate medium dryer by Raghavan and Harper (1974)

The machine was tested on corn with 15% to 21% (w.b.) moisture content fed at rates of 1-2.7 kg/min. Salt bed temperatures ranging from 134-274°C were used with residence times of 4-22 sec in the dryer. Results showed that the final moisture content of the grain ranged from 9% to 18% (w.b.). For all levels of initial moisture content, a salt bed temperature of 232°C with 13 to 20 sec residence time produced the required final moisture content of 12% to 14%. Drying efficiency, specific energy consumption and grain quality were not investigated in this study.

2.6.3 Lapp et al. (1976)

The prototype dryer consisted of a rotating drum 43.2 cm in diameter whose total drum length of 3.05 m was divided into a 1.22 m insulated drying section, a 0.61 m screened separating section, and a 1.22 m cooling and

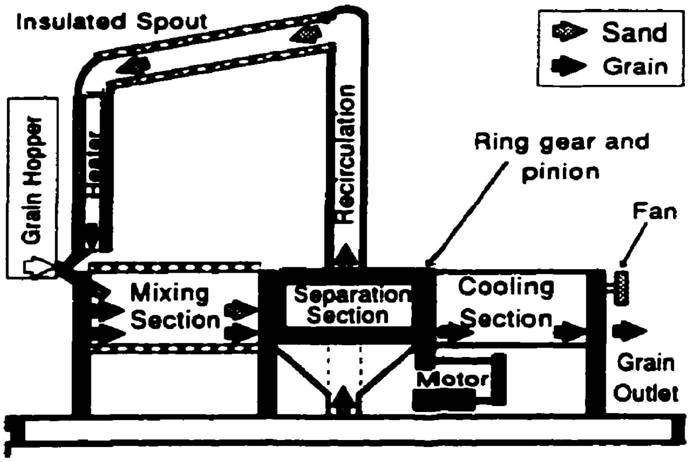

Figure 2.11 Particulate medium dryer by Lapp et al. (1976)

delivery section. The cylinder was driven by a small gear meshing with a large gear fitted to the rotating cylinder. The angular speed of the cylinder was varied using a variable speed reduction system driven by a 250-Watt electric motor. Two hoppers, one for damp grain and one for hot sand, were mounted above the drying section inlet. The hoppers deliver the grain and sand into the metering head. The metering head was used to achieve the desired sand-to-grain mass ratio into the drying section. Adjustable legs were installed on the frame of the machine to control the angle of inclination of the dryer (Figure 2.11).

The residence time (time spent by a particular grain kernel in the drum) of the sand and grain in the drying section was regulated by varying the cylinder slope, the rotational speed or the feed rate of wet material. After separation from the grain, sand was recirculated into the sand hopper by a 3.03 m bucket elevator and a 15.2 cm diameter pipe insulated with fiberglass. The sand hopper contained ten 2 kW electric heating elements. A fan capable of moving 17m^3 of air per min was installed at the cooling section.

Tests were conducted at a grain flow rate of between 1.5 and 5.0 kg/min with 60 sec residence time. Wheat conditioned to 17% moisture content was mixed with heated sand having an initial temperature of 105°C at a mass ratio ranging from 4:1 to 5:1. In drying wheat from 17% to 14.5%, the drying efficiency of the system varied from 42% to 62%. In all of the trials, moisture reduction from the grain ranged from 1.95% to 2.45% in a single pass. The specific energy consumption calculated for each trial varied between 6 and 9 MJ/kg of water evaporated. This figure compares well with findings by Pierce and Thompson (1975) who reported specific energy consumption of 6.9 MJ/kg of water evaporated for the drying of corn in a conventional heated air dryer.

The cleaning system of the dryer was found to remove 100% of the sand particles from the grain. A test for residual sand in the grain was conducted by washing a sample of grain with distilled water and evaporating the water at 110°C. After evaporation, no residue of sand was present.

2.6.4 Tessier and Raghavan (1984)

The drying unit consisted of a rotary drum, 0.69 m in diameter and 1.80 m long. An annular space of 0.05 m (A) was provided on the drum inner surface to allow recirculation of the sand by gravity along its entire length. A second spacing of 0.05 m (B) was also provided in the central section of the drum to allow for hot air flow. The hot air does not come in contact with the sand so heat transfer to the sand was by conduction through the drum walls. No provisions were made to force air into the center of the drum. Initial helical flighting was designed to precisely control residence time of grain in the drum, as well as the extent of mixing. Angle of inclination of the drum could be varied from 3.9° to 7.3° from the horizontal. Weighted average particle size of the sand used was 0.46 mm, as defined by Richard (1981). Automatic sand recirculation and separation were achieved by a set of sieves located at each end of the drum. When necessary, an additional sieve was added at the outlet to assist in separating the grain from the sand. The drum was driven by a 0.75 kW variable speed motor through a chain drive. By varying the motor speed, residence time could be varied from 26 to 40 sec. The sand was heated by a stream of hot flue gases forced into the second space (B) as shown in Figure 2.12. Heat was supplied by a propane burner, with the constant air flow rate for all test runs. The grain was fed at the inlet section of the drum by a variable speed auger.

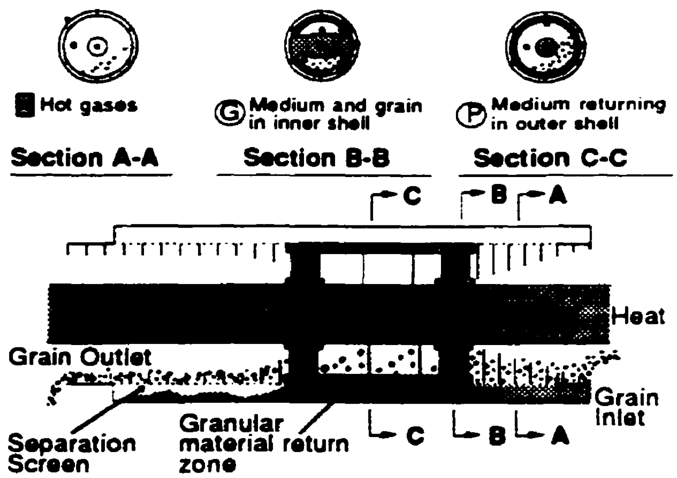

Figure 2.12 Particulate medium dryer by Tessier and Raghavan (1984)

The machine was tested using high moisture corn (36% w.b.) and sand at initial temperature of 150°C. Calculated sand/grain mass ratio ranged between 3.5:1 and 20:1 for a residence time between 26 and 40 sec. Results showed that under all operating conditions, the reduction of the moisture content was on average 3.4% (d.b.) with the final grain temperature varying between 75 and 90°C. Drying efficiencies varied from 25% to 39% while the specific energy consumption ranged between 6.5 and 10.3 MJ/kg of water evaporated. The specific energy consumption obtained in the tests were comparable to those reported by

Pierce and Thompson (1981) for crossflow air dryers and higher than those reported in the literatures for more efficient air dryers (Meiering et al., 1977; Morey et al., 1978; and Otten et al., 1980).

2.6.5 Pannu and Raghavan (1986)

The Grain Processor consists of three conical sections: inside conical drum, (Cone 1) for heating the medium, outer conical drum (Cone 2) for mixing the two media and their subsequent transportation into the separation section, and the last conical drum (Cone 3) for recirculation.

The internal conical drum was equipped with a torsion device made up of four steel rods welded to the interior of the minor diameter with a steel sleeve at its center. On the other end, the drum was held in place by eight steel rods (ribs) fixed to a ball bearing assembly unit. A 44-kW propane burner protruding into the central section through a hollow shaft was installed along with the regulatory valves. Several buckets were attached to the inside wall of the internal conical drum (Cone 1) covering approximately one-half of its length. These fixtures direct sand particles through the hot section of the flame several times before being discharged out of the heating zone.

Before installing the outer conical drum (Cone 2) an auger was constructed around Cone 1. The conveying auger consisted of 11 complete flights, out of which the first seven were encased by sheet metal and the remaining four were covered by a 3.2 mm hole steel wire mesh screen with an 84% open area. The part adjacent to the smaller diameter of the outer conical drum acts as the primary separator and the opposite end serves as the product entrance section. Such a design of the outer conical drum permits a three-stage operation in one unit: feeding grain and particulate medium, thorough mixing to enable particle-to-particle heat transfer, and finally separation of dry grain from the solid particulate media.

The third conical drum (Cone 3) serves a dual purpose: first, it acts as a collector and second, it carries the fine granular particles to one central point of discharge. The drive shaft of the drum also acts as a conveying auger to transport the medium back into the inside conical drum (Cone 1). The outside surface of the machine was insulated with 80 mm thick R-10 glass wool to minimize heat losses. The machine was equipped with a 0.75 kW variable speed DC motor for obtaining the desired rate of rotations (Figure 2.13).

The Grain Processor was tested using corn with a moisture content in the range between 18% and 36% (w.b.) fed at a rate of 240 kg/h to 520 kg/h. Heated sand was introduced at a temperature between 180°C and 250°C and a sand to grain mass ratio of 2.5:1 to 9:1. The grain and sand mixture was held in the machine for a residence time between 22 and 37 sec after which the grain emerged with a final temperature between 80°C and 102°C.

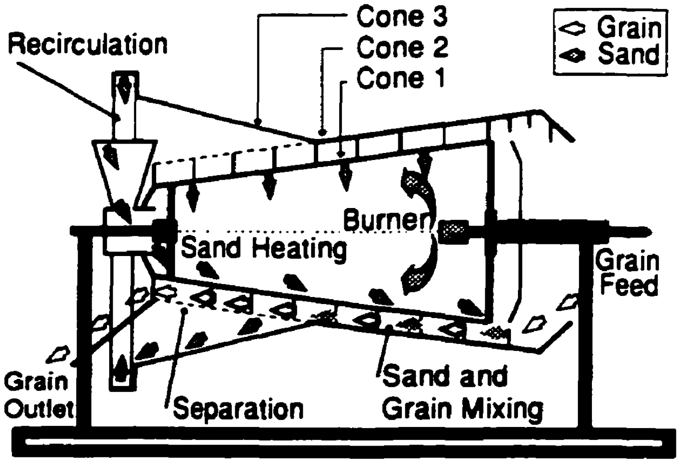

Figure 2.13 Particulate medium dryer by Pannu and Raghavan (1986)

Moisture removal from the machine ranged from 1.2% to 5.3% (w.b.) in a single pass. These results compared favourably with those reported by Tessier and Raghavan (1984), Lapp and Manchur (1974), Lapp et al. (1975, 1976), and Mittal et al.(1982).

2.6.6 Simonton and Stone (1986b)

The modelling and simulation work done by Simonton and Stone (1986a) resulted in the design and construction of a two-stage particle-to-particle heat exchanger with five cells per stage. Intricate inlet and heating cells were designed to allow two stages to be mounted back to back. Each module was 30.5 cm x 147.3 cm x 15.2 cm and it was covered with a 21.9 cm insulation board with a R-value of 2.6 m°C/W. A 0.56 kW DC motor rotated the machine, and electrical strip and cartridge heaters rated at 2.2 kW provided heat to the heat transfer medium. Two sets of slip rings were mounted on the heating section of the machine in order to transmit power to the heaters and instrumentation signals to the monitoring equipment. Operation of the heat exchanger was controlled by a Creative Micro Systems MC6809-based microcomputer (Simonton and Stone, 1986b).

The approach taken to carry out a counterflow heat exchange on particulate solids was that of discrete and repeated unit operations of mixing, heating and separating (Simonton and Stone, 1986a). A mechanism which utilizes gravity-induced flow over an inclined screen was chosen for separating the materials. This set up has the advantage of having less moving parts while in operation.

A number of tests were conducted with wheat as the drying material and salt or Interprop (a synthetic material) as heat transfer media. Three different rates of energy input (60, 80, and 100% duty cycle) at a rotational speed of 1 rpm were tested using Interprop. Eight tests were conducted with salt: four rates of energy input (40, 60, 80, and 100% duty cycle) at 1 rpm, and four speeds (0.75, 1.20, 1.45 and 1.75 rpm) at the 80% energy input level. The tests with salt showed an average thermal efficiency of 67.2% at 1 rpm while those with the Interprop averaged at 53.4%. Peak thermal efficiency of 84% was attained at 1.45 rpm. Since the experiments were designed to study the heat transfer characteristics of counterflow particle-to-particle heat exchange, no drying or specific energy parameters were available for comparison with other designs.

2.6.7 Noomhorm et al. (1994)

Noomhorm et al. (1994) developed a continuous flow rotary conduction heating unit. This unit is similar in design to the one developed by Khan et al. (1973) for the accelerated drying of high moisture peanuts, using sand as the heating medium. The horizontally mounted drum has an inside diameter of 0.50 m and is 1.96 m long. The front section of the drum which is 1.195 m in length is made up of steel sheet, and the rear section, having a length of 0.765 m, is made up of a perforated steel sheet with 4 mm diameter holes. Sand is heated in a sand pan and fed into the rotating drum by sand scoops of dimension 0.53 x 0.14 x 0.20 m (Figure 2.14).

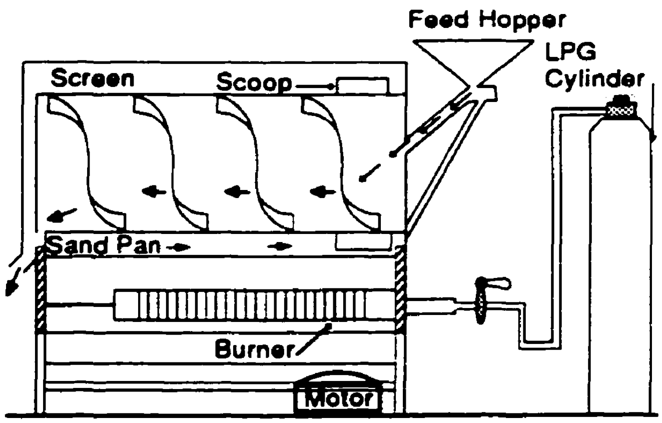

Figure 2.14 Particulate medium dryer by Noomhorm et al. (1994)

Tests were conducted on the

machine using peanuts with an initial moisture content of 49% (w.b.) fed to the machine at 5 and 7 kg/min. Sand was supplied into the mixing section at 70°C to 90°C at a rate of 4.2 to 6.3 kg/min giving a sand-to-peanut mass ratio of approximately 1:1. Residence time in the machine ranged from 60 to 210 s which resulted in a final peanut temperature ranging from 35°C to 40°C. Analysis of results of the tests were limited to quality index of the product. There was no significant difference between peanuts dried in the machine and those dried by sun drying or oven drying. Significant reduction in drying time was observed with the machine reducing kernel moisture to 10% in only 1.95 h compared to 58 h and 25 h for sun and oven drying, respectively. Comparison with other solid medium dryers could not be made since drying efficiency or specific energy consumption figures were not given by the authors.

2.6.8 Iqbal et al. (1996)

In 1993, Younis et al. designed a mechanical-cum-manual dryer employing sand as a heat transfer medium. The manual pouring and sieving caused heat losses and the machine was not considered practical for farmers in bulk grain drying. In 1996, Iqbal et al. developed a continuous flow rotary grain dryer using heated sand as heating medium. The dryer consists of a drying drum, a vibratory sieving system, heating system, a conveying system, and hopper/grain metering system (Figure 2.15).

The drying drum is a 0.15 m diameter by 1.13 m long cylinder containing an internal helix for conveying and mixing the materials and a conical feeding section for grain and heated sand entrance into the mixing chamber. The drying drum has an exit section 28 cm long for controlling the flow of material into the sieving section. The vibratory sieving section contains an adjustable sieve of 56 cm x 30 cm. Motion of the sieve can be adjusted in

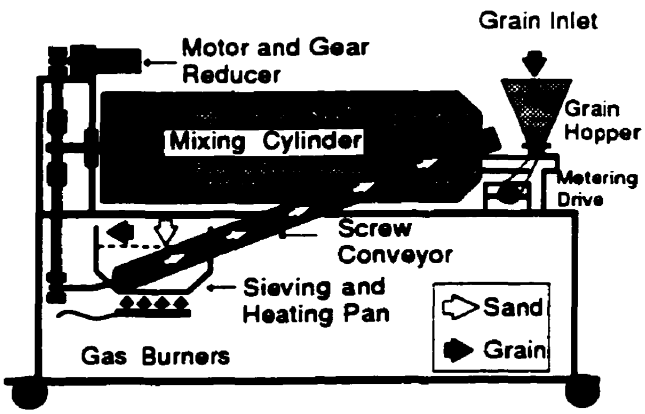

Figure 2.15 Particulate medium dryer by Iqbal et al. (1996)

both the horizontal and vertical direction by changing the hangers and length of the vibrating crank. Sand which was separated from the grain flows into a rectangular heating box under the sieve. Vibration of the sieve and the slope of the heating box moves the sand particles into the feeding end of the sand conveyor.

Sand is heated by a natural gas burner having a surface area of 1692 cm^2 as it moves from one end of the heating box to the feed end of the conveyor. The burner consists of four distribution pipes 2.5 cm in diameter having lengths of 29, 33, 39, and 40 cm. Holes of 0.156 diameter at 1.25 cm intervals provide uniform distribution of the flame under the heating box. The conveying system that recirculates hot sand into the drying drum is a 2.5cm diameter, 11 cm long screw conveyor. It is insulated with a mixture of asbestos and plaster of Paris to prevent heat losses while conveying sand. The grain hopper containing the grain before processing is 45 cm by 45 cm with 55.5 cm walls tapered at a 27° angle. It is connected to an adjustable grain metering mechanism having a stepped pulley that rotates its metering flute at 28, 43 and 72 rpm.

Corn was dried in the machine using initial sand temperatures of 90, 105, and 120°C with grain moisture contents 28, 23, and 18% (w.b.), and residence time 22, 14 and 8 sec. A 6:1 sand to grain mass ratio was used for all the trials. Grain moisture content, sand temperature and residence time were optimized. At optimum conditions, (i.e., initial sand temperature of 120°C, residence time of 22 sec and an initial corn moisture content of 28%) maximum moisture removed and drying efficiency were 3.44% (w.b.) and 58.8%, respectively. Furthermore, they found that the separated grains were free of sand.

2.6.9 Conclusions

In testing the performance of farm level dryers, the most common performance indices were the drying capacity, rated drying capacity, fuel consumption, and specific energy consumption. The drying capacity of the dryer was defined as the rate at which grain can be dried to the dry moisture content specified by the Canadian Grain Commission, when operating the dryer at standard conditions and the settings recommended by the manufacturer. It was based on the time to fill, dry, cool, and discharge the grain from the drying chambers. Drying capacity figures vary with the type of grain and the amount of moisture removed, as well as the initial moisture content of the grain. On the other hand, rated capacity was defined as the capacity of the dryer when removing 5% moisture in wheat, barley, and rapeseed, and 10% moisture content in corn. It was also based on the time to fill, dry, cool and discharge the grain under standard conditions (PAMI, 1985).

The fuel consumption of a dryer varies with the initial temperature and moisture content of the grain, ambient air temperature, the drying air temperature, airflow, and burner efficiency. It is a measure of the fuel used to dry a quantity of grain and expressed in gallons of propane per 100 bushels, or liters of propane per ton of grain dried. The specific energy consumption also varies with the operating conditions of the dryer as well as with its design. It is related to the total amount of energy used to remove a quantity of water from the grain. Total energy includes electrical and mechanical energy required for control and monitoring, and the total fuel consumed in heating and drying the grain. Specific energy consumption is a measure of the overall efficiency of the dryer.

It is not possible to characterize and assess the performance of particulate medium dryers based on the performance criteria used for farm level dryers because of the different test methods employed by researchers and operating conditions the dryers are subjected to. Aside from the dryer developed by Lapp et al. (1976), no other prototype dryer has a cooling section. The described prototypes can be compared only on the basis of their operating parameters and possibility of scale-up to industrial level. Of the eight particulate medium dryers studied, the machine developed by Pannu and Raghavan (1986) exhibited good control of operating parameters and the best scale-up potential. Their machine easily achieved and maintained steady-state conditions for continuous flow thermal processing operations.

CHAPTER III
DESIGN OF THE PROCESSOR

3.1 Preliminary Study on Corn Drying

3.1.1 Introduction

The machine developed by Pannu and Raghavan (1986) was found to remove between 1.2% to 5.3% (w.b.) of moisture from the grain at a drying efficiency of 11 to 26% and showed potential for scale-up to industrial level of operation. However, the design did not permit optimization of the parameters because the components were lumped together, making it impossible to vary the operation of one component without affecting the functions of the other machine components. Furthermore, the parameters which influence the relative size of the machine was not adequately studied. It was therefore necessary to conduct preliminary studies to identify and evaluate the effects of several variables on moisture reduction, overall heat transfer effectiveness and relative size of the machine components. The tests would also compare the suitability of two materials as heating medium for corn.

A study on particulate medium drying was undertaken using salt and natural zeolite as media and yellow dent corn as the drying material. Twelve drying experiments were conducted with six using salt and the remaining six using natural zeolite as the heat transfer medium. Salt has a uniformly small particle size compared to natural zeolite which ranged from fine powders to angular particles with equivalent diameters of around 2-3 mm. The size and angularity of the particulate used determines the configuration and screen opening of the separation section.

Three temperature-contact time (T-CT) combinations and two medium-to-grain mass ratios (MGMR) were used. The three temperature-contact time combinations (T200-C30, T150-C60, T100-C120) were used to compare the effectiveness of high temperature-short contact time (HT-SCT) with low temperature-long contact time (LT-LCT) drying. The initial temperature of the medium determines the capacity and size of the heater, while the contact time relates to the size and capacity of the mixer.

Medium-to-grain mass ratios of 4:1 and 6:1 were used since they were considered to represent a practical range. Mass ratios beyond this value may result in a relatively large mixer and heater for the machine.

3.1.2 Experimental Materials

Two types of particulate media were used in the experiments. Salt and natural zeolite (chabazite) were used in the twelve drying experiments. The salt used was of a uniform particle size, averaging 0.358 mm in diameter. The natural zeolite consisted of crushed chabazite with a particle size ranging from fine powder to chunks 2-3 mm in equivalent diameter.

The corn used in the experiments was obtained from a commercial corn supplier (Le Centre Agricole, St. Clet Inc.) and was put in cold storage for a month prior to the experiments. Before the drying experiments, corn was re-moistened by adding a pre-calculated amount of water and mixed thoroughly. The samples were then put in a sealed plastic pail and stored in the cold room at 5°C for 24 h.

3.1.3 Equipment and Instrumentation

A laboratory scale adiabatic mixer was constructed for the experiment (Figure 3.1). The mixer was composed of a metal cylinder 0.18 m in diameter and 0.45 m long. It was heated on its outside surface by three-245 W electric heaters. The heaters were attached to a temperature controller to regulate the temperature of the cylinder. A stepless variable speed motor attached to one end rotates the cylinder at speeds ranging from 0 to 120 rpm.

A slide type separating screen was fabricated from welded wire mesh. The screen was tapered at one end where grain was collected and dropped into an insulated catch pan. The catch pan was made out of thermos bottles fitted with thermocouples for measuring grain temperature.

A ceramic coated metal container was placed underneath the separating screen to keep the medium after separation

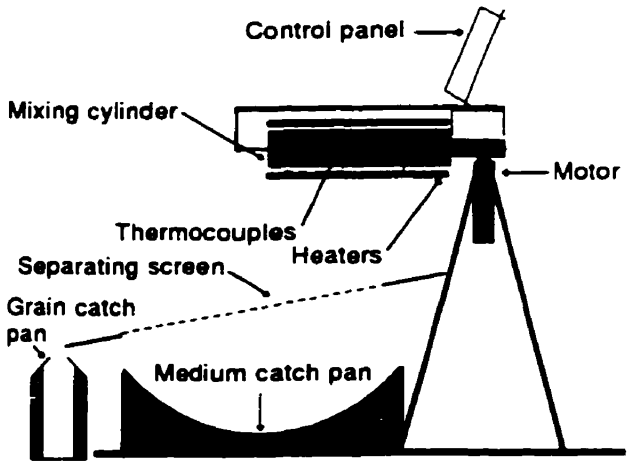

Figure 3.1 Adiabatic mixer

from the grain. The container was also fitted with a thermocouple to measure medium temperature after mixing.

An Omega OM-2 thermocouple thermometer coupled to a 10-probe multiplexer was used to measure temperature of the grain and medium before, during and after mixing. The media used in the experiments were heated to their initial temperature using a Fisher Model 230F electric convection oven.

3.1.4 Experimental Methods

Salt or zeolite were heated in the oven for 24 h before the experiments. The media were heated to 240°C and cooled down to the initial medium temperature by exposure to ambient air while being agitated in the mixer. The mixing cylinder was also heated to the initial medium temperature using the electric heaters attached to its outer surface. Heating of the cylinder was stopped the moment grain was loaded for mixing with the medium.

Re-moistened corn retrieved from the cold storage was mixed for 30 minutes using a concrete mixer to obtain uniform moisture distribution and temperature equilibrium with ambient air. Samples for determination of initial moisture content were taken and loaded in the Fisher Model 230F electric convection oven which was pre-heated and stabilized at 105°C.

Specific amounts of corn and media were prepared for mixing. For the ratio 4:1, 1600 g of medium and 400 g of corn were used. At 6:1 ratio, 1800 g of medium and 300 g of corn was used.

A temperature-contact time combination and medium-to-grain ratio was randomly chosen from the table of treatment combinations to be applied to the corn. The 300 or 400 g samples were weighed and their initial temperatures recorded.

The mixing cylinder was pre-heated to the desired initial temperature and the required quantity of medium was loaded. Once the medium temperature reached the desired initial level, the corn was placed in the mixing cylinder.

The grain and medium were mixed by rotating the cylinder at 18 rpm for the designated contact time. Two thermocouples placed inside the cylinder registered the reduction in medium temperature during mixing. At the end of the time interval, the cylinder was tilted to pour out the grain-medium mixture into a separating screen. The final temperatures of grain and medium were recorded by the Omega data logger.

Three samples of the grain were cooled to room temperature and placed in the oven for moisture content determination. The same procedure was repeated for other experiments and combinations using salt or zeolite.

Moisture content determinations in all samples were carried out according to ASAE Standard S352 for corn as outlined in ASAE (1982).

3.1.5 Results and Discussions

a. Mixing temperature (MT)

The decrease in the temperature of the hot particulate and grain mixture was plotted and is shown in Figure 3.2. The general trend showed that higher initial medium temperature exhibit a steep slope for the reduction in temperature. The drop in mixing temperature was faster for MGMR of 4:1 than for a ratio of 6:1. Both results were expected. The higher medium temperature resulted in greater thermal gradient between medium and grain thereby accelerating heat transfer to equilibrate the temperature of the two particulate. The difference in the relative mass of the two particulate also affected the rate at which heat was transmitted. At a higher mass ratio, the medium hold a larger quantity of heat such that, with all other parameters being equal, its temperature

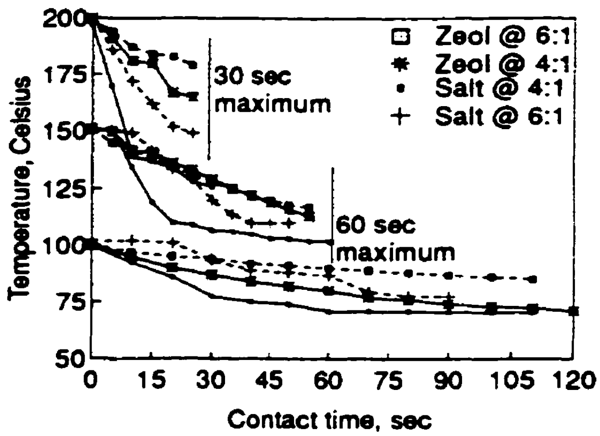

Figure 3.2 Mixing temperature

Table 3.1 Drop in medium temperature

Media/Mass Ratio	Temperature - Time Combination		
	T100-C120	T150-C60	T200-C30
Salt / 4:1	28.6	52.4	74.0
Salt / 6:1	14.0	26.8	63.4
Zeol / 4:1	35.4	50.7	59.0
Zeol / 6:1	22.8	58.3	33.0

change was much slower than if both materials have equal mass.

b. Drop in medium temperature (DMT)

The drop in medium temperature indicate the total amount of energy expended by the medium to heat the grain and its immediate environment. The total drop in medium temperature over the three T-CT combination is presented in Table 3.1. It can be noted that at 4:1 ratio, medium temperature drop increases with the change in the T-CT combination from LT-LCT to HT-SCT. These results showed that the choice of combinations for temperature and contact time fitted the ratio of heating medium to grain. The practical options for thermal treatment being either low temperature-long contact time (LT-LCT) or high temperature-short contact time (HT-SCT) between medium and grain.

Table 3.2 Increase in grain temperature

Media/Mass Ratio	Temperature - Time Combination		
	T100-C120	T150-C60	T200-C30
Salt / 4:1	47.4	63.6	73.3
Salt / 6:1	63.8	61.8	71.2
Zeol / 4:1	34.8	57.1	67.8
Zeol / 6:1	47.8	34.8	71.2

Salt was more sensitive to the change in T-CT combination compared to zeolite at 4:1 ratio. Overall, salt at both 4:1 and 6:1 mass ratio increased in DMT in its response to the change in T-CT combination from LT-LCT to HT-SCT.

c. Increase in grain temperature (IGT)

In relation to the drop in medium temperature, shown in Table 3.2 is the resultant increase in grain temperature over the three T-CT combination for 4:1 and 6:1 ratio. The table shows the same variation as with the figures for DMT. The 4:1 ratio showed similar IGT change when the T-CT combination moved from LT-LCT to HT-SCT for both salt and zeolite. IGT describes the magnitude of heat actually transmitted by the medium to

Table 3.3 Final grain temperature

Media/Mass Ratio	Temperature - Time Combination		
	T100-C120	T150-C60	T200-C30
Salt / 4:1	69.6	85.8	95.5
Salt / 6:1	75.3	84.1	93.4
Zeol / 4:1	57.1	79.3	90.1
Zeol / 6:1	70.1	81.5	93.4

the grain.

d. Final grain temperature (FGT)

The effect of 4:1 ratio on the final grain temperature over the three T-CT combination (Table 3.3) was similar to the increase in grain temperature. Furthermore, salt showed a much higher FGT compared to zeolite. The FGT was one of the critical considerations of this study. In combination with the duration of exposure, it can determine seed viability and probable damage to other grain attributes. Even with the unusual variations in DMT and IGT, the final grain temperature showed a constant increase. The effect of medium-to-grain mass ratio as well as temperature-contact time combination on the final grain temperature showed that particulate medium method of heat transfer can raise the grain temperature to a high level in a short contact time.

e. Moisture reduction (MR)

Moisture reduction was the primary concern in the drying application of particulate medium heating. One of the limitations of the method was the lack of air movement in the grain-medium mixture which prevent the efficient removal of moisture from the heated grain. Since both media were hygroscopic, there was no point of comparison over the actual amount of moisture removed while the particulate materials were mixing.

Table 3.4 Moisture reduction

Media/Mass Ratio	Temperature - Time Combination		
	T100-C120	T150-C60	T200-C30
Salt / 4:1	2.30	3.11	4.05
Salt / 6:1	2.42	3.12	3.14
Zeol / 4:1	2.15	2.65	3.60
Zeol / 6:1	2.48	2.54	3.41

Results of the tests (Table 3.4) showed that at the 4:1 mass ratio, moisture reduction increases with the change from LT-KLCT to HT-SCT combination for both salt and zeolite, with salt having a slightly higher moisture reduction than zeolite. At T100-C120 combination, moisture reduction of salt at 4:1 ratio was lower than those achieved by both salt and zeolite at 6:1. However, at T200-C30 combination, salt at 4:1 ratio had as much as 0.5 % moisture reduction over zeolite at 4:1 and 6:1 ratio.

3.1.6 Conclusions

The values shown in Tables 3.1, 3.2, 3.3, and 3.4 indicated the heat transfer effectiveness of using either 4:1 or 6:1 medium-to-grain mass ratio. Based on the foregoing discussion, the following conclusions can be derived:

1. At higher initial medium temperatures heat transfer from the medium to the grain occurs at a faster rate, with the temperature gradient between the materials serving as a driving force for the rapid transfer of heat.

2. A medium-to-grain mass ratio as low as 4:1 was sufficient in removing moisture from the grain. This means that a small particulate mixer can handle a relatively large amount of grain for processing.

3. The moisture reduction from the grain increased with the change in the temperature-time combination from LT-LCT to HT-SCT. Salt at both 4:1 and 6:1 ratio raised grain temperature over 65°C. This means that a small heater operating at high temperature will perform better than a similar unit operating at low temperature.

These findings showed that equipments using the particulate medium method of heat transfer could achieve increased moisture removal through higher initial medium temperature even at shorter contact times. The results also showed that a small machine operating at high medium temperature will be capable of removing more moisture than a similar machine operating at low temperature, even with extended contact time. Furthermore, a 4:1 medium-to-grain mass ratio resulted in moisture reduction of 2% to 4%, comparable to findings by Pannu and Raghavan (1986) which found a 1.2% to 5.3% moisture removal. This moisture reduction was achieved over initial medium temperatures of 100, 150, 200°C at contact times 120, 60 and 30 seconds, respectively.

3.2 Design and Fabrication of the Processor

The main objective of the work presented in this thesis was to design and build a particulate medium processor suitable for a number of on-farm thermal treatment applications. Based on the review of literature, the principal design criterion was to arrive at a unit permitting full operational control over temperature and contact time between the medium and the grain. The findings of the preliminary study on corn drying showed that a 4:1 mass ratio was sufficient to achieve uniform heating of the grain and that a higher medium temperature could raise the temperature of the grain for drying even at very short contact times. These observations form the basis for designing the Processor to accomplish thermal processing operations which demand different temperature and contact times (e.g. roasting, disinfestation, popping, etc. . .).

As pointed out earlier, the machine developed by Pannu and Raghavan (1986) exhibited a good potential for scale-up, were it not for the difficulty in achieving independent control of process parameters. To avoid this problem, each component of the Processor will be designed to accomplish a single operation, with full operational control over the parameter associated with that segment of the process. This means constructing individual components for each process, with its drive and control system. This way, all thermal processing operations can be studied adequately to yield better design criteria for a commercial scale unit. The pilot unit of the Processor will be designed to perform small-scale farm level processing.

The Processor is made up of a particulate heater, medium and grain mixer, separation unit, and a cooling/aeration unit. It also contains several associated parts for controlling machine operation and coupling the major machine components. A detailed description of the design and fabrication of these parts follows. The data collection instruments employed to gather performance information is also described.

3.2.1 Heating section

In this section of the machine, the medium is heated with a flame from a propane burner. It consists of the rotary heating unit, burner assembly, medium feed and discharge chute, and heater drive assembly.

a. Rotary heating unit

The heating unit contains the medium while it makes contact with the flame and flue gas from the propane burner. It consists of a heating tube, elevator cups, lateral transfer plates, and heat reclaim cylinder.

aa. Heating tube

In evaluating the performance of the machine developed by Pannu and Raghavan (1986), Tromp (1992) found that the major source of inefficiency was in heating the medium to its initial temperature. Even with a significant layer of insulation and placement of the heating section at the center of the machine, the machine still lost a lot of heat to the environment. To develop a more efficient heater for the Processor, it was decided to study the factors involved so as to enhance heat transfer from the flame to the medium and reduce heat loss from the exiting flue gases.

A horizontal cylinder 0.30 m in diameter by 3 m long was chosen to contain the medium during the heating process so that a large amount of medium is available to maintain a medium-to-mass ratio of over 4:1. To accomplish the heating more efficiently, elevator cups were installed to shower the medium over the flame, and lateral plates used to move medium from inlet to outlet.

bb. Elevator cups (Flights)

One area which requires improvement is the duration of contact between the medium and the flame. The amount of time the medium is airborne and making contact with the flame is so short that it required several passes before the medium attains the initial temperature demanded by the process. To achieve uniformity in heating, a flight configuration giving equal horizontal distribution (EHD) of medium over the flame was developed. The design of the flight was developed using the method described by Kelly (1992). Before actually using the result of the flight profile generated in the calculations, it was verified by constructing a full-scale, two-dimensional acrylic model of the heating tube incorporating the flight configuration developed using Kelly's method. Figure 3.3 shows the full-scale acrylic model.

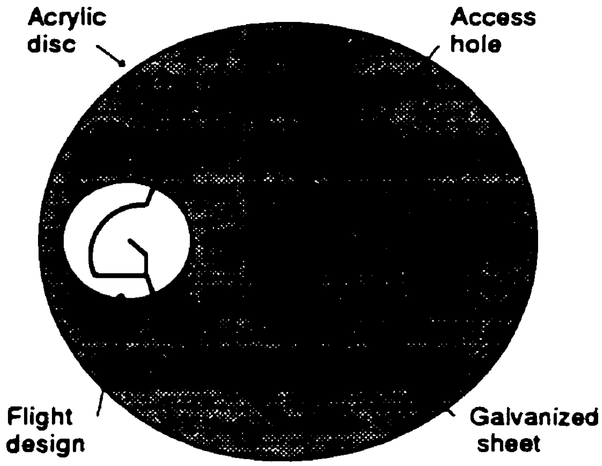

Figure 3.3 Full scale acrylic model

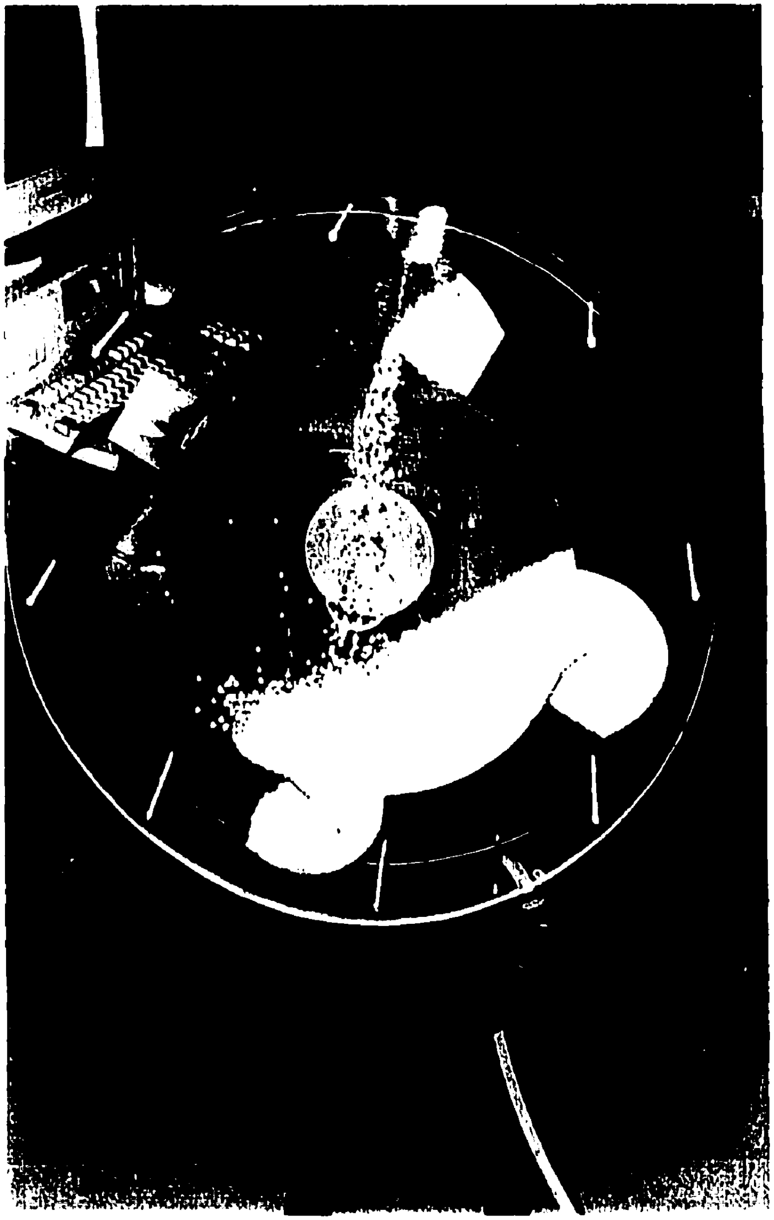

Figure 3.4a Photograph of acrylic model

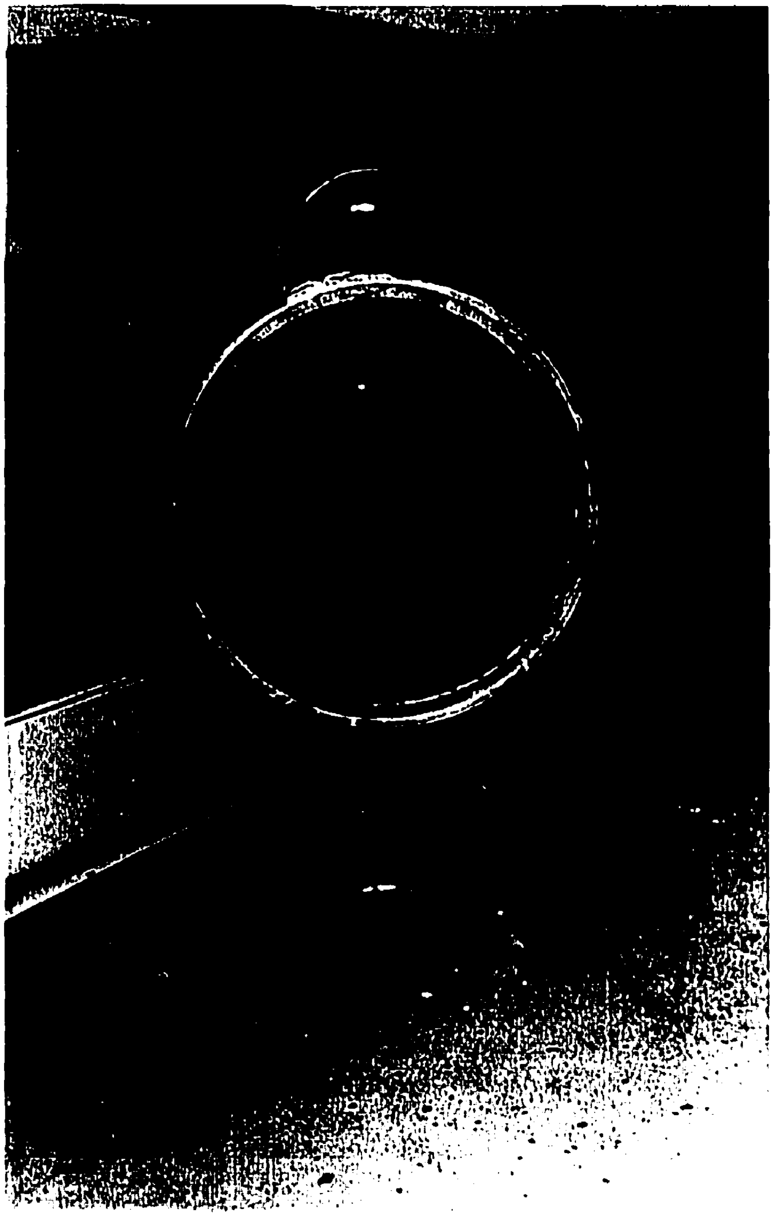

Figure 3.4b Model installed in heater tube

The cascade pattern of the flight was tested by attaching the model into a variable speed motor mounted on a steel pedestal. The model was tested on a range of rotational speeds up to the point where cascading stopped. It was tested using salt, natural zeolite, and 3 sizes of molecular sieves. The salt test was conducted to verify the effect of using fine particulate, natural zeolite to verify the effect of angularity, and molecular sieves to determine the model's response to various sizes of purely spherical media.

A video camera was used to capture particle movement during the tests. It helped in the comparison of cascade patterns of different materials at varying speeds. Its use was also found necessary when the model was rotated at high speed where the human eye cannot clearly see the cascade pattern generated by the model.

Results of the tests showed the flight design to have satisfactorily delivered an equal horizontal cascade of materials over a certain range of speeds. It was observed that at speeds over 60 rpm, the cascade pattern shifts from a purely vertical cascade to particulate discharge at an angle. As the speed reaches 180 rpm, discharge of media from the flights totally stopped. It was at this speed that centrifugal forces reached equilibrium with the normal force exerted by the particles. Although various shapes and sizes were tested, their response to rotational speed and hold-up volume remained similar.

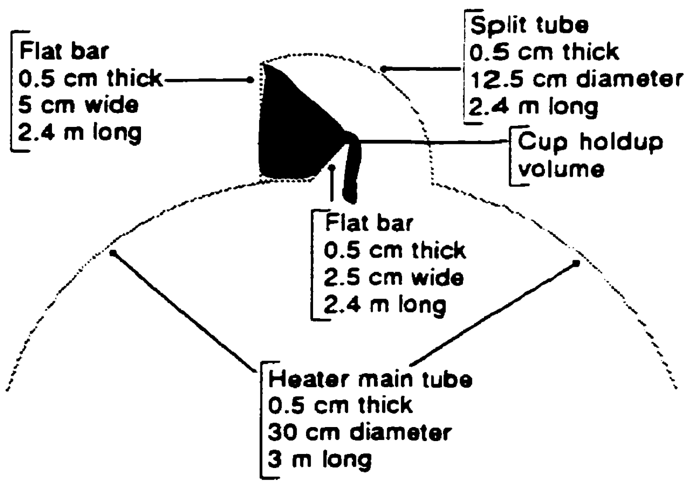

Figure 3.5 Flight design for EHD cascade

With the satisfactory performance of the model, the flight design was translated as accurately as possible into the actual cup construction used in the heating tube. The shape of the cup was made by splitting a 12.5 cm tube and welding a 5 cm flat bar on one side and two-2.5 cm flatbars below it as shown in Figure 3.5. The cup was welded over a rectangular hole cut out of the main cylinder. The main cylinder of the heating tube was made of a 5 mm thick pipe30 cm in diameter by 3 m long. 4 flight cups were constructed following the flight design tested in the model. Caps were welded at both ends of the cup to prevent leakage of the medium. The assembly was mounted on a full-floating support and tested. Test results showed cascade patterns similar to that of the acrylic model.

cc. Lateral transfer plates

Another problem associated with cascading is the transport of the medium from one end of the heating tube to the discharge chute. Most rotary dryer designs tilt the cylinder at an angle in the range of 2 to 4° with the horizontal to accomplish movement of the particles. This design performs lateral transport of materials while the particle is airborne. The method works well with larger or heavier particles since movement is by gravity flow. However, for fine particles such as sand or salt the velocity of heated air affects the trajectory of the particles as they fall from the flights. In this situation, a positive lateral movement is necessary, preferably while the particle is flowing at the bottom of the tube. In the Processor, this operation was accomplished by installing 16 lateral plates inside the tube. The plates were 5 cm wide by 15 cm long with a semi-circular shape as shown in Figure 3.11. The tube had a 12 cm pitch, designed to move the particles 12 cm along the length of the tube for every revolution of the heater.

Several tests were conducted to verify the flow of the medium through the heating tube. The tests were designed to evaluate the effect of the total amount of medium circulated through the machine on the actual flow rate using salt as the heating medium. Four salt loads were tested. The heater was tested with 100, 150, 175, or 200 kg of salt loaded in the heater. It was tested with the heating tube rotating at

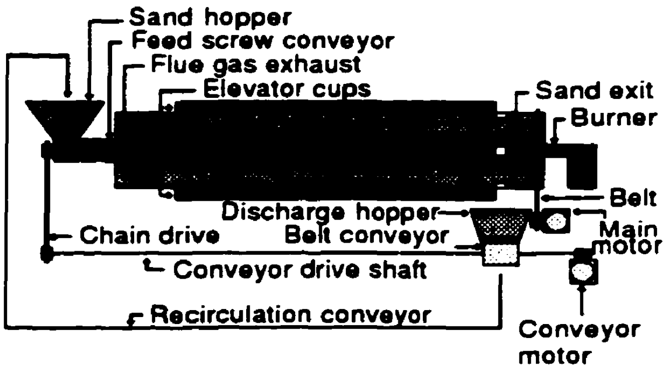

Figure 3.6 Heater flow rate test unit

speeds of 5 to 48 rpm. The test unit is shown in Figure 3.6.

The tests were performed as follows. The machine was operated at the set speed for 15 minutes before starting the experiment. This was to stabilize the flow of the medium. Once the flow was stabilized, a 0.15 m diameter by 3 m long aluminum tube was inserted in the outlet of the heater to by-pass the flow and to feed the salt into a container placed on top of a weighing scale. The amount of salt accumulated in the container in one minute was recorded. The test was repeated three times and the average value used to calculate the medium flow rate through the heater. Between sampling, a 5 min stabilization period was observed to reduce the effect of the temporary reduction in salt load created by the by-pass and re-entry of the salt taken in the sampling. The same procedure was followed in testing the heater at different salt loads and rotational speeds. Results of the tests are shown in Figure 3.7.

It can be observed that at 100 kg total salt load, a lower flow rate was attained over the range of rotational speeds tested. At 150 and 175 kg salt loads the flow rate was similar at almost all rotational speeds. Only at 200 kg load was the flow rate significantly increased with rotational speed. However, it was also at this speed that salt overflowed at the discharge end. Overall, the three salt loads showed a linear response to increased rotational speed of the heating tube. The trend lines shown in the figure has a correlation coefficient between 0.95 and 0.99, with the larger salt load (200 kg) having the highest value. This response was expected since the lateral plates had a fixed pitch designed to move salt particles a specific distance along the length of the tube for every revolution of the heater.

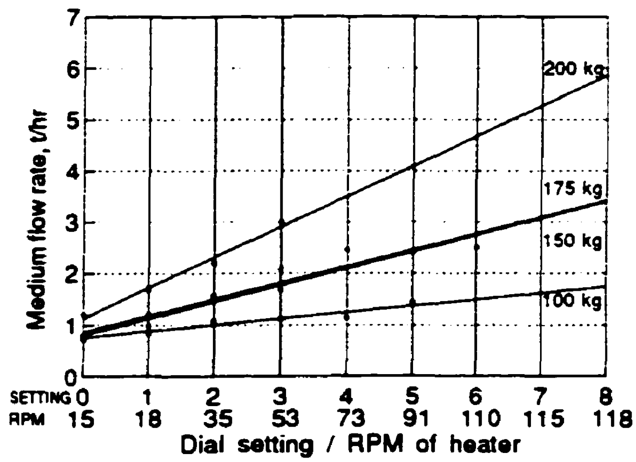

Figure 3.7 Flow rate vs. heater rotation

Furthermore, the rotational speeds tested were far below the speed limitation of the flight design. Although the cascade has been uniform throughout the 180° arc the flight travels, a certain amount of salt remained in the cups after completing the cycle at a salt load of 200 kg. This finding shows that the load was too big for the heater tube or that additional cups were needed to carry the particles. This problem should be dealt with when designing a commercial scale unit for thermal processing.

A preliminary test was conducted to evaluate the performance of the system in terms of increase in medium temperature and heating efficiency at 5 levels of power inputs. They were performed at an average medium flow rate of 1000 kg/h. As expected, increasing the power input into the system resulted in increased inlet and outlet medium temperatures. The data generated fitted a logarithmic curve with correlation coefficients between 0.88 and 0.95. The lowest power input (9kW) fitted the curve best having a 0.95 coefficient, while the 19kW input resulted in a 0.88 correlation coefficient.

Furthermore, the change in power input also affected the magnitude of change in medium temperature as can be seen in Figure 3.8. This finding shows that the heater's operating temperature can be adjusted by increasing or reducing power input into the heater. This makes it easier to adapt the Processor to the different temperature demands of applications it is intended for.

Further analysis of the data yielded the heating efficiency of the

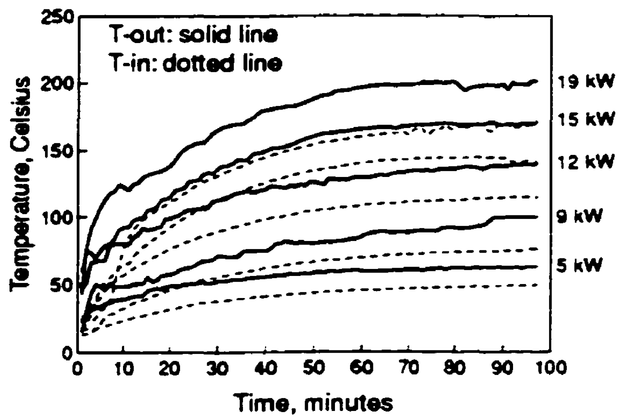

Figure 3.8 Temperature profile

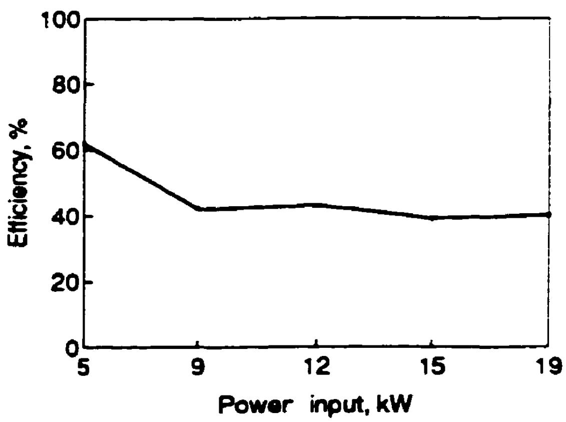

Figure 3.9 Heating efficiency

system as shown in Figure 3.9. Although there was an almost linear increase in the medium temperatures with power input as shown in Figure 3.8, heating efficiency actually dropped from a high of 60% at 5 kW to remain almost constant at 39% in the higher power levels. This indicates that there is

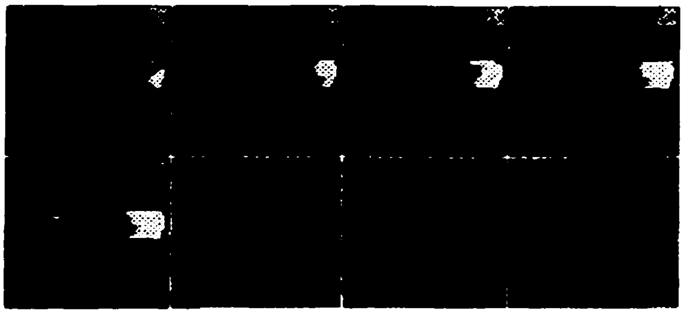

Figure 3.10 Thermal image of test unit

an enormous heat loss generated by the exiting flue gas and the heat lost through the wide uninsulated surface of the heating tube. The higher the operating temperature the larger was the temperature gradient between the outer surface of the tube and ambient air.

Surface temperature of the tube was evaluated by taking thermal images of the heating tube at each power input (Figure 3.10). A LAND infrared camera was used to capture thermal video images of the hot tube and a frame grabber software called Land Image Processing System (LIPS) was used to convert the images into a format (*. IMG) compatible for use with a Personal Computer. The pictures show the heating tube surface temperature after maximum medium temperature was attained. It can be observed that the high temperature zone located near the burner end of the tube gradually spread towards the middle of the tube as the power level was increased. This increase in surface area of the high temperature zone means that there was a lot of heat radiated by the surface into the environment, consequently lowering the overall efficiency of the heating tube.

dd. Recirculation tube

In order to improve the performance of the heater, it was

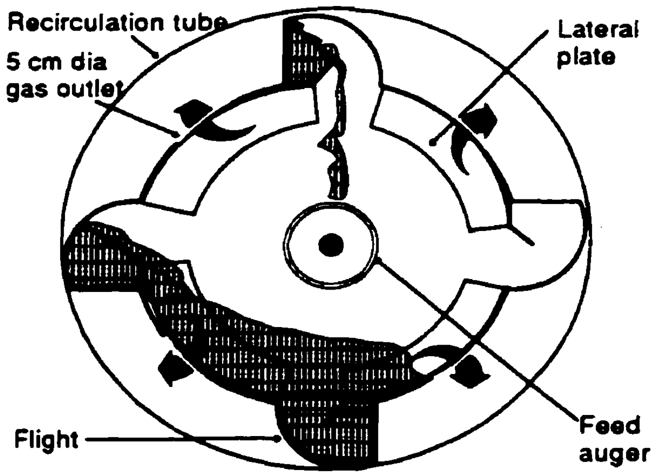

Figure 3.11 Recirculation tube

necessary to either insulate the tube or recycle part of the flue gas into the heating chamber. Since the existing configuration of the diameter of the tube showed a depression beside the area where the cups were welded, it was decided to recycle the flue gas through these "channels" by welding another cylinder over the elevated section of the cups as shown in Figure 3.11. This channel forces flue gas over the outer surface of the heating tube, recovering most of the heat that was exhausted to the environment. A test was conducted at 20 kW input after the installation of the outer cylinder and results showed a heating efficiency of around 65%. This means an increase in heating efficiency of 67% was achieved compared to the previous value. Finally, a control system was installed to effectively regulate the operation of the heating unit.

b. Burner assembly

Another area of improvement in heating was the propane burner. The efficiency of combustion depends on the correct air-fuel mixture. However, the majority of particulate medium equipments using gaseous fuel depend on induced air flow to supply primary air for combustion. For high capacity thermal processing operations, induced air flow will not provide sufficient oxygen to sustain combustion. Considering the proposed applications of the Processor and their different temperature demands, two burners of varying capacity were used.

The burner assembly consists of two propane tanks, a pressure regulator, gas flow meter, two propane burners, process controller, and type K temperature sensors. Each propane tank holds 50 kgs of liquefied propane gas. Both are attached to a central gas pressure regulator by a stainless steel braided pressure hose. The pressure regulator reduces and regulates the pressure fed to the gas burners at around 107 kPa from a tank pressure of approximately

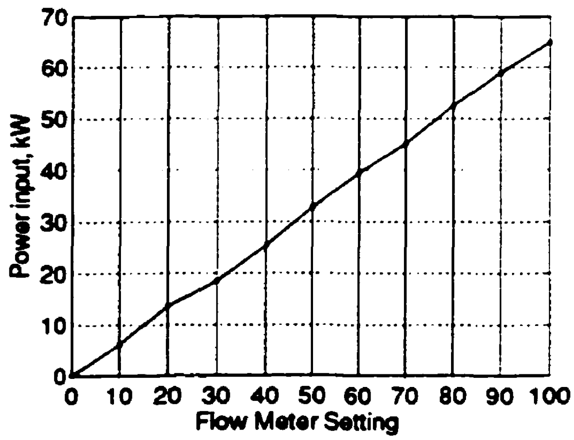

Figure 3.12 Rotameter calibration chart

800 kPa. Propane flows from the regulator through a rotameter flow meter. A 150 mm rotameter flow meter was used for this purpose. Graduations in the rotameter are calibrated in liters per minute of gaseous propane. This unit is further converted into calibrations giving actual kilowatt input by the burner.

The gas flow meter was calibrated using the following procedure. First, a 14-kg propane cylinder was filled with a specified amount of fuel. The tank was placed on top of a platform balance (digital) and its valve was opened to feed propane gas into the machine's fuel line. Then, the burner was started and the flow of propane was adjusted at the rotameter setting being tested in the scale. Initial and final weight of the tank after one minute were recorded. Three tests were conducted and the average propane flow rate was taken. The average weight loss of the tank was used to calculate the power input into the Processor at the specified setting. The tests were repeated through several settings over the operating range of the rotameter. The values for propane flow rate were eventually converted into equivalent kilowatt settings in the rotameter. The kilowatt equivalent of the rotameter settings was plotted and made the basis for all power calculations. The trend line drawn based on the data has a correlation coefficient of 0.99, showing power input as a linear function of the flow meter setting. Results of the calibration test are shown in Figure 3.12.

From the flow meter, propane is fed into a manifold containing two proportioning valves. The proportioning valves regulate the flow of propane to the two burners. The burners used in the Processor were designed to deliver different ranges of power input. One unit has a capacity of 100 kW and is used as the main burner. It supplies the base amount of heat to maintain a stable medium temperature. This burner used to be fuelled by #2 oil, but was modified to burn propane. The unit consists of an automatic flame starter, a centrifugal blower, and an 8

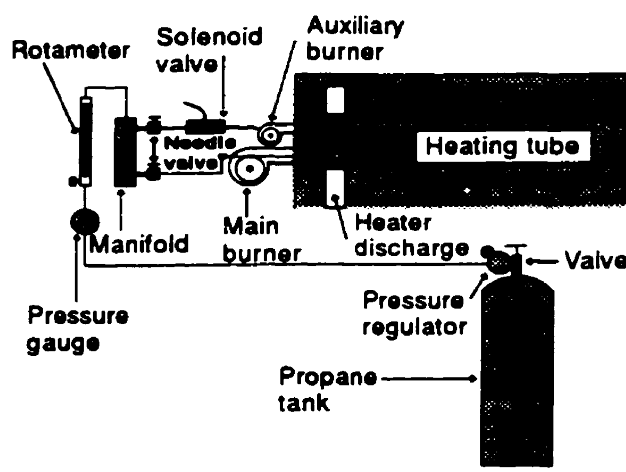

Figure 3.13 Schematic of burner assembly

cm diameter by 30 cm long manifold for mixing air with propane and burning the mixture in a swirl pattern. The amount of propane fed into the burner is regulated manually using a needle valve attached to the central gas manifold.

Another burner with a capacity of 25 kW is used to regulate the medium temperature automatically. This burner is attached to the central gas manifold by a needle valve, similar to the main burner, and a solenoid valve hooked up to a process controller. The burner is switched on and off to augment power input from the main burner to stabilize the temperature of the medium. Outlet medium temperature is monitored by a type K thermocouple and the signal is fed to a process controller which opens the valve when medium temperature goes below its set-point, and shuts-off propane flow to the burner when the medium temperature overshoots the set-point.

The process controller used to regulate medium temperature is an Omega CN9000A controller. The controller receives feedback from a thermocouple located at the discharge spout of the heater. The process controller can also use grain temperature readings at the separation section to regulate the outlet temperature of the grain. Figure 3.13 shows a schematic diagram of the burner assembly.

c. Medium feed auger and discharge chute

The feed auger used to introduce the medium into the heating tube is 15 cm diameter by 60 cm long and is driven by a 0.785 kW induction motor. It moves a regulated amount of medium

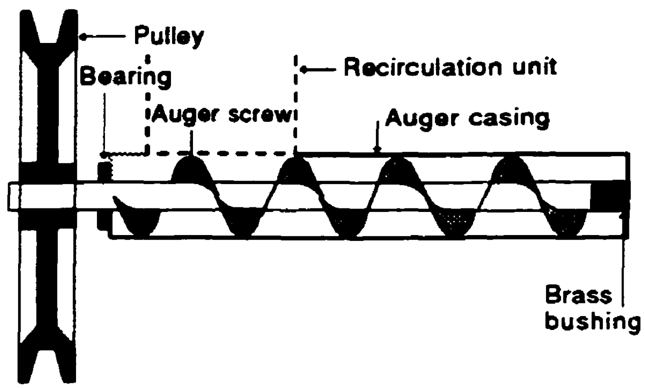

Figure 3.14 Schematic of feed auger

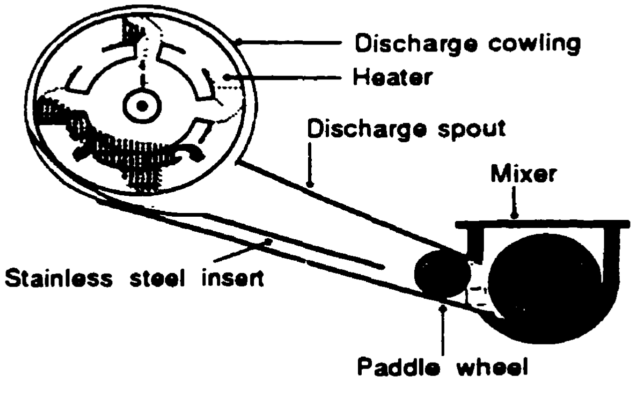

Figure 3.15 Schematic of discharge spout

from the separator chute into the heating chamber. The auger screw is held in place by a ball bearing at the drive end and a brass bushing at the discharge. The bushing at the discharge end is necessary since it is located within the heating chamber where temperatures usually reach 600°C which can significantly reduce the life of an ordinary ball or roller bearing. Figure 3.14 shows a schematic of the medium feed auger.

Heated medium from the cylinder is exhausted through a discharge chute measuring 10 cm wide, 100 cm long, with side walls 25 cm high. The chute is angled at 60° off horizontal and is perpendicular to the heating cylinder and the mixing cylinder. It contains an inner lining made of stainless steel to improve the flow of medium, and a paddle wheel to regulate the flow of the medium into the mixing cylinder. A thermocouple was installed inside the spout to monitor medium discharge temperature and provide feedback to the process controller. The paddle wheel is driven by a 1.5 kW variable speed motor driving the heating cylinder. Figure 3.15 shows a schematic of the discharge spout.

d. Heater drive assembly

The rotary heating unit, the central part of the Processor, needs to be properly coupled to other parts of the machine in order to provide heated medium to the mixer and receive recirculated medium with minimal heat losses. This requires that both ends of the tube be open for access by the burners in one end and the feed auger at the other. In order to reduce the complexity of the mechanism driving the heater and provide easy access, the heating unit is mounted on a full-floating configuration. It is supported by two pairs of rollers mounted on a M-frame which is bolted into a support base constructed out of 15 cm channels.

The two burners and their control boxes are mounted on the frame at the front end of the tube. The motor for the cooling/aerating cylinder, the main electrical load center, and the

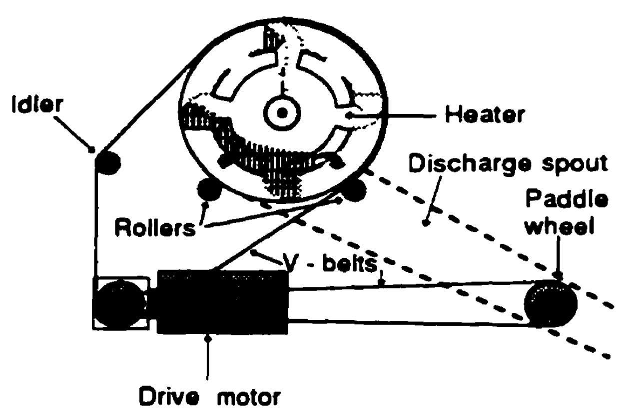

Figure 3.16 Heater drive assembly

speed controller of the three drive motors are also mounted here. The feed auger holding the set of rollers is bolted into the frame at the rear end. The base of the 0.785 kW motor that drives the feed auger is welded directly into the lower end of the frame right where it is bolted into the support base.

The 1.5 kW motor that serve as the main drive for the heating unit is bolted into an adjustable frame which is welded directly on to the support base. The drive motor transmits power to the heating tube using a V-belt and pulley arrangement, with a 30 cm diameter Type B pulley welded into the end of the heating tube. The motor also drives the metering paddle wheel attached to the discharge chute. Power is transmitted into the paddle wheel using a Type A belt and pulley. A stepped pulley is used in the paddle wheel to adjust its speed when synchronizing the heater and mixer flow rates. Figure 3.16 shows a schematic of the heater drive assembly.

3.2.2 Mixing section

Particulate medium thermal processing replaces air-to-solid heat transfer with particle-to-particle heat transfer. The transfer of heat occurs inside a mixing chamber where the two materials make contact for a specified period of time. The primary consideration in mixing is efficient heat transfer at the shortest possible time. This is made possible by ensuring maximum contact between the particulates. Another consideration is to reduce the heat lost to the immediate environment during mixing.

With the option of using hygroscopic media, mixing time has to be adjustable for the process to accomplish heat and mass transfer simultaneously. This situation points to two possibilities for enhancing the performance of the system. For purely heating applications, non-hygroscopic media can be used with the heating process accomplished at the shortest possible time. However, for processes that require significant moisture removal, time of contact can be extended to exploit the moisture gradient between the medium and the material to enhance moisture transfer. Several alternatives exist to accomplish this operation.

One factor to consider in the choice of method for mixing is to integrate mixing with material transport in a single unit. Most of the particulate medium heating equipments tested so far use spirals inside a horizontal cylinder to accomplish mixing and transport; however, the large revolving cylinder requires a complicated mounting and drive train to transmit power for tube rotation. Furthermore, only a very small fraction of the cylinder volume is used in the mixing process. A large surface area outside the cylinder radiates heat into the environment lowering the overall heating efficiency of the machine. Other methods such as vibratory conveyors and pneumatic equipments require complicated mechanisms and found to be impractical for this purpose.

To avoid this complication, an auger design is employed to mix and move the medium-grain mixture from the inlet to the discharge end of the mixer. Since the medium-grain mixture behaves like a fluid, the auger mixing method ensures that the casing is full before any material is discharged from the mixer. This results in a more effective contact between the two materials. Also, the rate of movement of the materials inside the casing is determined by the auger's pitch and revolution. Power for rotating the screw can be transmitted either directly by coupling a variable speed motor to the auger shaft or by using a belt and pulley arrangement. Support of the mixer is simplified since it is stationary with only the auger screw moving inside it.

Calculations of the relative size of the mixer based on a machine capacity of 3000 kg/h of grain gave a casing diameter of 30 cm. The length of the auger is close to the overall length of the heater to ensure that coupling of the two components can be achieved thru gravity flow of the medium by raising the discharge end of the mixer to make it coincide with the inlet of the feed auger. Contact duration between the medium and grain is also a factor in deciding the final length of the auger. Although the flow rates of the mixture can be altered to suit a certain contact time, it is better to design the auger such that contact time can be varied independently without any significant change in machine capacity. Considering both constraints, the auger length is made to accommodate contact times between 15 s and 5 min by varying the rotational speed of the auger screw.

The auger used as the mixing unit of the Processor was purchased from a local agricultural machinery fabricator. The casing is U-shaped and made of 2 mm thick galvanized steel. It measures 30 cm on the inside diameter and is 3 m long. The screw is made of 3 mm thick steel plate, 25 cm in diameter and mounted on a 5 cm diameter pipe. Two end pieces were machined to fit as shafts which support the auger screw through two rectangular flange bearings at the end caps of the casing.

The mixing auger is driven by a variable speed motor coupled to the shaft of the auger screw by a belt and pulley arrangement. Use of the variable speed motor is necessary to vary contact duration by changing the rotational speed of the auger screw. The use of a belt and pulley system to transmit power to the auger screw provides a non-engaging drive which prevents damage to the motor and gear reducer in the event a large particle or piece of metal jams the auger screw. The drive mechanism is positioned at the upper end of the mixer to prevent exposure of the motor and gear box to extreme temperatures at the inlet of the mixer. Figure 3.17 shows a schematic of the mixer and its drive system.

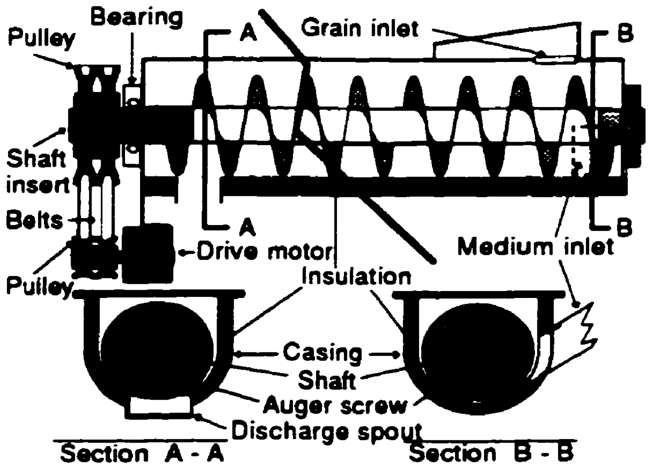

Figure 3.17 Schematic of mixing unit

3.2.3 Separation and recirculation section

In almost all particulate medium equipment described in Section 2.6 of Chapter II, the separation unit used is active screening. This involves the use of rotating screens or variable stroke vibratory screens. Active screening is a very effective method of separation, especially when particle size classification to several levels is necessary. The disadvantage of active screening is the power required and the complicated mechanism associated with power transmission to operate the unit. Active screening only wastes power in applications with large relative particle size ratios that do not require any form of classification.

Another function of the machine that has a similar problem is recirculation of the medium. Recirculation has presented some problems to a lot of researchers. Almost all of the designs mentioned in the review of particulate medium equipments used some type of mechanism to recirculate the medium from the separation unit to the heater. Pannu (1984)

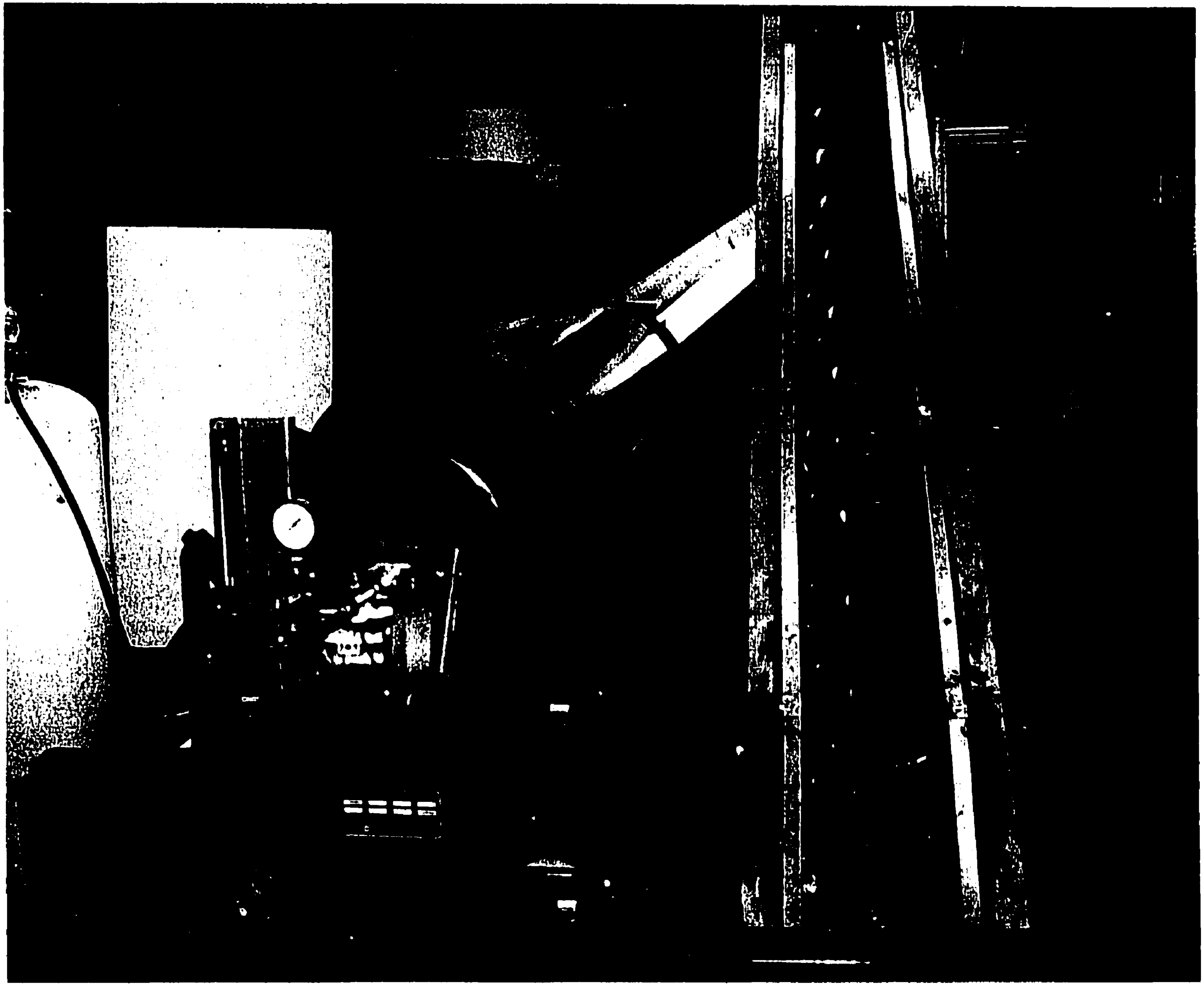

Figure 3.18 **Photograph of mixing auger**

used elevator cups, Khan (1969) and Noomhorm et al. (1992) used paddles to move material through the heater and scoops to load it into the mixer, Lapp (1973) used bucket elevators, and Iqbal et al. (1996) used an auger screw to move medium from the separator/heater unit into the mixing cylinder. The use of active recirculation requires input power and the movement of the material has to be synchronized with the flow rate in the heater and mixer. All of these mechanisms tend to complicate a relatively simple process. The simplest way to reduce the complexity of these components is to design the separation and recirculation process into a single unit and move the particulate by gravity. This way unnecessary parts can be avoided.

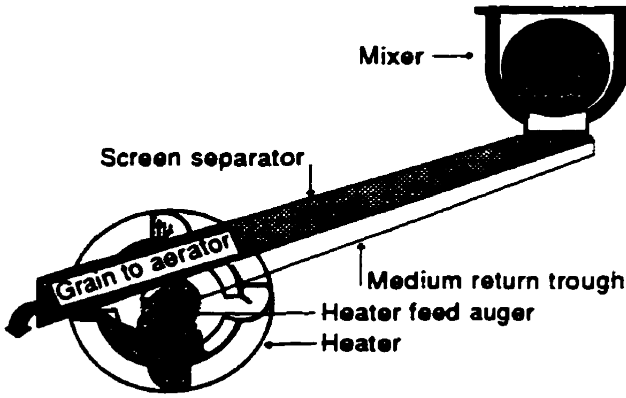

Figure 3.19 Separation and recirculation section

In the Processor, separation and recirculation were accomplished in a single unit by gravity flow. The unit consists of a slide screen, metal trough, and metering plates. The screen forms a rectangular channel where the medium-grain mixture slides down and separates. It is 0.15 m wide, 0.10 m deep and 1.50 m long. It is sloped at an angle of 40° from horizontal. The screen is fixed to a rectangular trough made out of 2 mm thick steel plate having similar dimensions as the screen. The screen and trough are spaced 2 cm at the top, increasing to 10 cm at the bottom. The upper portion of the trough is bolted into the discharge spout of the mixer while the lower end is bolted into the feed auger of the heater. Two plates located in the lower end of the screen regulate the flow of grain into the aeration cylinder. Figure 3.19 shows a schematic of the separation and recirculation section.

The separation and recirculation section works solely on gravity flow. Since the discharge end of the mixer is higher than the inlet of the heater, the difference in height provides the needed slope to the screen. The grain flows from the screen into the aeration unit and its flow is metered by two stainless steel plates placed on the lower end of the rectangular screen. The medium that falls through the screen as the mixture travels downwards is collected in the rectangular trough placed under the screen. Since the trough is secured at a 45° angle, the medium flows downwards by gravity into the feed auger of the heater. And since the auger is operated by a motor, the feed rate into the heater is regulated by the rotation of the auger screw. The present set-up is open to ambient air in order to make it easier to replace screen sizes to suit the different grains being tested. However, for a commercial scale unit, these components must be totally enclosed and properly insulated to reduce heat loss from the recirculating medium. For applications with smaller particle ratios, the unit can be fitted with eccentric vibrators to give a more effective separation.

3.2.4 Aeration section

In drying applications, the primary measure of performance is the moisture reduction capacity of the machine. In most of the equipments developed for particulate medium processing, emphasis has been given to the heat transfer capacity. In consequence, these machines were designed without a component for moisture removal. Given that the process of thermal transfer occurs in an almost total absence of moving air for moisture transport, these equipments could not be considered as dryers since there is low moisture removal in the machine itself. Of all the models developed, only the machine designed by Lapp (1963) included a component specifically designed for moisture removal.

In the Processor, the applications can be either purely heating or also drying. Heating processes demand raising the temperature of grain and maintaining the grain at such a temperature for a specified length of time. Drying processes on the other hand requires that with the amount of heat transmitted to the grain, a certain amount of moisture be removed from the grain as a consequence. Operations such as roasting, thermal disinfestation and de-germination are classified as heating processes since moisture removal is not the primary objective. In fact, the process is designed to result in the least moisture removal.

In order to perform drying in the Processor, an aeration section was constructed to undertake mixing of heated grain with ambient air. This section consists of a rotary aerator and centrifugal blower. The rotary aerator is made of a 2 mm thick galvanized perforated sheet formed into a cylinder 0.35 m in diameter and is 190 m long. It is supported on a 2.5

cm diameter hollow shaft connected to the cylinder by 3 sets of support webs. The shaft is directly coupled to a 0.785 kW variable speed motor, while the other end is supported by a pillow block.

The centrifugal blower consists of a rectangular box 1.25 m wide, 0.30 m high and 0.30 m deep. Two centrifugal fans are placed inside the box to move air. Air enters through a 0.18 m by 0.20 m opening at the back and comes out through a 1 cm by 1.20 m long slit on the top edge of the box. The blower is located right under the aerator. It blows air through the perforated sheet into the cascading mass of grain inside the aerator.

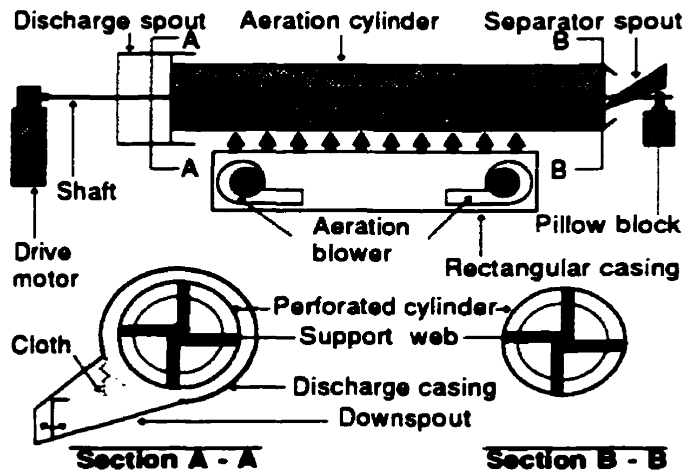

Figure 3.20 Schematic of aerator section

Grain is fed into the aerator by the separator spout made of perforated galvanized sheet. As the cylinder rotates, grain is pushed from the inlet end by the four plates of the support web which is arranged like fan blades. Movement of the grain through the cylinder is aided by the fluidizing effect of the cooling air being pushed upwards from the blower. Cooled grain exits through a grain discharge spout located near the drive end of the aerator. Figure 3.20 shows a schematic of the aerator section.

3.3 Conclusions

The preliminary study on particulate medium corn drying showed that effective heat transfer from the medium to the grain is possible at medium-to-grain mass ratios as low as 4:1. It showed that high temperature-short contact time is more effective than low temperature-long contact time. Furthermore, it showed that small salt particles is a better medium compared to chunks of natural zeolite since it covers a large surface of the grain.

Based on these findings, a particulate medium thermal Processor was designed and fabricated which will operate at high temperatures, a medium-to-grain mass ratio over 4:1, and using salt as the heat transfer medium. The machine will be tested in the drying of corn, roasting of soybeans, as well as the disinfestation and de-germination of wheat.

With the integration of an aeration section after the medium and grain mixer, it is expected that the Processor will be able to remove at least 10% (w.b.) moisture in drying corn. Furthermore, a study of moisture removal for each section will determine the usefulness of integrating an aeration section into the machine.

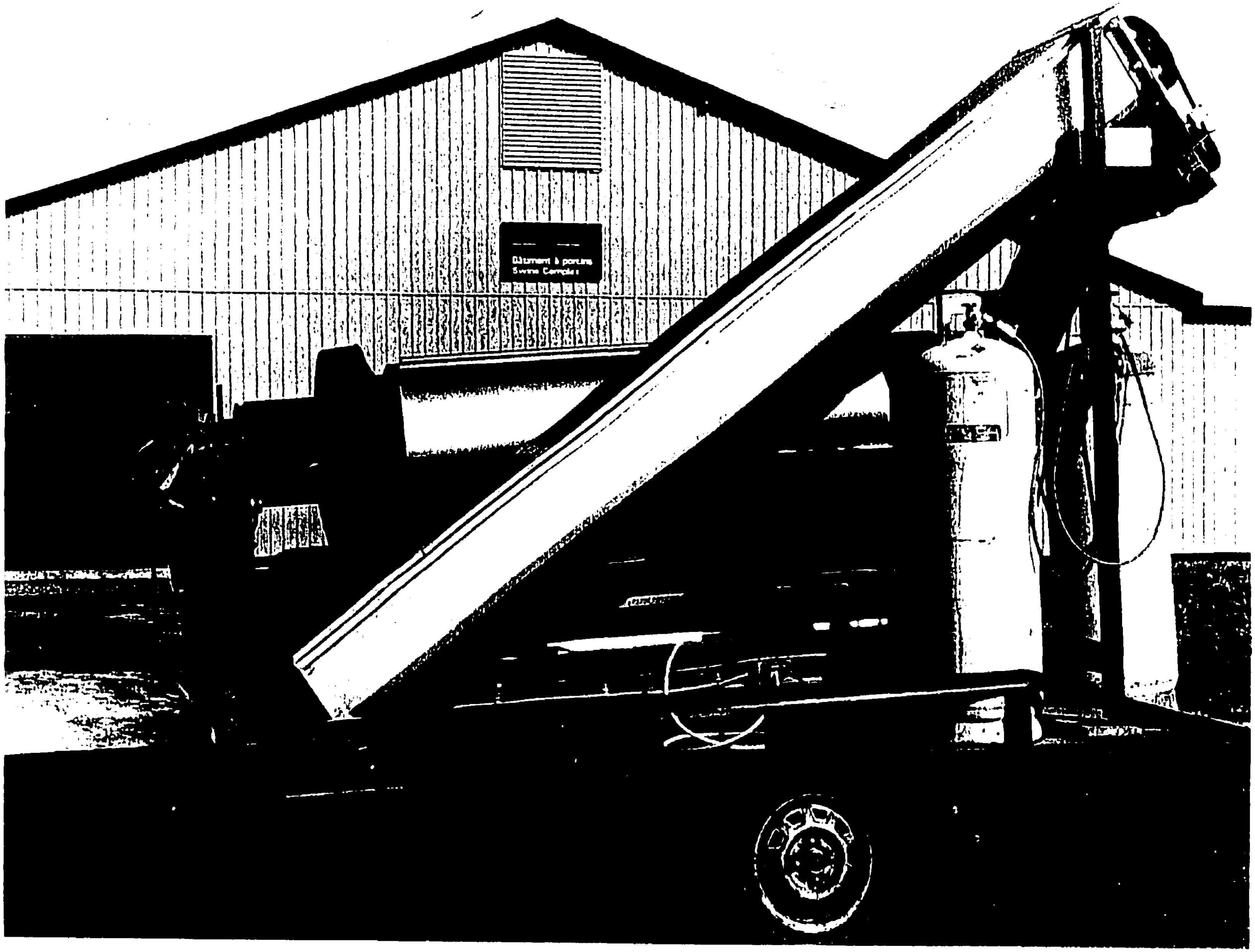

Figure 3.21 **Right side view of the Processor**

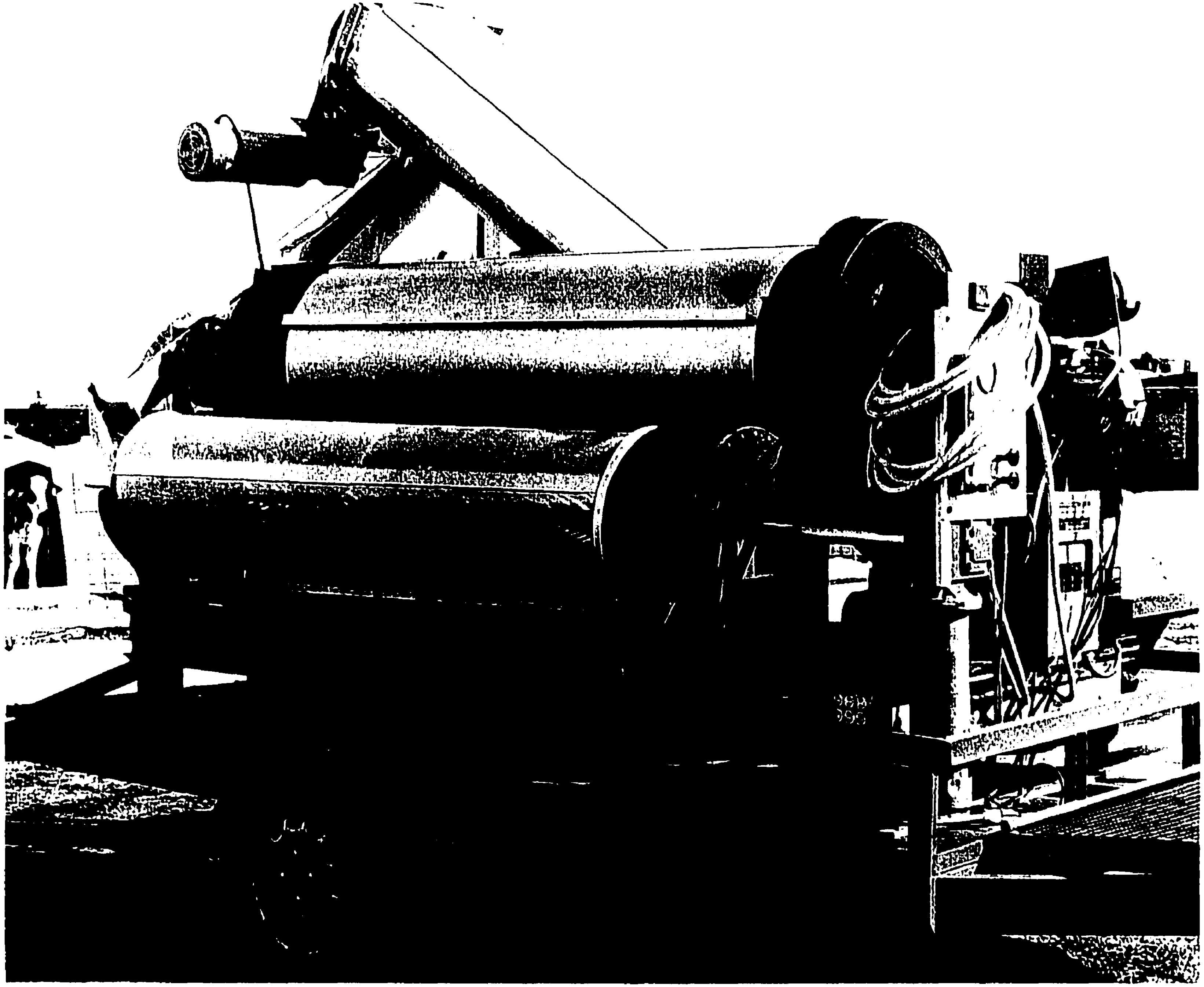

Figure 3.22 Left side view of the Processor

CHAPTER IV
TESTING OF THE PROCESSOR

4.1 Introduction

The main purpose of constructing the machine described in the preceding chapter was to determine the suitability of the particulate medium method in performing several farm level operations. Unlike its predecessors, which were designed solely for drying grains, this particulate medium grain processor was developed for drying, roasting, thermal disinfestation and de-germination of grains.

Before testing the ability of the unit to accomplish such operations, it was necessary to evaluate its performance in terms of rate of heating and heating efficiency. This was accomplished by performing convective heating trials on a crossflow grain dryer and the Processor to compare their relative performance.

Several researchers have compared convection and particulate medium drying using different methods. Raghavan (1973) compared particulate medium drying of corn with convection drying data reported by Pickett et al. (1963). He used heated sand for drying corn and compared temperature and moisture content conditions of both methods. His results showed particulate medium drying to be 7.5 times faster than convection drying. A similar study was reported by Savoie and Desilets (1978) showing particulate medium drying to be 2 to 10 times faster than convection drying. They used a fluidized mixture of sand and corn where the main mode of heat transfer was by conduction through sand particle contact with corn.

Although the two studies were conducted using different techniques of conduction heating, both came to the conclusion that the rate of drying using particle-to-particle heat transfer was significantly faster than that of convection using air as the heat transfer medium. The studies mentioned above confirmed that a faster rate of drying is possible using particulate medium heat transfer. However, they failed to quantify the magnitude of heat transmitted by the medium to the grain to achieve the drying effect reported. Furthermore, their tests were conducted on small-scale models where results were compared with data in literature where experimental conditions may not be similar. By quantifying the actual amount of heat transmitted using particulate medium heat transfer, values of actual heating efficiencies can be known at several power inputs. These values should be valuable in evaluating machine performance for different applications.

4.2 Objectives

This study was aimed at generating information on the heating rate and thermal efficiency of particulate medium thermal processing using the new Processor developed here. The results were compared with data from convective heating in a crossflow dryer. Specific objectives of the study were:

1. To construct a crossflow dryer using a design commonly used in drying cereal grains.

2. To conduct thermal treatment tests using the same input power and grain flow rate in both machines.

3. To compare thermal performance of the two methods in terms of heating rate, drying rate and thermal efficiency.

4.3 Materials and Methods

4.3.1 Design of the study

In order to compare the performance of the two machines, they were operated at the power levels. The input power used were 10, 15 and 20 kW. For the convective method, 4 units of 5 kW heaters were connected in parallel and combinations of the 4 heaters were used to provide the necessary heating capacity demanded by the study. Heating of air using electric heating elements results in lower efficiency compared to direct heating by burning propane. To compensate for the lower heating efficiency, the increase in air temperature generated by the blower (which go as high as 10° C) was not counted as power input but rather as an allowance to compensate for the lower heating efficiency.

In the particulate medium grain processor, the flow meter which monitors propane flow rate was calibrated in the equivalent kW input range. Section 3.2.2 of Chapter III describes in detail the calibration procedure used in determining the heat output of the burners. Parasitic loads of both units were not quantified or included in the calculations of power input since they can change depending on how process design is accomplished. The machines were tested at corn flow rates 65, 100 and 125 kg/h. Preliminary tests were done to determine the conditions of maximum change in grain temperature using both heating media (air/salt).

Analysis of the data generated from the tests were evaluated as follows:

- Since both methods were tested at their maximum performance, a descriptive analysis was done, covering increase in medium and corn temperature, time to attain maximum temperature, maximum stable temperature taken after one hour of heating, and the drop in the temperature of medium used.

- Average increase in grain temperature was calculated using data on grain temperature after one hour of operation when both units were assumed to be in stable operation.

- Using the average increase in grain temperature, the actual amount of heat transmitted by the media was calculated. With this information thermal efficiency of the method was calculated as the ratio of the actual heat transferred to the known input power into the system at stable machine operation.

- Temperature increase of the grain was plotted and a comparison on same power level and flow rates were made.

- The rate of heating was evaluated by calculating the amount of time each process attains a certain grain temperature.

- After the machines attained stable operating condition, two-500 gram samples were taken for moisture content analysis. Samples were also taken before treatment. The result of this analysis determine the effective moisture reduction possible with each method at a specified input power and grain flow rate.

4.3.2 Materials

A convective drying unit was constructed to compare convective and particulate medium heating of corn. The unit consisted of a drying column, an air compressor, an electric air heater unit, and a variable flow rate feed and discharge auger. Figure 4.1 shows the components of the convective drying equipment.

The air compressor delivers 420 SCFM of air at full open discharge driven by a direct coupled 7.5kW AC motor. The discharge of the compressor was connected to an air heater rated at 20kW maximum capacity. The heater consisted of a 0.25 m tube 1 m long containing four-finned tubular heaters. The heating elements were configured to deliver 10, 15, and 20kW to heat incoming air.

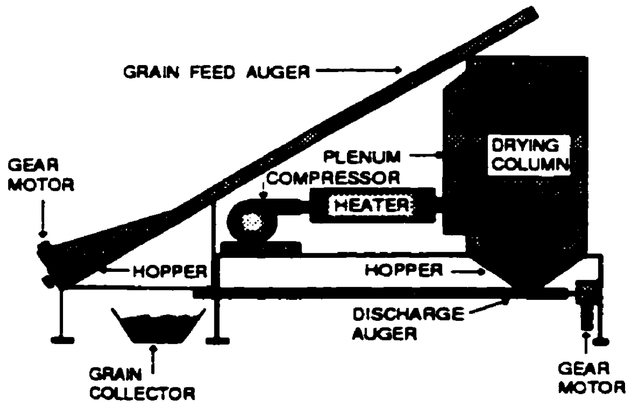

Figure 4.1 Convection dryer

The heater was directly coupled to the air inlet of the column dryer. The dryer column is composed of a wooden outer wall on the back and both sides, and a 12 mm acrylic front plate. Eleven V-shaped channels, arranged alternately, provide air inlet in one level and air outlet in the next. Alternate inlet and outlet channels provide a column of downward flowing grain with an average thickness of 10 cm. A hopper was bolted into the lower end of the column. Below the hopper, a variable flow rate auger discharges the grain out of the column. The auger measures 7.5 cm in diameter by 1.5 m in length. The flow rate of the discharge auger was synchronized with the flow at the feed auger which delivers grain to the top of the column. The feed auger was 15 cm diameter by 5 m long and driven by a 0.785 kW stepless variable speed motor. The operating range of both augers was 50 to 3000 kg/h of corn.

The grain used in both experiments was obtained from a commercial grain supplier located near Macdonald Campus. One ton of corn was allotted for each method. Grain used was destined for animal feed and contains a significant amount of impurities (chaff, broken

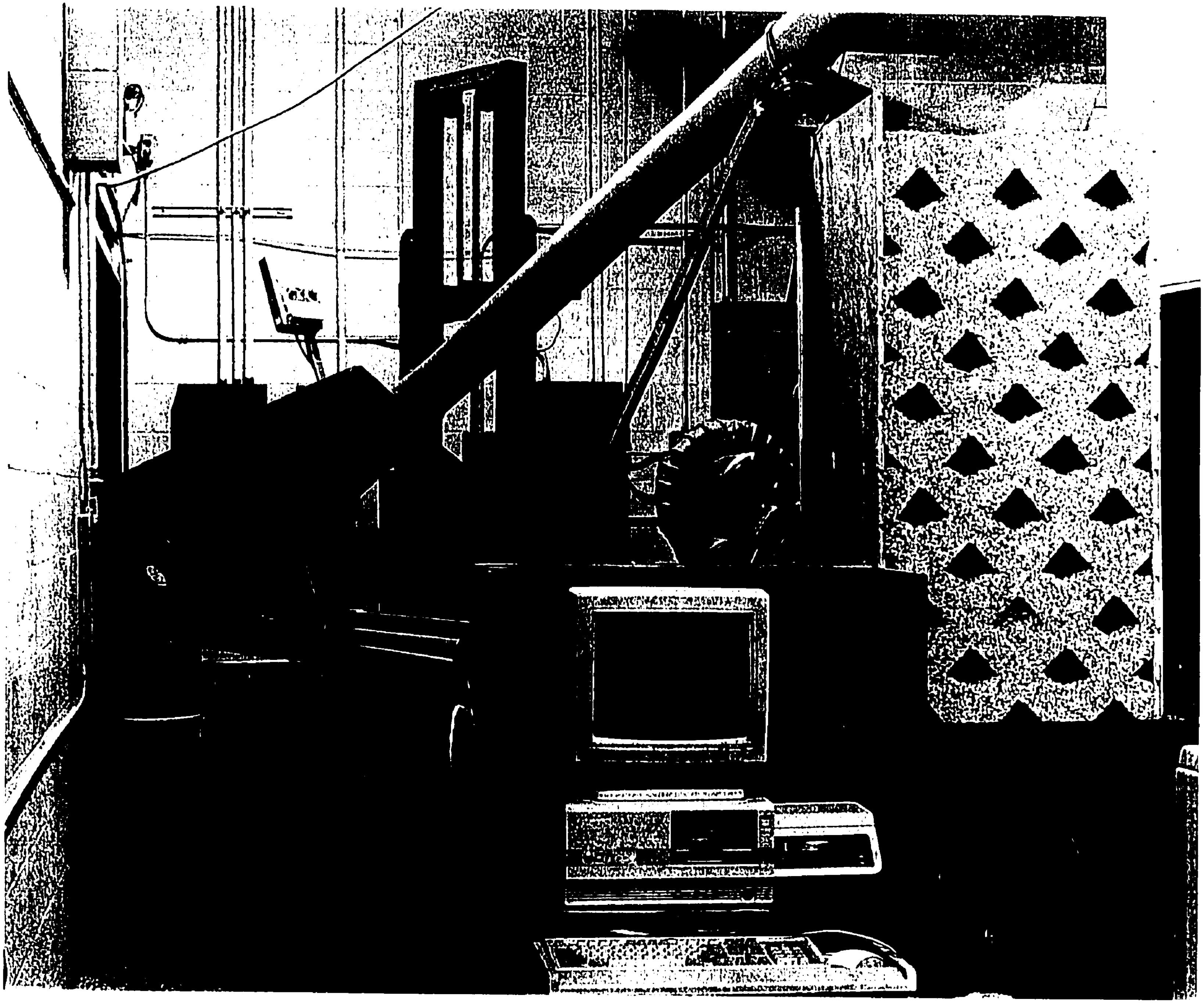

Figure 4.1a Photograph of convection dryer

grain, etc...) so it was cleaned using an aspirator. The grain was stored in a cold storage before the experiments to prevent deterioration since the moisture content was still quite high.

The medium used in the processor was table salt of the same quality used in the preliminary studies on drying. A total of 175 kg of salt was loaded into the machine to achieve a medium-to-grain mass ratio from 4:1 and 6:1.

To gather accurate data on the operating temperature and time in the two machines, a Cole Parmer thermocouple thermometer was used. For the convective dryer, four type K thermocouples were installed. They monitor the input and output grain temperatures, and the input and output air temperatures in the drying column. In the Processor, six type K thermocouples were installed to monitor the operation and gather similar information as the convective dryer. Two thermocouples monitor input and output temperatures of sand in the heater, one thermocouple measures temperature of the grain/medium mixture, two thermocouples monitor input and output grain temperatures in the mixer, and the last thermocouple measures final grain temperature after aeration. Data generated from the thermometer was transferred to a Packard Bell personal computer. All information generated in the computer was saved as delimited ASCII files for ease of data manipulation.

Propane used in the particulate medium study was taken from a 50 kg capacity tank purchased from a McGill University accredited supplier. The heating value of propane used in the study was taken as 46,390 kJ/kg.

4.3.3 Methods

Prior to the tests, the corn was equilibrated for 8 h to raise its temperature from about 10°C to room temperature which was around 20°C. While the corn was equilibrating, the feed auger was calibrated to the actual flow rate required in the test. Three samples were taken and the average used as the actual flow rate for each setting.

a. Convection method

Lower grain flow rates were used because the heating tests were stopped only when outlet grain temperature stabilizes to a certain value. This usually required running the unit for more than one hour. Three flow rates were chosen. They were 65, 100, and 125 kg/h. To test the effect of increasing the power input on the final grain temperature, three power levels

(10, 15, and 20 kW) were also used.

The tests were started by filling the column with corn at ambient temperature. The data acquisition system was activated and temperature readings from four points in the system (air in/out and grain in/out) were monitored until they gave similar temperature readings. Once the data acquisition was ready, the air compressor was started. The heaters were then energized and grain flow through the column was initiated. Additional grain was fed into the auger's hopper as soon as the level of the grain dropped below a specified level. The feeding was continued until a maximum stable discharge temperature for grain was attained. About 30 min after the grain temperature had stabilized, the heater was stopped. The compressor was switched off 3 min after the heaters were stopped. The column was unloaded and allowed to cool down to ambient temperature before the next test was conducted. Succeeding experiments were conducted using the same procedure. The temperature profiles generated at every minute were plotted.

b. Particulate medium method

Experiments using the particulate medium dryer were started after the heater and mixer were calibrated to attain the maximum grain temperature at the power input and grain flow rate being tested. To calibrate the heater and mixer, the desired grain flow rate was selected and the grain was allowed to flow into the mixing chamber. The flow of propane into the burners was set to the input power being tested and the burners were started. The heater and mixer were set to the highest rotational speed. As soon as the outlet grain temperature from the mixer attained a stable value, the rotation of the heater and mixer was reduced until the outlet temperature of the grain reached its highest level. The heater and mixer settings were recorded and used for subsequent tests using the same power input at different flow rates of grain through the machine. The same procedure was repeated in calibrating the machine for the two other power levels.

The test was started by filling the hopper of the feed auger with corn equilibrated to room temperature. The machine was adjusted to the optimum setting determined in the previous calibration. The data acquisition system was activated and the thermocouples monitored for unusual readings. This step was found to be very important because any malfunction of the system during the test would waste an enormous amount of grain as well as the initial effort in setting the machine in operation.

As soon as the data acquisition system indicated uniform initial temperature readings in all six thermocouple probes, the flow of grain was started and the burners were fired up to the power input being tested. While the machine was in operation, the settings were checked periodically for changes. Temperature readings in the computer were constantly scanned to verify that all readings were within range. The salt flowing into the heater was also periodically sampled for foreign material that may have fouled up the medium. Air flow into the burners was constantly checked to ensure adequate supply of air for proper flame color.

When the grain temperature reached the maximum level, all the machine settings were once again checked and recorded. The machine was allowed to operate until it was absolutely certain the readings were stable. This normally required operating the machine for approximately 90 min.

After the machine had reached this state, the feed auger was stopped, the burners were switched off, and the machine was allowed to discharge whatever grain was still being held in the mixing chamber. Data on the computer was saved to disc and transferred into another personal computer for analysis. Once all of the grain was unloaded from the mixer, the machine was cooled off for several hours. The next experiment was conducted as soon as the machine had reached ambient temperature. The process was repeated for all other particulate medium experiments.

4.4 Results and discussions

Data were monitored every minute of machine operation. Figures 4.2, 4.3 and 4.4 show the temperature profiles from convective heating tests. Figures 4.5, 4.6, and 4.7 shows similar data for the particulate medium heating tests. Visual comparison of the charts showed particulate medium heating led to higher grain temperatures at the same power input and grain flow rate.

4.4.1 Medium temperatures

As expected, air temperature in the convection experiments increased with an increase in power input. At 10 kW input air temperature quickly stabilized to 60°C 5 min after the

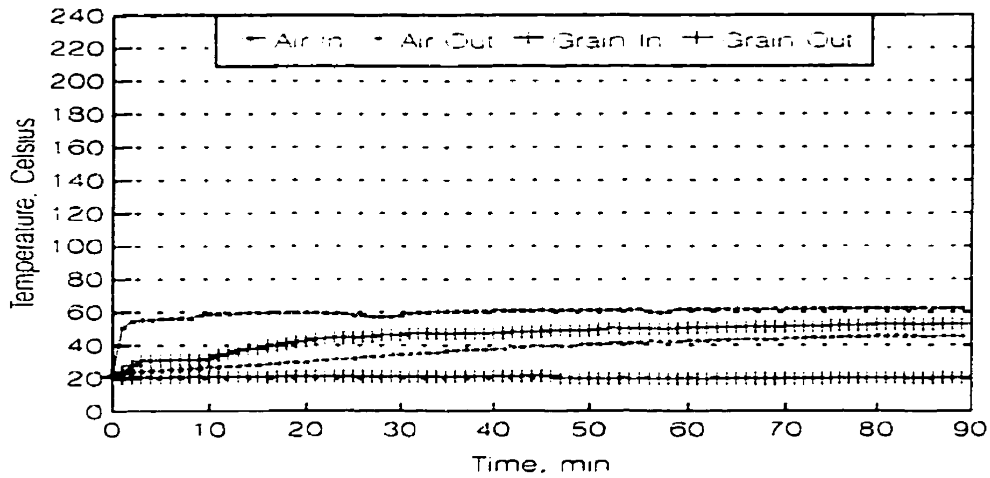

Figure 4.2a Convection heating 10K@125kg/h

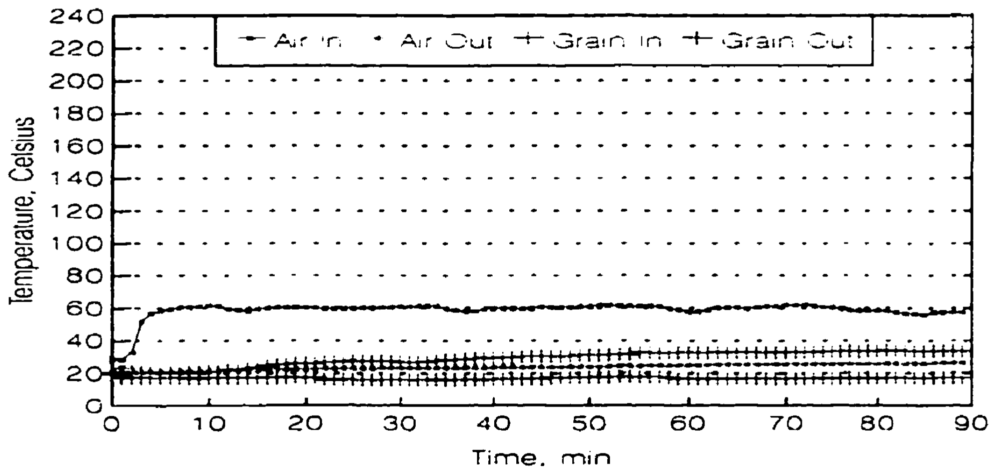

Figure 4.2b Convection heating 10K@100kg/h

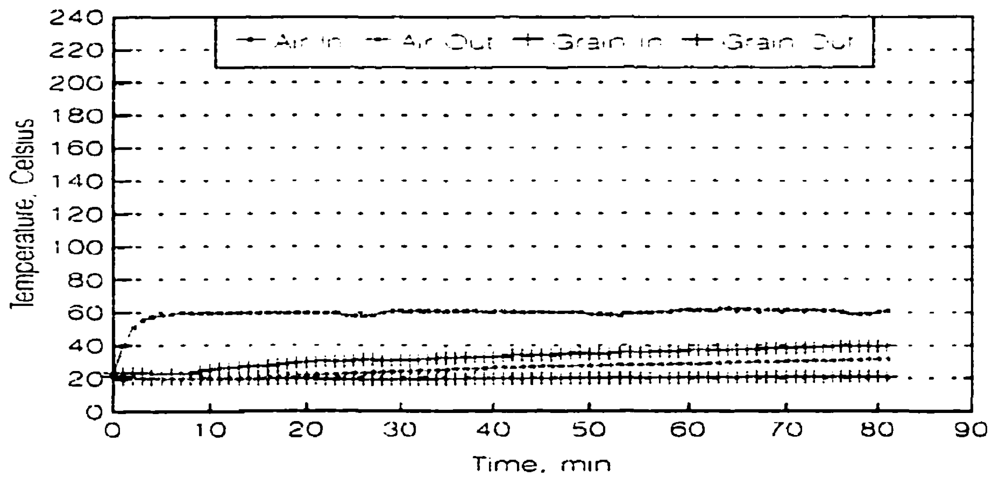

Figure 4.2c Convection heating 10K@65kg/h

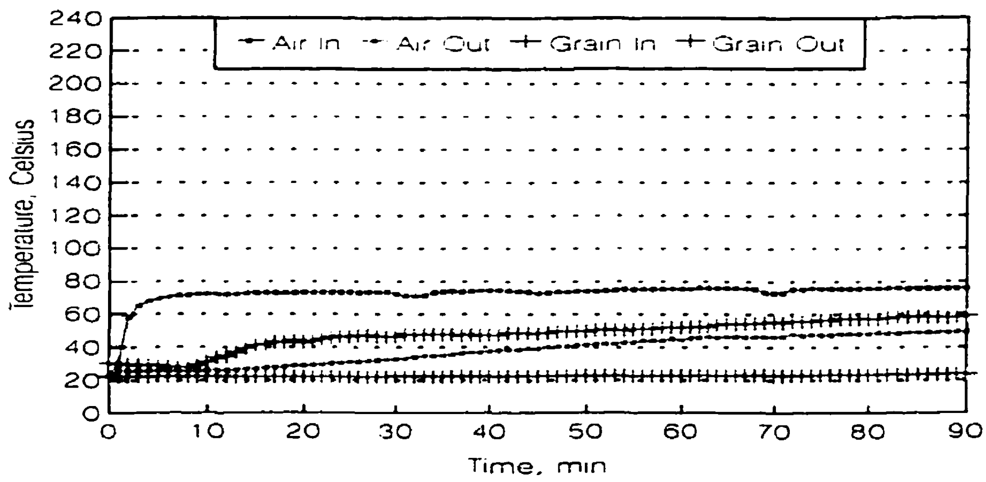

Figure 4.3a Convection heating 15K@125kg/h

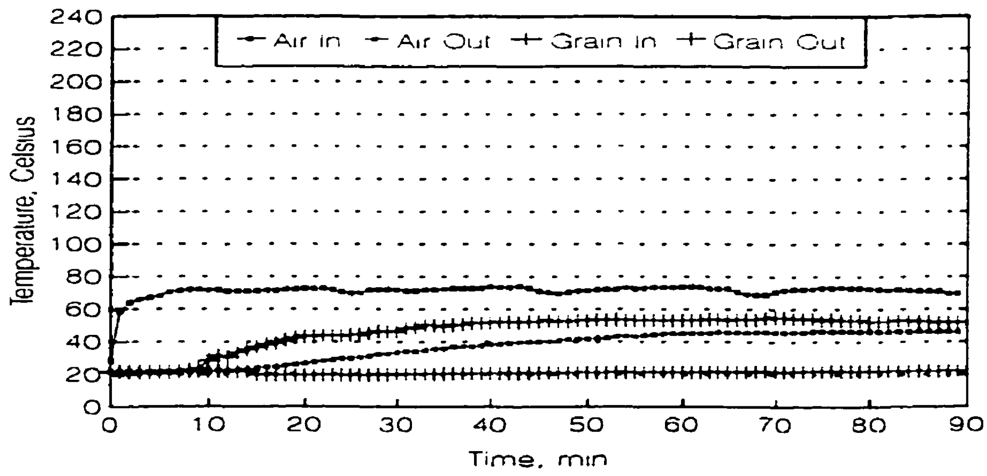

Figure 4.3b Convection heating 15K@100kg/h

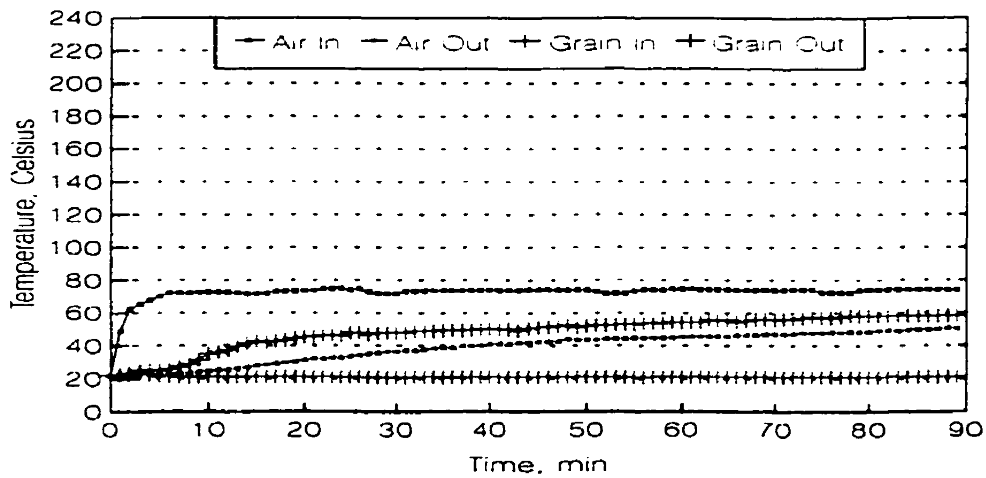

Figure 4.3c Convection heating 15K@65kg/h

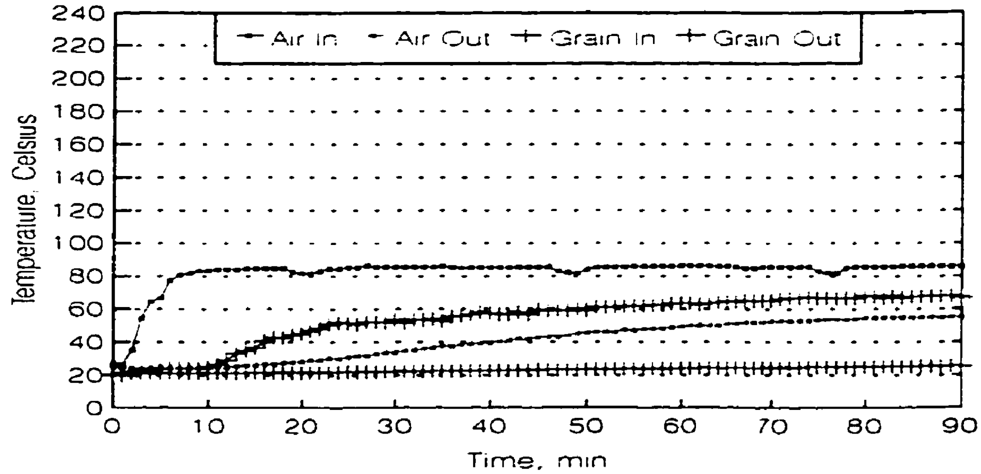

Figure 4.4a Convection heating 20K@125kg/h

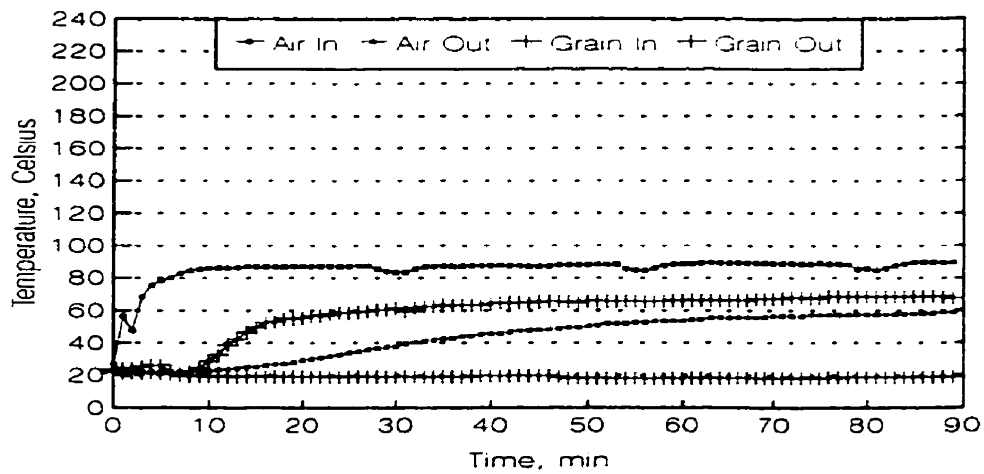

Figure 4.4b Convection heating 20K@100kg/h

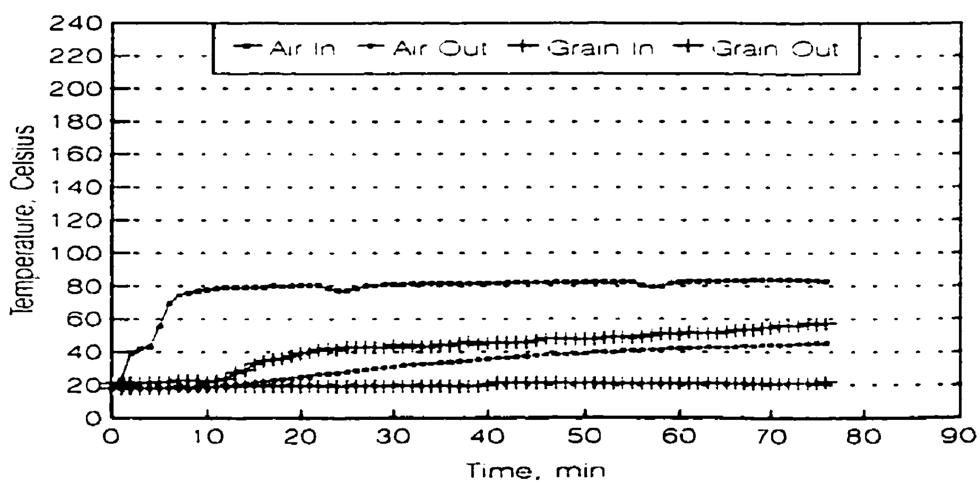

Figure 4.4c Convection heating 20K@65kg/h

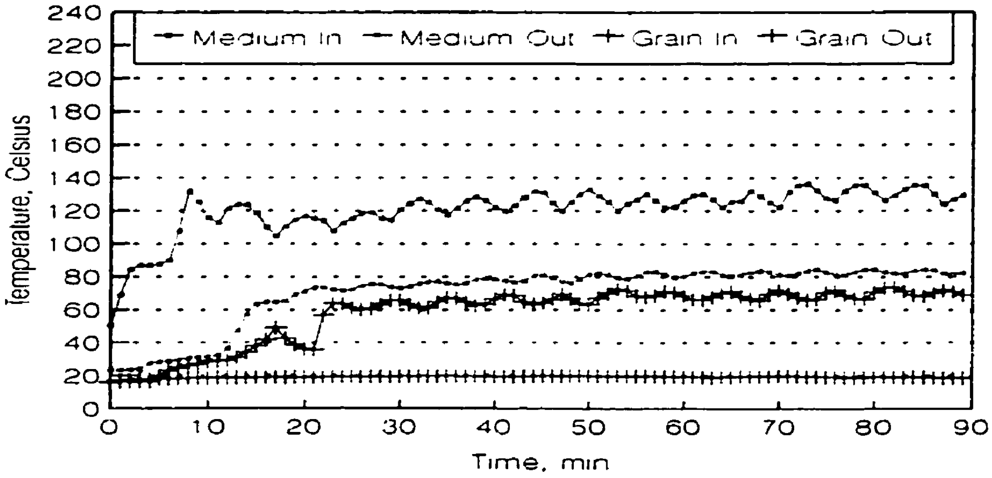

Figure 4.5a Conduction heating 10K@125kg/h

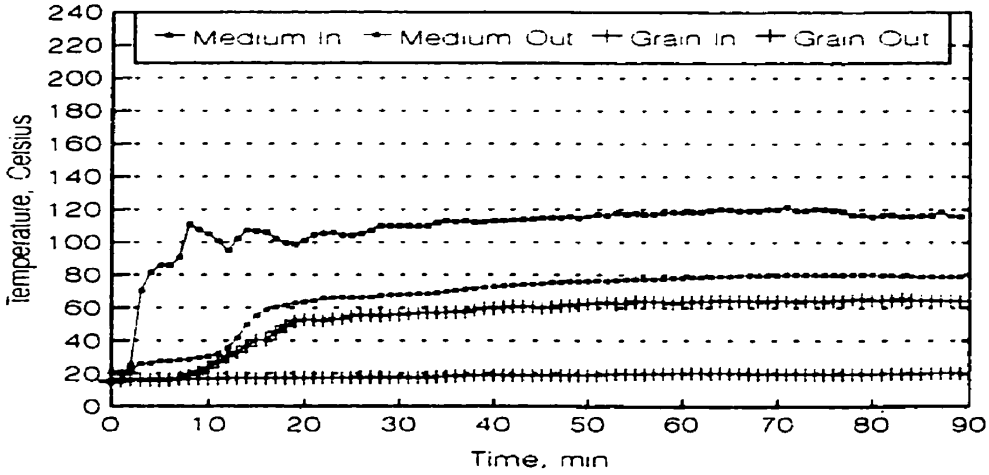

Figure 4.5b Conduction heating 10K@100kg/h

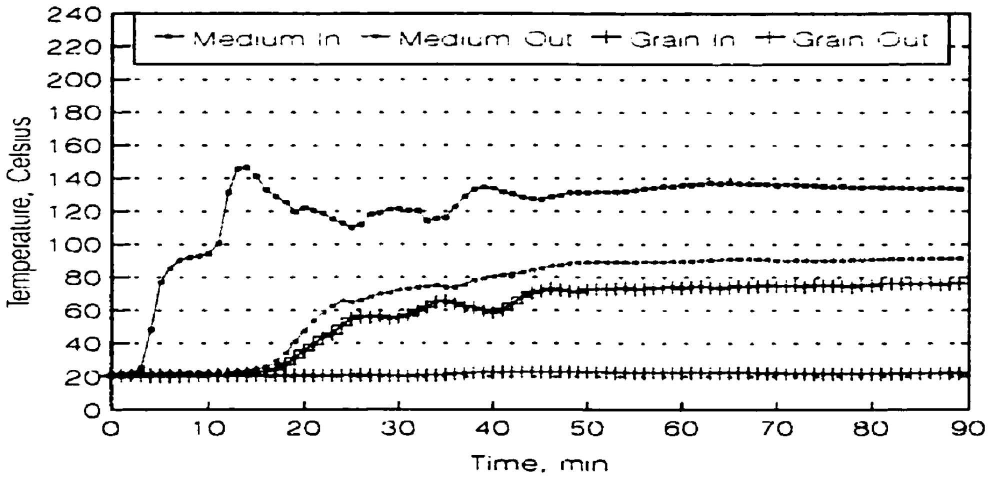

Figure 4.5c Conduction heating 10K@65kg/h

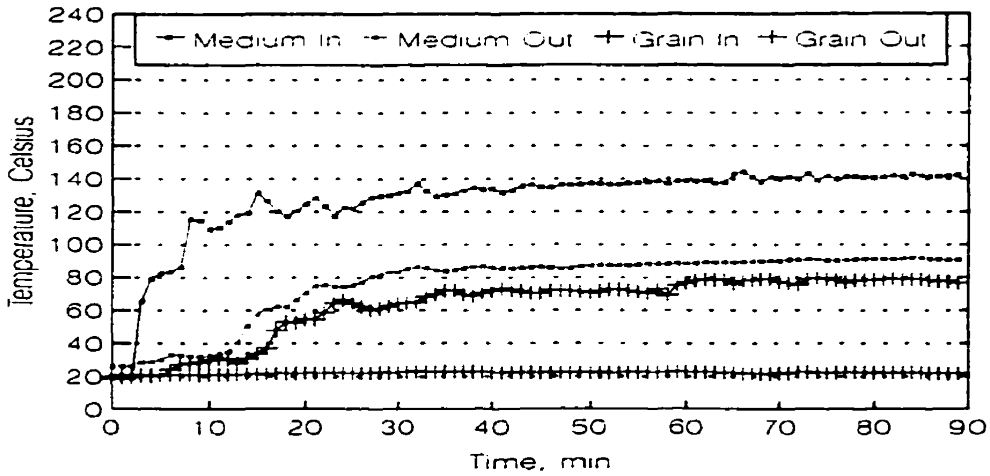

Figure 4.6a Conduction heating 15K@125kg/h

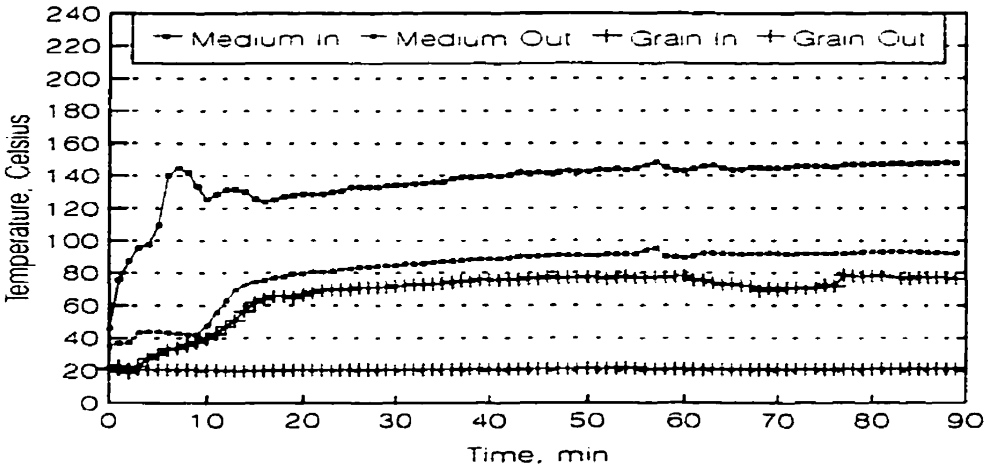

Figure 4.6b Conduction heating 15K@100kg/h

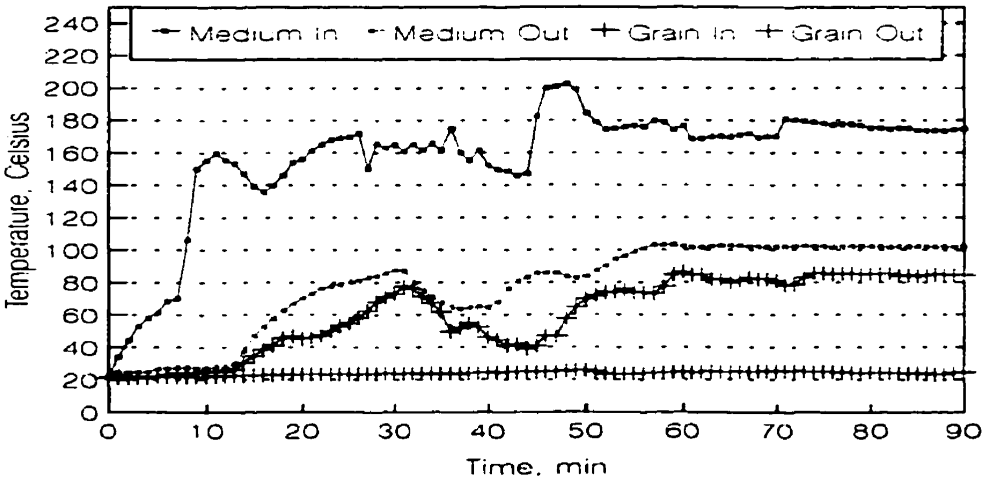

Figure 4.6c Conduction heating 15K@65kg/h

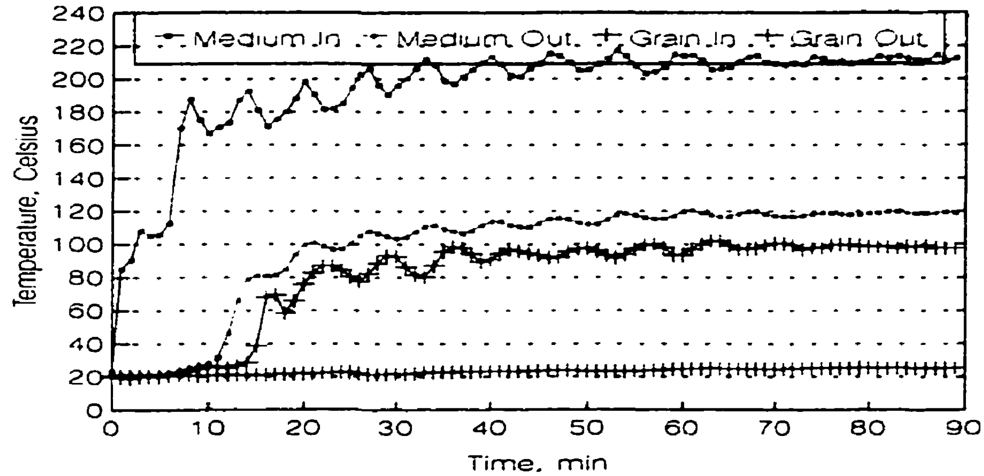

Figure 4.7a Conduction heating 20K@125kg/h

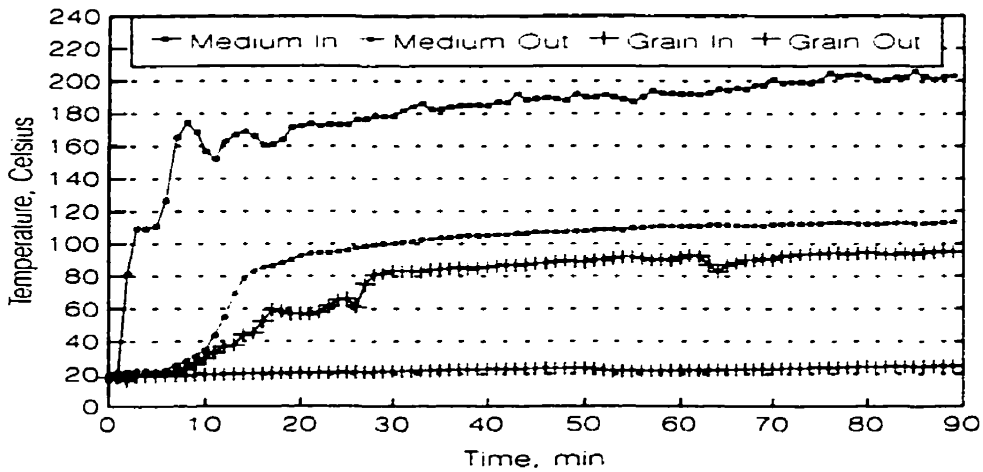

Figure 4.7b Conduction heating 20K@100kg/h

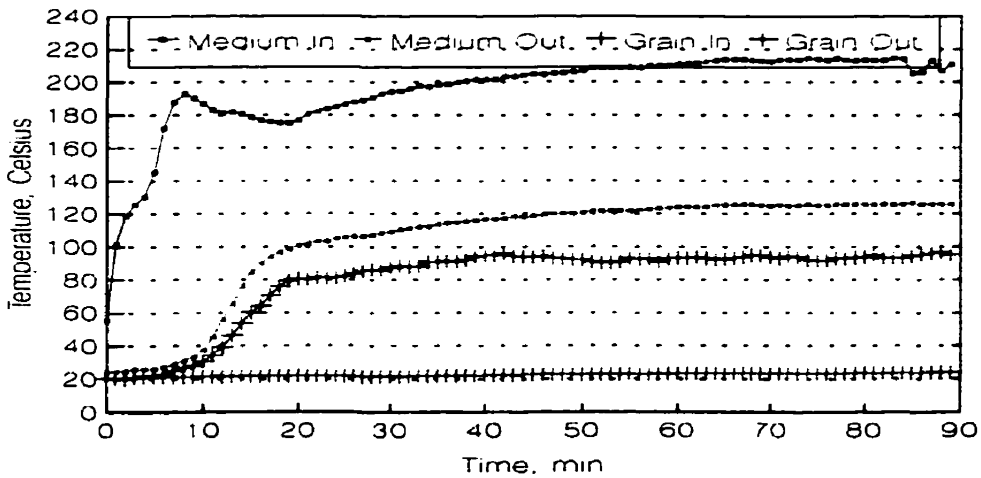

Figure 4.7c Conduction heating 20K@65kg/h

heaters were energized. At this power level maximum temperature of the air was the same for all grain flow rates.

At 15 kW the temperature stabilized at around 75°C and also remained the same over all grain flow rates. The temperature was achieved after 7 min of operation.

At 20 kW air temperature stabilized at around 85°C. Unlike the 10 and 15 kW tests, there were some variations in air temperature in the three levels of grain flow rate. At 65 kg/h temperature was about 82°C, while at 100 and 125 kg/h the temperatures were about 88°C and 85°C, respectively.

The exit temperature of air from the drying column stayed lower than the temperature of grain at the outlet. This shows that the heat capacity of air was low such that in transmitting heat to the grain, the heat transfer process effectively lowered the temperature of the air. As such, a large volume of heated air was required to raise the temperature of the grain to a certain level.

On all of the nine convection heating experiments, a periodic depression in medium temperature readings was evident. At first glance, the problem could be attributed to sensing noise with the data acquisition system. However, further observations showed the fluctuations to be caused by the cycling of the room's ventilation system which had a discharge spout right above the drying column.

In the particulate medium heating experiments, the charts show a period of temperature instability in the first 10 to 20 min of operation. This was due to variations in salt flow to the heating section as a result of settling in the mixing section and the cycling of the medium through the machine. The first 5 min of operation showed a very steep temperature increase which levelled off at temperatures between 70°C and 110°C. This period indicated that the medium had made a full cycle of the unit. One full cycle of the medium means that there would be an increase in salt temperature going into the heater. This in turn was responsible for the second jump in the outlet salt temperature which continued for 3 to 4 min, after which a slight temperature drop occurred. This temperature drop was the result of heat absorption by the grain. As can be seen in the charts, the period where outlet temperature dropped coincided with the start of the increase in outlet grain temperature. After these two distinct periods of adjustment, the medium temperature gradually stabilized to a certain level.

Compared to the air temperature in the convection experiments there appeared to be a wider variation in the salt temperatures. These variations were more pronounced in the tests 10kW@125kg/h, 15kW@65kg/h, and 20kW@125kg/h. At the 15kW@65kg/h test, there was a flame-off at the 25th min momentarily dropping the outlet salt temperature. In the 10kW@125kg/h and 20kW@125kg/h tests there were periodic fluctuation in the flow of salt due to a loose V-belt driving the mixing auger.

Overall, the salt temperatures achieved in the particulate medium experiments were more than twice those achieved for air in the convection tests. Consequently, the discharge temperature of salt from the mixer was also almost twice that of the air exiting from the drying column of the convective heating unit. Even with a very high salt temperature exiting the mixer the conduction method retained most of this heat since the salt was recycled. In the convection method, hot air was discharged to the environment and none of the heat was recovered.

A study conducted on a crossflow dryer by Otten (1985) found that recovering heat from the dryer exhaust will result in a 23% reduction in power consumption. However, the addition of a heat exchanger to recover heat has an estimated payback period of 11 years. This means that the system has to be operated longer hours each year to justify the cost of installing a recovery system.

4.4.2 Grain Temperatures

In terms of grain temperature, the trend was similar. Particulate medium heating led to higher grain temperatures than convection heating at all power input and grain flow rate combinations. The highest grain temperature recorded for particulate medium heating was 102.4°C achieved with an power input of 20 kW at a flow rate of 125 kg/h. For the convective heating experiments, the maximum grain temperature attained was 68.6°C at an power input of 20 kW and a flow rate of 100 kg/h. Both temperatures correspond to the maximum increase in grain temperature which was 73 and 48°C for particulate medium and convection heating, respectively.

4.4.3 Heating Rate

Table 4.1 shows the maximum temperature and heating times for both particulate medium and convection tests in all treatment combinations. The column "Time, CvH" shows the time it took for the convective dryer to attain the maximum grain temperature shown in the preceding column. The time it took for the particulate medium Processor to reach the same grain temperature is shown in the column "Time, PMH Equivalent. The column "Time, PMH" shows the time it took for the particulate medium Processor to attain maximum grain temperature. The ratio of the time it took the convection dryer to achieve maximum grain temperature (Time, CvH) with that of the particulate medium Processor (Time, PMH Equivalent) to attain the same grain temperature shows how much faster particulate medium heating is, compared to convection heating.

An average of 77 min was required to achieve maximum grain temperature in both particulate medium and convection experiments. However, with particulate medium heating, it took only an average of 16 min to reach the maximum grain temperatures achieved in the convection experiments. This amount of time was averaged over all treatment combinations. A more detailed analysis of heating time showed particulate medium heating to be 5 times faster than convection heating.

4.4.4 Heating Efficiency

In order to determine the heating efficiency of both methods, the actual change in temperature of the grain was used to calculate the total amount of heat transmitted by the medium to the grain to increase its temperature. It was calculated using the equation:

$$\eta = \frac{m \times C_p \times \Delta T}{E} \tag{4.1}$$

where: η = heating efficiency, %

m = mass flow rate of corn, kg/h

Cp= specific heat of corn, kJ/kg-°C

ΔT= increase in corn temperature, °C

E = power input set in flow meter, kW

The constant pressure specific heat of corn was calculated using the following equation (ASAE, 1982):

$$Cp = 1.4654 + 3.5631 \times 10^{-2} * MC \qquad (4.2)$$

where:

Cp = specific heat of corn, kJ/kg-°C

MC = moisture content, % (w.b.)

Since all of the experiments were conducted using corn from the same batch, the specific heat was the same, i.e. 2.1424 kJ/kg-°C. Table 4.2 shows heating efficiencies for particulate medium and convective heating of corn. The convective experiments gave heating efficiencies of 6% to 23%, while particulate medium heating efficiencies ranged from 14% to 37%. Average values over all treatment combinations were 12.57% and 23.47% for convective and particulate medium heating, respectively. Based on these figures, particulate medium heating efficiency was 87% higher than convection heating efficiency.

Particulate medium heating efficiencies achieved in these experiments were surprisingly low when compared to the results presented by Pannu (1984) which showed heating efficiencies of between 69% and 90%. However, when compared with the results presented by Tromp (1992) the present values were much higher. He obtained efficiencies of only 15% to 18% using the same equipment that Pannu (1984) built and tested.

Careful analysis of the methods used by both researchers showed two different approaches used in evaluating the thermal performance of the same machine. Pannu (1984) evaluated heating efficiency by equating the amount of heat used to raise the temperature of the grain plus the amount of heat used to evaporate moisture, to the amount of heat supplied by the hot sand to raw corn. He used the equation:

$$\eta_h = \frac{m_w \times h_{fg} + (m_g \times C_{pg} \times \Delta T_g)}{m_s \times C_{ps} \times \Delta T_s} \qquad (4.3)$$

Table 4.1 Maximum increase in grain temperature

Treatment Convection	Maximum Grain T,°C	Time, CvH Min	Time,PMH Equiv.,Min	Time Ratio
10 / 65	39.60	74	13	5.69
10 / 100	34.20	72	14	5.14
10 / 125	53.00	89	22	4.04
15 / 65	58.30	78	18	4.33
15 / 100	55.10	65	12	5.42
15 / 125	59.20	82	22	3.73
20 / 65	57.30	75	13	5.77
20 / 100	68.60	70	18	3.89
20 / 125	67.90	88	14	6.29
			Average =	**4.92**

Particulate Medium	Max T, °C	Time,PMH
10 / 65	76.40	89
10 / 100	65.40	79
10 / 125	73.60	82
15 / 65	86.30	60
15 / 100	78.80	77
15 / 125	79.50	74
20 / 65	96.70	88
20 / 100	95.50	88
20 / 125	102.40	63

where:

η_h = heating efficiency, %

m_w = mass of water removed, kg/h

h_{fg} = latent heat of vaporization, kJ/kg

m_g = mass of grain, kg/h

C_{pg} = specific heat of grain, kJ/kg-°C

ΔT_g = increase in grain temperature, °C

m_s = mass of sand, kg/h

C_{ps} = specific heat of sand, kJ/kg-°C

ΔT_s = drop in sand temperature, °C

Tromp (1992), on the other hand, divided the overall efficiency of the machine into heating and drying efficiency. To evaluate the actual heating efficiency of the machine, he used the equation:

$$\eta = \frac{m_c \times C_{pc} \times \Delta T_c}{m_p \times h_p} \tag{4.4}$$

where:

η = heating efficiency, %

m_c = mass flow rate of corn, kg/h

C_{pc} = specific heat of corn, kJ/kg-°C

Δt_c = increase in corn temperature, °C

m_p = mass flow rate of propane, kg/h

h_p = heat of combustion of propane, kJ/kg

In the former method of analysis, the heating efficiency was lumped together with drying efficiency thereby getting an unusually high value. If heating efficiency was considered as the amount of heat responsible for raising the temperature of the grain, this method is unacceptable. A much bigger error in this method of evaluation was the use of heat supplied

Table 4.2 Average increase in temperature and heating efficiency

Treatment	Minimum	Maximum	Average	Heating
Convection	**Inlet T,°C**	**Outlet T,°C**	**Increase,°C**	**Eff,%**
10 / 65	22.70	39.60	16.96	6.58
10 / 100	20.40	34.20	16.41	9.76
10 / 125	21.40	53.00	31.77	23.63
			Average =	**13.32**
15 / 65	22.20	58.30	35.81	9.23
15 / 100	20.80	55.10	31.50	12.49
15 / 125	27.90	59.20	31.92	15.83
			Average =	**12.52**
20 / 65	21.10	57.30	30.67	5.93
20 / 100	21.40	68.60	48.96	14.57
20 / 125	20.60	67.90	40.63	15.11
			Average =	**11.87**
Particulate Medium				
10 / 65	20.10	76.40	52.99	20.50
10 / 100	15.10	65.40	44.37	26.40
10 / 125	16.10	73.60	49.87	37.09
			Average =	**28.00**
15 / 65	21.10	86.30	65.20	16.81
15 / 100	18.70	78.80	53.84	21.35
15 / 125	19.20	79.50	55.89	27.71
			Average =	**21.96**
20 / 65	19.50	96.70	70.18	13.57
20 / 100	16.10	95.50	68.61	20.41
20 / 125	19.10	102.40	73.50	27.34
			Average =	**20.44**

by the heated sand to raw corn as the denominator. This negated the inefficiency of the heating stage of the process.

Tromp's evaluation was more accurate as it uses propane flow as the basis for heat supplied to the process. In evaluating machine performance, all components of the process should be included in the analysis. Since his study concerned the performance of the machine as a roasting equipment, dividing the efficiency into drying and heating was logical. The overall efficiency (drying + heating) achieved in his experiments were lower than Pannu's results because of the inefficiency in heating the medium, which the former study did not consider.

In the present study, the heating efficiency of both methods was evaluated using the method of evaluation used by Tromp (1992). The overall efficiency of the two methods will be discussed right after the evaluation of moisture reduction. More emphasis was placed on the analysis of heating efficiency since most of the potential applications of the particulate medium Processor would require raising the temperature of the grain, rather than removing moisture from the grain.

4.4.5 Drying Efficiency

In order to quantify the actual amount of heat used in evaporating moisture from the grain, it was necessary to calculate the amount of water removed in each test. The ratio of the mass of water removed to the original mass of the grain was obtained using the equation:

$$\Delta_m = [M_i - M_f (\frac{1 - M_i}{1 - M_f})] \qquad (4.5)$$

where: M_i = initial moisture content (w.b.)

M_f = final moisture content (w.b.)

Since the treatment combinations resulted in different grain temperatures, the heat of vaporization of water was calculated for each test using the equation (ASAE, 1983):

$$h_{fg} = 2{,}502{,}535.144 - 2{,}385.76424\ (T - 273.16) \qquad (4.6)$$

$$273.16 \le T \le 338.72$$

$$h_{fg} = (7{,}329{,}155{,}978{,}000 - 15{,}995{,}964.08\ T^2)^{1/2} \tag{4.7}$$

$$338.72 \leq T \leq 533.16$$

The drying efficiency was determined as the ratio of the actual amount of heat used in evaporating moisture to the total amount of heat available from the burners. Drying efficiency was calculated using the equation:

$$\eta_d = \frac{m_g \times \Delta_m \times h_{fg}}{m_p \times h_p} \tag{4.8}$$

where:

η = drying efficiency, %

m_g = mass flow rate of grain, kg/h

Δ_m = ratio of water evaporated to grain flow rate

h_{fg} = heat of vaporization, kJ/kg

m_p = mass flow rate of propane, kg/h

h_p = heating value of propane, kJ/kg

Drying efficiency values for both convection and particulate medium experiments are given in Table 4.3. It can be observed that the convection tests have a much higher drying efficiency than the particulate medium tests on all treatment combinations. This result was expected since there was minimal moisture removal during the mixing of the medium with the grain. While the drying efficiency values for convective drying were not consistently high in all treatment combinations, overall drying efficiency was 95% higher than particulate medium drying. In comparison, the heating efficiency values for particulate medium heating were consistently higher than those achieved with convective heating in all treatment combinations. The overall heating efficiency for particulate medium heating was 87% higher than convective heating.

4.4.6 Thermal Efficiency

The thermal efficiencies of both methods were calculated as the sum of the heating and drying efficiencies and are presented in Table 4.3. It can be observed that the average thermal efficiencies for particulate medium heating was higher than those using convective heat transfer over the three power input levels. Aside from the combination 10kW@65kg/h and 20kW@100kg/h, all treatment combinations showed a higher thermal efficiency for particulate medium than convection.

The table further showed the overall efficiency of both methods was higher at lower power input levels. This can be explained by the fact that the machines were not totally insulated, resulting in higher heat losses at elevated temperatures. Overall, the thermal efficiency using particulate medium heat transfer was 28% higher than convection heat transfer.

4.5 Conclusions

It has been shown that particulate medium heat transfer was superior to convection heat transfer in terms of the rate of heating, heating efficiency and in overall thermal efficiency. However, convection method was better than particulate medium method in drying efficiency. These results confirm the findings of other researchers working on alternative drying methods. As pointed out earlier, the processor tested was not primarily designed for grain drying. These findings show that the processor was suited for thermal processing applications which do not require moisture removal from the grain. In applications like roasting, disinfestation and de-germination, such moisture removal during thermal treatment will reduce the marketable weight of the product. Furthermore, should the processor be used in drying applications a suitable hygroscopic medium should be found to enhance mass transfer during mixing to improve drying efficiency. The use of zeolite have been shown to enhance moisture removal in small-scale laboratory experiments. Alikhani (1990) found that with increased residence times, the mean moisture removal percentage using zeolite was about twice those achieved by sand.

Table 4.3 Overall efficiency of the system

Treatment	Heating	Drying	Overall
Convection	Efficiency, %	Efficiency, %	Efficiency, %
10 / 65	6.58	23.05	29.63
10 / 100	9.76	8.99	18.75
10 / 125	23.63	7.46	31.09
Average	**13.32**	**13.17**	**26.49**
15 / 65	9.23	1.77	11.00
15 / 100	12.49	12.62	25.11
15 / 125	15.83	9.52	25.35
Average	**12.52**	**7.97**	**20.49**
20 / 65	5.93	5.86	11.79
20 / 100	14.57	16.31	30.88
20 / 125	15.11	1.53	16.64
Average	**11.87**	**7.90**	**19.77**
Conduction			
10 / 65	20.50	1.10	21.60
10 / 100	26.40	4.34	30.74
10 / 125	37.09	3.43	40.52
Average	**28.00**	**2.96**	**30.95**
15 / 65	16.81	2.67	19.48
15 / 100	21.35	9.69	31.04
15 / 125	27.71	3.74	31.45
Average	**21.96**	**5.37**	**27.32**
20 / 65	13.57	6.54	20.11
20 / 100	20.41	4.64	25.05
20 / 125	27.34	8.41	35.75
Average	**20.44**	**6.53**	**26.97**

CHAPTER V
PARTICULATE MEDIUM CORN DRYING

5.1 Introduction

A preliminary study was conducted to evaluate the potential of particulate medium method in the drying of corn. Results of this study was made as the basis for designing a particulate medium thermal Processor which will be tested in the drying, roasting, degermination and thermal disinfestation of grains. Before any of this processes are conducted, a test was performed to verify the advantage of particulate medium method of thermal processing over the conventional convective method of heating. Results of this experiment showed the particulate medium method to be superior in terms of heating rate, heating efficiency and overall thermal efficiency over the convection method. However, in terms of drying efficiency, the method failed to achieve the expected level. This low moisture removal can be attributed to rapid saturation of the limited air supply in the mixer. The moisture removal takes place to its limited extent, mainly in the mixer. As the grain exits the cylinder, the air that escapes carries this moisture away. During screening and aeration, some more moisture is driven out by the residual heat, but at a rapidly decreasing rate. The question therefore arises as to whether higher initial medium temperatures could improve the extent of moisture removal.

5.2 Objectives

To study the problem of low moisture removal in detail, experiments were conducted to evaluate the operating parameters related to drying of grains in the Processor. Based on the findings in the preliminary study conducted on corn, increased moisture removal can be attained by increasing the initial medium temperature. The preliminary study was performed with temperatures 100, 150, and 200°C and contact times 120, 60, and 30 s, respectively. In this study the temperature of the medium was increased to a higher value of 250°C to confirm this initial findings.

The specific objectives were:

1. To dry feed quality corn on the Processor and evaluate its performance over

different temperatures and initial moisture contents.

2. To evaluate the amount of moisture removal in the mixing and aeration sections of the Processor.

3. To determine the maximum moisture removal capacity of the Processor.

5.3 Materials

The corn used in the experiments were obtained from a commercial grain supplier located near Macdonald Campus. The grain was destined for animal feed and contains some impurities like chaff, broken grains, and other seeds so it was passed through an aspirator for cleaning. The corn was stored in a cold storage prior to the experiments.

The medium used in this experiment was the same salt used in the performance testing of the Processor. Additional salt was added to make-up for the amount lost due to attrition during the previous experiment. The actual amount of salt loaded in the Processor was 175 kg.

The propane used in this study was taken from two-50 kg propane tanks. The heating value of propane used was taken as 46,390 kJ/kg.

The same data acquisition equipment used in the previous study was used in this experiment. Two thermocouples measure the temperature of the medium as it goes in and out of the mixing section, and three thermocouples monitor the grain temperature at the inlet and outlet of the mixer and the outlet of the aeration cylinder. Data generated by the thermocouple thermometer was transferred to a personal computer and saved as delimited ASCII files to facilitate data manipulation during analysis.

5.4 Methods

The corn has a moisture content of around 18% when received from the supplier so in order to run the experiment at a higher initial moisture content, water was added. This was done by spraying a calculated amount of water into the grain while it was being mixed inside a concrete mixer. The rewetted corn was then stored in a cold storage prior to testing. Before each experiment, the corn was again mixed using the concrete mixer and kept at ambient temperature for 2 h to equilibrate its moisture content and temperature.

While the corn samples were equilibrating, adjustments to the Processor were made. To ensure that the desired initial medium temperature will be achieved the process controller was connected to the thermocouple which monitors the heater outlet temperature.

The heater, mixer and aeration cylinder were calibrated to a setting that gave a contact time of 60 s and a medium to grain ratio of 4:1 at a corn feed rate of 500 kg/h. The feed auger was calibrated to deliver the feed rate required in the experiments. The aeration cylinder was adjusted to provide a 3 min aeration to heated corn coming from the mixer.

To start the experiment, the data acquisition system was switched on and observed for any unusual readings. As soon as the temperature readings were stabilized, the process controller was set to the desired grain temperature and the pilot flame of the burner was lighted. Feeding of corn into the mixer was started and the main burner of the heater was activated. As temperature of both the medium and grain increased, it was monitored every minute for 5 min to make sure no sensing problems occur.

Once the medium attained the set temperature and the process controller starts cycling, samples were taken every 2 min from the inlet and outlet of the mixer and also from the outlet of the aeration cylinder. Once the last sample was taken, the controller was adjusted to the next higher temperature to be tested. While the temperature of the process increased to the next setting, the corn samples were loaded into the oven for moisture determination. As soon as the next setting was attained and the process controller started cycling, samples were once again taken every 2 min. The same process was repeated until the last setting of 250°C was tested and samples were taken and loaded into the oven. All the corn samples taken during the experiment were kept in the oven set at 103°C for 72 h as per ASAE Standard S352.2 (ASAE, 1982). Temperature data taken during the experiment were converted into delimited ASCII files and transferred to a Personal Computer for analysis.

5.5 Results and discussions

Calibration of the grain feed auger was performed and the results are shown in Figure 5.1. It shows the amount of corn flowing through the feed auger to vary depending on the moisture content. This chart was made as the basis for setting the feed rate of corn into the mixer. The speed settings used in the experiments were adjusted to feed 500 kg/h.

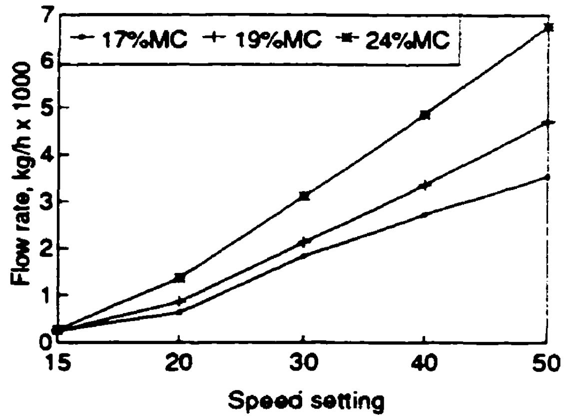

Figure 5.1 Feed auger calibration

5.5.1 Operating temperature

In order to reduce the amount of grain needed for each experiment, the medium was first heated to its initial temperature before the corn was fed into the mixer. The tests were first done at the lowest moisture content since the corn required does not need to be rewetted to a higher moisture content. The temperature first tested was 150°C. As soon as the corn samples for moisture determination were taken, the temperature was adjusted to the next higher setting to be tested. Figures 5.2, 5.3, & 5.4 shows the temperature profile generated on tests conducted at an initial moisture content of 17%, 19%, and 24% (w.b.), respectively.

The chart contains 5 lines which correspond to each temperature sensor located in different parts of the Processor. The top line, designated **Tmi,** shows the variation in initial medium temperature, **Tmf** is the final medium temperature after mixing, **Tgh** is the grain temperature after heating, **Tga** is the grain temperature after aeration, and **Tgi** is the initial temperature of the grain before mixing with the heated medium. Although the experiment was designed for 120 min, the tests were usually terminated right after grain samples for moisture determination were taken for the 250°C experiment. The sampling periods during which MC samples were taken are designated by a box in the chart.

As can be seen in the chart, a lot of variability exist in all of the temperatures recorded. The readings were interrelated in such a way that grain flow lowers the inlet temperature of medium in the heater which correspondingly lowers the inlet temperature of the medium in the mixer. These variations in inlet medium temperature in the mixer were supposed to be regulated by the process controller. However, there was a large thermal inertia to overcome

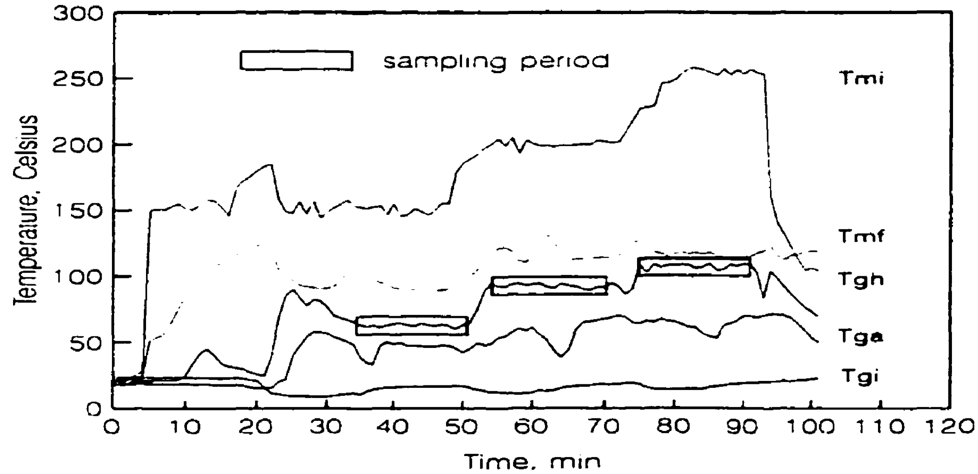

Figure 5.2 Temperature profile @ 17% MC

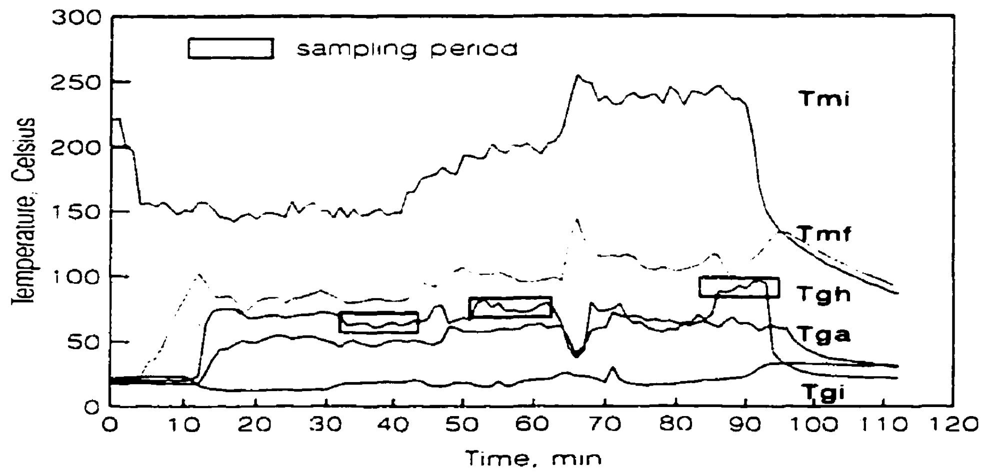

Figure 5.3 Temperature profile @ 19% MC

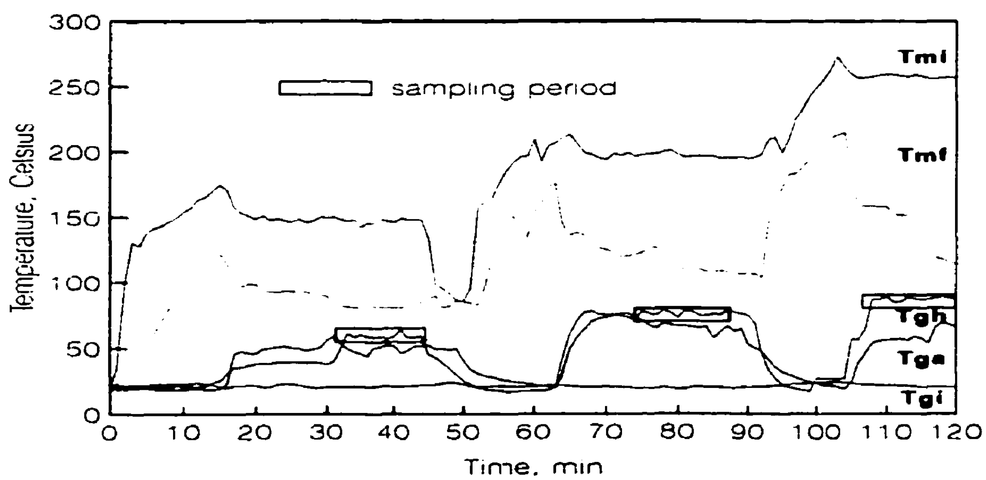

Figure 5.4 Temperature profile @ 24% MC

in actively exercising control. As an example, the first "spike" in **Tmi** observed 20 min after start-up, rippled through the other sensors and registered in the **Tga** sensor 10 min later. With this time lag in sensing at the **Tmi**, stability of the temperatures took much longer to achieve. The response of **Tmi** on the reduction of grain flow rate was swift. It took less than a minute for **Tmi** to increase to a higher level as soon as the flow of grain into the mixer was interrupted. In all of the 3 charts, whenever **Tgh** plunged down, there was a resultant increase in both **Tmi** and **Tmf**.

It can also be observed that the plot of **Tmi** follows a ladder pattern with several ripples in the top land. These ripples were caused by a combination of the process controller cycling and the variation in thermocouple contact with the medium. The variations in thermocouple contact was expected since the experiment was run on continuous flow and it takes a much longer time to stabilize all material flows within the machine. However, as shown in the previous experiment where no variation in power input (controller was not cycling) was required, the temperatures of both the medium and grain stabilized much faster.

Over the three moisture contents tested, it can be observed that the final grain temperature decreases with increased initial moisture content of the grain for a given initial medium temperature. This result was expected since evaporation of moisture from the grain tends to lower its temperature by evaporative cooling. This finding will be validated by evaluating the amount of moisture reduction for each of the moisture contents tested.

5.5.2 Moisture reduction

Table 5.1 shows the average moisture content of the 5 samples taken during the experiments. The first column showed the initial moisture content of the corn before loading into the mixer, the second column is the moisture content after mixing, and the last column showed the moisture content of the corn after it has been aerated for 3 min. These values were plotted individually for each initial MC in Figures 5.5, 5.6, and 5.7.

The slope of the line generated by the three points (initial, heated, and aerated) showed that at 17% initial MC, the slope was gradual and showed very little difference for the three temperatures tested. At 19% initial MC, the two temperatures 150°C and 250°C showed a similar trend. However, at 200°C the moisture content dropped drastically from an

Table 5.1 Average moisture content of 5 samples

Temperature / MC	Initial MC, %	MC heated, %	MC aerated, %
150 / 17	17.06	15.61	14.81
200 / 17	17.51	15.55	14.98
250 / 17	17.64	15.23	14.96
150 / 19	18.75	16.04	15.86
200 / 19	18.53	16.03	15.36
250 / 19	18.93	13.88	12.76
150 / 24	24.52	22.14	21.67
200 / 24	23.38	21.13	20.35
250 / 24	25.50	22.09	21.57

initial value of 18.93% to 12.76%. This gave a drop in moisture content of 6.17% which is so far the biggest reduction in average moisture content for all of the experiments. The test performed at 24% MC showed a similar slope with the 17% MC samples. Although the average of the experiment performed at 250°C was much lower in all three phases, the slope of the line still remains similar with the two other temperatures tested.

Figure 5.8 shows the magnitude of moisture reduction at different initial MC over the three process temperatures tested. The highest value of moisture reduction shown is in the 19% initial MC at the 250°C temperature level. Increases in moisture reduction between 150°C and 200°C were similar for all three initial MC, but between 200°C and 250°C, the 24% and 19% have greater moisture reductions. However, the 17% initial MC has exhibited a more linear response to the three levels of process temperatures. These findings confirm the result of the preliminary study that an increase in initial medium temperature results in greater moisture reduction at all levels of initial moisture content.

In order to evaluate the moisture reduction in the mixer and aerator, the MC reduction

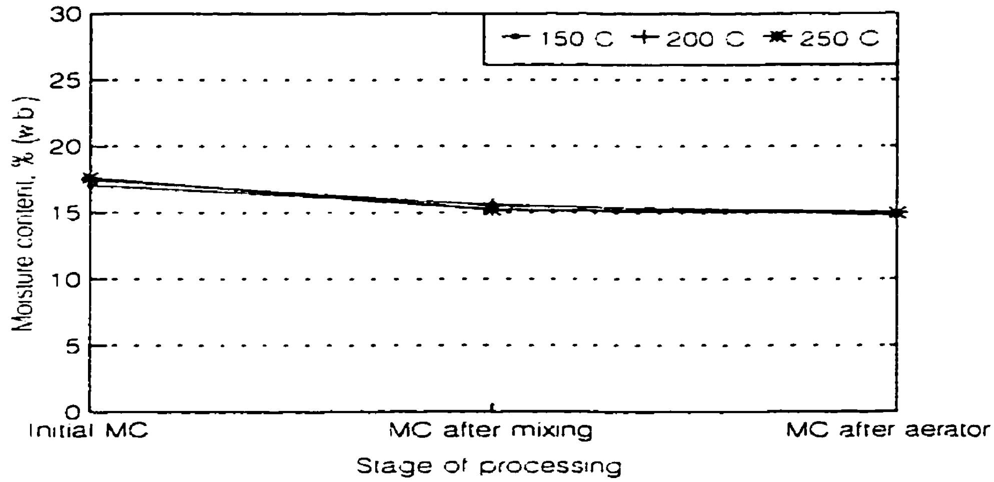

Figure 5.5 Corn moisture content @ 17%

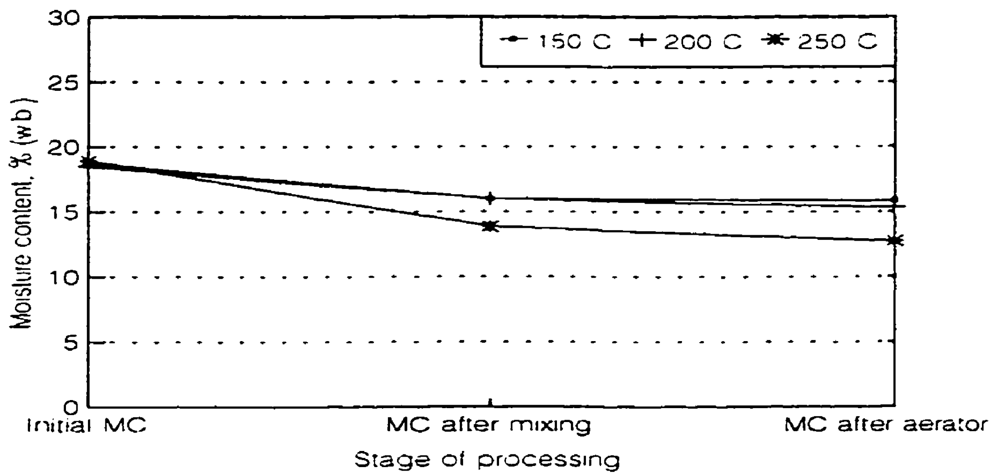

Figure 5.6 Corn moisture content @ 19%

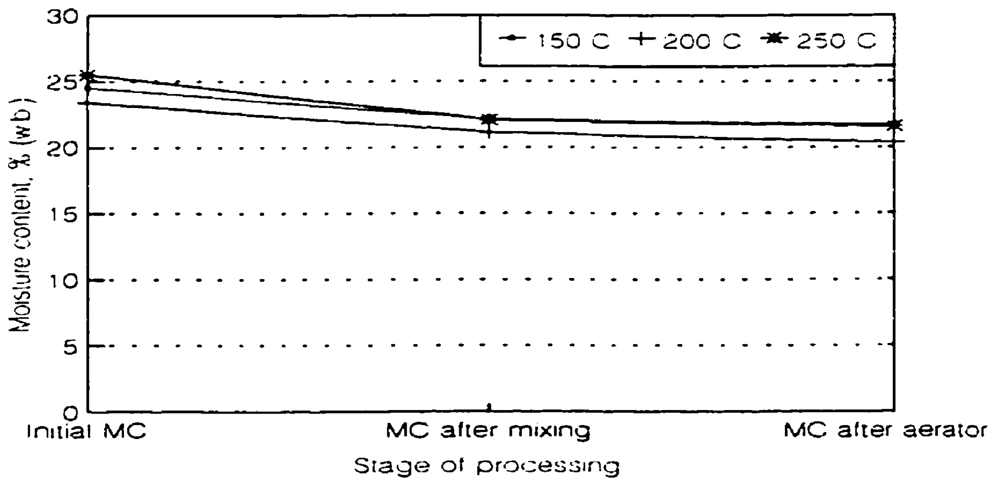

Figure 5.7 Corn moisture content @ 24%

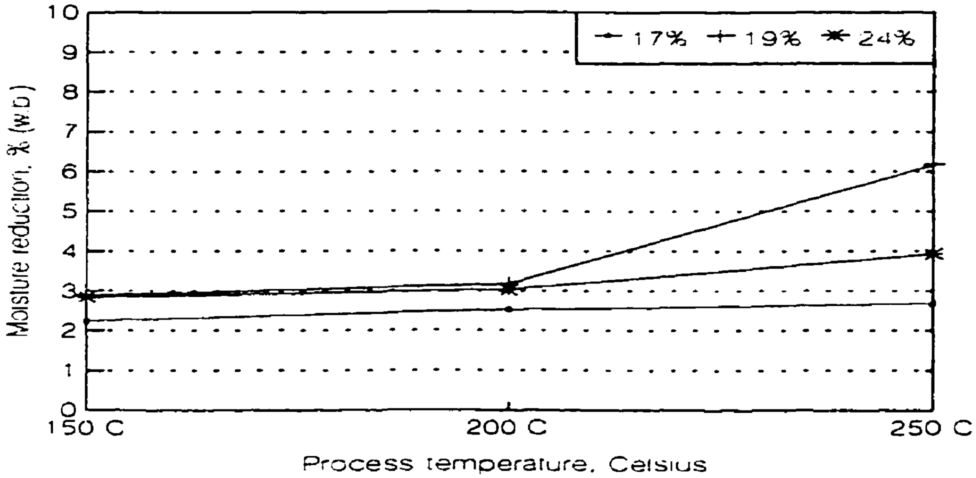

Figure 5.8 Total moisture reduction vs. temperature

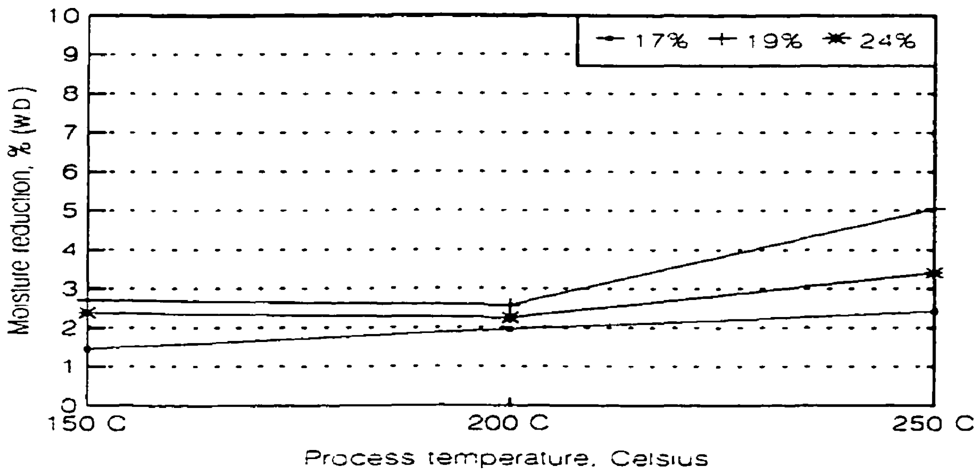

Figure 5.9 MC reduction @ mixer vs. temperature

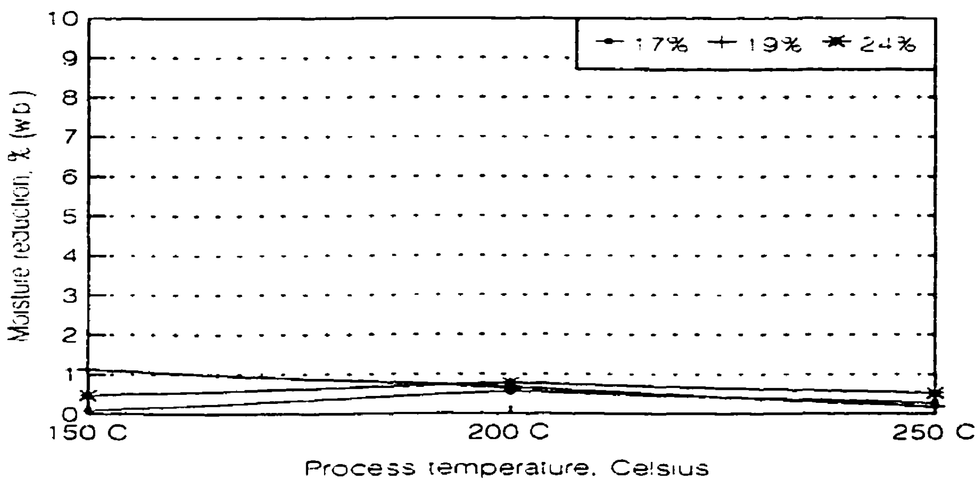

Figure 5.10 MC reduction @ aerator vs. temperature

in the two components were plotted vs. the three levels of initial medium temperature as shown in Figure 5.9 and Figure 5.10. Figure 5.9 shows the proportion of total moisture removed from the corn that can be attributed to the mixing section. It shows a low value of 1.5% at the 17% initial MC with initial medium temperature at 150°C. The highest percentage removal in the mixer was with the 19% initial MC at 250°C which amounts to 5.05% reduction in moisture content. The trend exhibited in the mixer showed moisture reduction increasing with increased initial medium temperature. In contrast, the moisture removal in the aeration section (Figure 5.10) does not exhibit any specific trend. The values achieved in the aerator ranged from 0.2% to a high of only 1.12%. This result showed that there was actually a very minimal amount of drying that occurred in the aeration section.

Figure 5.11 shows the percentage moisture reduction in the heater vs. the three levels of initial medium temperature. At the lower initial MC of 17%, the percentage of moisture removed in the mixer varied linearly with the initial temperature of the medium. Surprisingly, the percentage of moisture removal for the 19% case showed a high value at the lowest initial medium temperature of 150°C amounting to 94% of the total moisture removed. At 250°C the percentage removal was only 82%. This result can be explained by going back to the plot of process temperatures. The higher initial medium temperature resulted in high grain temperature at the aerator. Elevated grain temperatures during aeration tends to reduce more moisture because of the greater water vapor pressure deficit between the grain and ambient air. This results in a higher proportion of total moisture removal at the aerator.

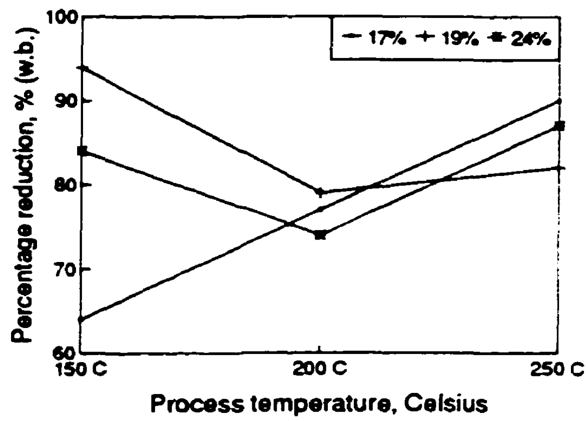

Figure 5.11 Percentage removal @ mixer

5.6 Conclusions

Based on the preceding discussion, the following conclusions can be derived:

1. The Processor dried corn at the rate of 500 kg/hr, with a peak moisture reduction of only 6.17%, which fell short of the 10% moisture reduction desired in the study.

2. Steady-state conditions were achieved during processing and satisfactory control over temperature was attained at different initial moisture contents of corn.

3. The high initial moisture content resulted in a lower final grain temperature in all levels of initial medium temperature.

4. A greater proportion of moisture removal in the Processor occurred in the mixing section.

5. The highest moisture removal in the Processor was 6.17% with the corn at an initial moisture content of 19% and exposed to salt at an initial medium temperature of 250°C for 60 s.

These findings show that the Processor cannot remove more than 10% moisture from corn in a single pass. It also confirmed the results of the preliminary study that initial medium temperature plays a significant role in increasing the drying capacity of the machine. The high moisture reduction percentage in the mixing section requires further study to evaluate methods of enhancing moisture removal. The high rate of heating also highlights the potential of the Processor in thermal treatments that would not require moisture removal (e.g., roasting and thermal disinfestation).

CHAPTER VI
ROASTING OF SOYBEANS

6.1 Introduction

Early studies on high temperature thermal processing of grains were undertaken to determine the maximum safe range of temperatures for drying. However, tests on the grains dried at higher temperatures showed no significant reduction in nutritional value. In fact most grains showed increased digestibility when subjected to relatively high temperatures (McKenzie and Gottbrath, 1971). Consequently, several studies have been conducted to evaluate the effects of high temperature thermal treatment on the nutritional value of grains (Raghavan et al., 1973; Tromp et al., 1993; Alikhani et al., 1991). Although responses of different animals vary, the overall conclusion drawn from these studies was that high temperature thermal treatment of feed grains resulted in more beneficial effects than normal drying temperatures. The thermal treatment was also found suitable for denaturing trypsin inhibitor in soybeans which interferes with the proper digestion of the soybean protein.

Studies on the method of thermal treatment were also conducted. Five methods were used to apply heat to the grain to modify its nutritional characteristics. They include roasting, extrusion, gelatinization, popping, and steam flaking. Earlier, the processing costs of these methods were so expensive that they outweighed the benefits derived from thermal treatment. However, with significant progress in heating technologies, methods which are potentially adaptable to small-scale processing make thermal treatment of grains more economically feasible.

Of the five methods available to heat the grain, dry heat roasting using hot air, flue gas, or heated particulates were the most promising. Equipments such as the Roast-a-Tron, Sukup Grain Roaster, and the Roast-a-Matic used a mixture of heated air and flue gas to roast soybean. The first well-documented study on the use of heated particulates for roasting was the work of Raghavan et al. (1973).

Evaluation of particulate medium thermal treatment parameters in the study by Raghavan et al. (1973) showed the best operating conditions to be 272°C medium temperature, 20 s contact time, and a 120 s holding time. This temperature-time combination resulted in a soybean temperature of 110 to 122°C. A subsequent study conducted by Tromp et al. (1993) used medium temperatures of 225 to 275°C with contact times of 15 to 60 s. These resulted in soybean temperatures between 107 and 134°C. The increase in soybean temperature during roasting was accompanied by a significant moisture reduction averaging 14.2%.

The studies by Raghavan et al. (1973) and Tromp et al. (1993) were performed on laboratory scale models of particulate medium thermal processors. They showed that the best range of grain temperatures to achieve the beneficial effects of high temperature thermal treatment for soybean was 107°C to 134°C. In order to bring this method into practical application, tests on large scale processing should be conducted to determine whether these operating conditions can be economically attained in a commercial scale continuous flow thermal processor.

6.2 Objectives

The previous studies performed on roasting soybeans using the particulate medium method demonstrated its technical feasibility. The feeding trials and chemical analyses showed that this thermal treatment was sufficient for animal feed. In this study, the general objective was to use the Processor to roast soybean at the same range of temperatures and contact times as in the previous study, in order to evaluate the performance of the Processor in high temperature thermal treatment of grain for animal feed purposes at the commercial scale of operation.

The specific objectives were:

1. Roast soybean and evaluate the degree of control of medium temperature and grain temperature.

2. Determine the level of moisture reduction in roasting commercially dried soybeans.

3. Compare the performance of the Processor with similar roasting equipments available in the market.

6.3 Materials and methods

6.3.1 Materials

Two materials were used in testing the performance of the Processor. Tests were conducted to evaluate the ability of the Processor to achieve the temperature-time combination necessary to roast soybean and peanuts.

Maple Glen variety soybeans were purchased from a grain dealer near Macdonald Campus. The average moisture content was 6.8%. The medium used in this experiment was salt, as used in the previous tests.

Since soybean is more spherical than either corn or wheat, the velocity with which individual grains roll down the sloped separation screen is faster. To prevent soybean from flowing over the inlet spout of the aeration cylinder, the sidewall of the spout was elevated by adding a 5 cm by 15 cm perforated plate. An aluminum/foam tape was placed over this plate to prevent cracking of the soybean due to impact as it hits the sidewall.

6.3.2 Methods

The soybean samples were already dry when purchased. However, the samples were passed through an aspirator to remove chaff and other foreign matter before the tests. This prevented fouling of the medium by unwanted materials. After cleaning the soybean, the feed auger was calibrated to set the actual flow rate of grain to be used in the experiments.

The experiment was designed to evaluate the ability of the Processor to achieve the roasting temperature and duration of exposure to heated medium for the soybean to be roasted. Three initial medium temperatures were tested. They are 175, 200, and 250°C. The contact time was set at 60 s with a medium-to-grain mass ratio of 4:1. Flow rate of the soybean was set to 500 kg/h.

Prior to the experiments, the heater, mixer and aerator were calibrated to the flow rates required to achieve the parameters needed for roasting. First, the amount of salt in the machine was verified and additional salt was added to bring the total load to 175 kg. The rotational speed of the mixer was then set to give a 60 s contact time. The heater flow rate was adjusted to deliver the required amount of heated medium to achieve a 4:1 mass ratio in the mixer at the feed rate of 500 kg/h of soybean.

Once all of these parameters were set, the data acquisition system was activated. After the temperature readings stabilized, the pilot burner of the heater was started. The feed conveyor was switched on and the main burner of the heater energized. Data generated on the first 5 min. of operation was closely monitored for unusual variations in the sensing performance of the thermocouples. Setting of the process controller was adjusted to the first temperature being tested (175°C). After 30 min at this temperature the setting was adjusted to the next test temperature. Before adjusting to this temperature, 5 samples were taken at the inlet and outlet of the mixer, and at the outlet of the aeration cylinder. The same process was repeated for the other temperatures tested during the roasting experiment. All grain samples taken during the experiment were kept in the oven set at 103°C for 72 h to determine moisture content. Data taken during the tests were converted into delimited ASCII files and transferred to a Personal Computer for analysis.

6.4 Results and Discussions

6.4.1 Process parameters

The calibration of the grain feed auger was conducted before the tests since the flow rate of grain through the auger was affected by the moisture content of the material. Figure 6.1 shows the calibration chart for commercially dried soybean at 6.8% moisture content which was used in the experiments. Based on this chart, a speed setting of 17 which corresponds to 500 kg/h of soybeans was used in the three roasting experiments.

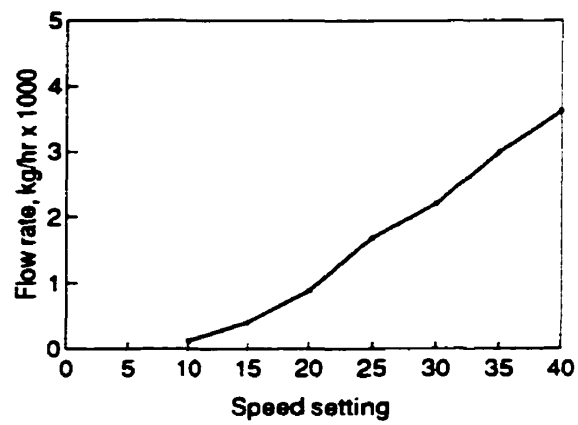

Figure 6.1 Auger calibration for soybean

During the experiment, several adjustments were made on the machine to be able to gather reliable data. The speed at which soybean grains move through the separation section created sensing problems. The contact between the grain and the thermocouple sensor was too short and irregular resulting in error readings by the data acquisition equipment. The problem was solved by installing two spring loaded weir plates to regulate the flow of grain through the thermocouple sensor on the lower end of the separating screen. This modification made heated grain temperature sensing more reliable by making the grain flow over the sensing plate and slowing down the passage of grain over the sensor.

Figure 6.2 shows the temperature profile generated when the temperature readings were stabilised at the first setting of 175°C. The chart showed the medium entering the mixer at an average temperature of 179°C and exiting at 130°C. It also shows the soybean fed by the auger at 22°C and exiting the mixer at 104°C. Although the process controller was set to regulate outlet medium temperature of the heater, the temperature fluctuates between 173 and 186°C. Most of the time, the process temperature overshoots the set point because of the big mass of the heater. This mass tends to slow down the variation in medium temperature by storing excess heat and giving it off when the burner is in the off cycle.

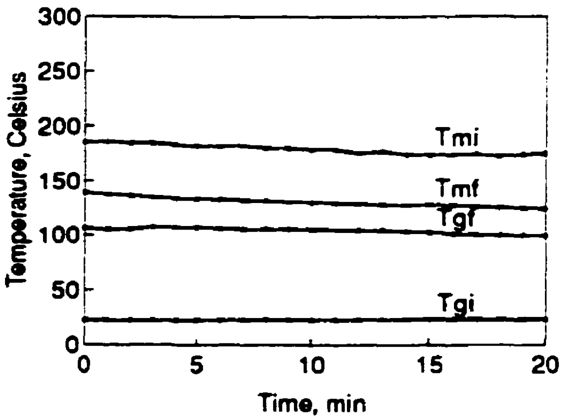

Figure 6.2 Temperature profile at 175°C

At 175°C initial medium temperature, the grain did not reach the desired processing temperature. The minimum target temperature was 107°C as per the previous findings in Raghavan et al. (1973) and Tromp et al. (1993). However, with the 26°C difference between the grain and medium temperature at the outlet of the mixer, the desired temperature could be attained by increasing the contact time between the medium and grain.

Figure 6.3 shows the temperature profile when the process controller was set to 200°C. At this setting, the average initial medium temperature was 188°C and it dropped to 141°C as it came out of the mixer. The grain on the other hand was fed at 23°C and came out at an average temperature of 107°C. The grain temperature barely met the minimum target temperature for roasting. In this experiment, the actual medium temperature was very low compared to the set point in the process controller. The trend shown in the chart showed that the medium temperature was decreasing while the grain temperature was increasing. This means that the machine was still trying to stabilize the operating temperature when the data were taken. The actual stabilized temperature could have been much higher if the test was extended for a few minutes more. However, the length of time was limited by the amount of soybean available for each test.

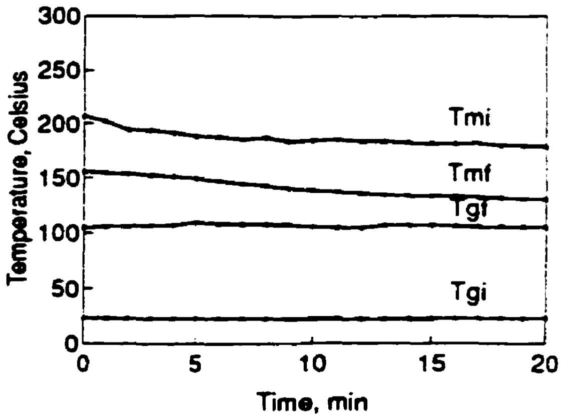

Figure 6.3 Temperature profile at 200°C

The results of the third test are presented in Figure 6.4. The process controller was set to 250°C medium temperature. At this temperature, the actual process temperature was only 238°C and 178°C for the initial and final mixing temperature, respectively. As with the 200°C trials, the trend for medium temperature is still decreasing. This signifies that the operating parameters were not fully stabilized when data was taken. This can be confirmed by the grain temperature which exhibits an increasing trend. Average value for grain temperature was 23°C and 127°C for the inlet and outlet temperature, respectively. This is the best value of grain temperature for roasting. It falls almost midway between the maximum (134°C) and minimum (107°C) temperatures aimed at in this study.

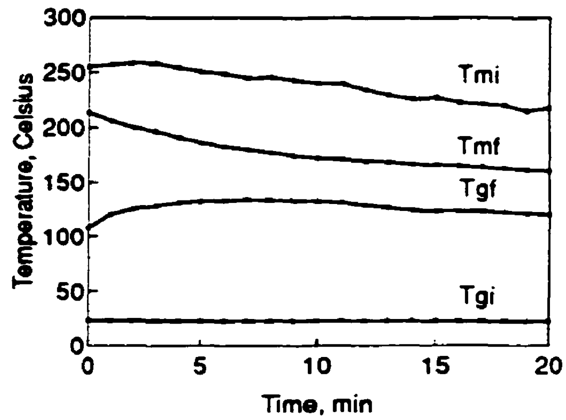

Figure 6.4 Temperature profile at 250°C

Although there were differences between the process controller set point and the actual medium temperature, the desired soybean temperature and contact time were achieved. At a processing rate of 500 kg/h, the results are comparable to the capacity of the Roast-a-Tron and the Sukup Grain Toaster. The Processor was designed to handle 3 t/h of grain and the flow rate used in this study was only meant to generate temperature-time data at the half ton level because of limitations in the amount of material available for the tests.

6.4.2 Moisture reduction

In the commercial processing of grains, control over the moisture content of the product is critical. Too little moisture removal in fresh grain could result in spoilage, while too much moisture removal (over drying) will result in the loss of marketable weight of the product. Since the soybean used in this study was dry, it was necessary to evaluate the effect of the three temperatures tested on the amount of moisture removed from the grain. While roasting may improve the value of the product, too much loss of weight could offset this advantage.

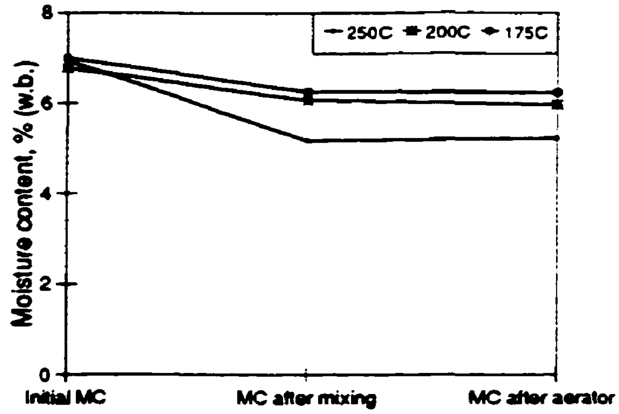

Figure 6.5 Average moisture content

Figure 6.5 shows the average moisture content of soybean when processed over the three temperature levels. The chart shows moisture content of the grain right after mixing and after the grain was cooled in the aeration cylinder of the Processor. It can be observed that the moisture removal increases proportionately with the temperature used in roasting. Furthermore, the amount of moisture removed in mixing the soybean with heated salt was greater than those removed in the aeration cylinder.

There were five samples taken on each of the three test conducted and on the 250°C test, the largest moisture removal was observed. Although the average reduction in moisture was only 4.11% the highest

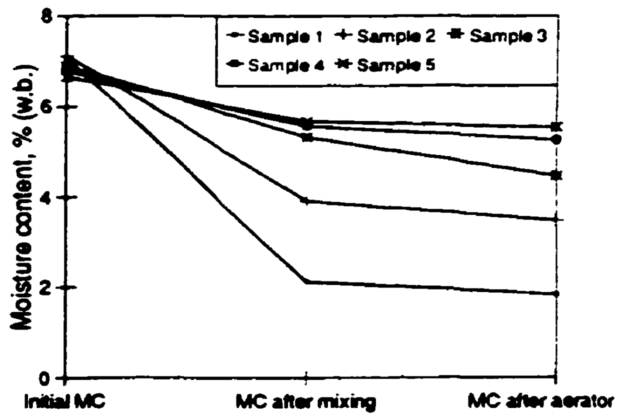

Figure 6.6 Moisture content at 250°C

reduction was 5.22%. With this moisture removal a large amount of the marketable weight of the soybean was lost. While the moisture reduction seems high when compared with the other temperatures tested, it is still far from the values observed by Tromp et al. (1993) which showed an average of 14.2 percentage points. As pointed out by McKenzie and Gottbrath (1971), this reduction in moisture of the roasted soybean could be advantageous when the roasting process is done on freshly harvested soybean. The combined process of drying and roasting into one operation would improve the overall thermal efficiency of the processing equipment. Figure 6.6 shows the moisture contents of the five samples taken at the 250°C experiment.

6.5 Conclusions

Based on the preceding discussion, the following conclusions can be derived:

1. The Processor is capable of roasting soybean at a commercial scale of operation.

2. The variation in initial medium temperature has minimal effect on the outlet grain temperature because the mass of the heater tube as well as the combined mass of the materials store heat which tend to stabilize process temperature.

3. The amount of moisture removed from the soybean increases with increase in the temperature of the particulate medium. The moisture reduction in the Processor is much lower than published results by Tromp (14.2 %).

4. The performance of the Processor in roasting soybeans at 500 kg/h was comparable with the capacity of the Roast-a-Tron (340 kg/h) and the Sukup Grain Toaster (364 kg/h). The capacity of the Processor could have been tested at a higher level if more material was available.

CHAPTER VII

THERMAL DISINFESTATION OF WHEAT

7.1 Introduction

Major insect pests have developed resistance to common grain protectants and industries are using new expensive insecticides as a short term solution. Fumigation subjects the grain to very high concentrations of toxic chemicals, such as methyl bromide, which leave unwanted residues in the grain. A physical means of insect control is needed to reduce the entry of hazardous chemicals into the food chain. Thermal disinfestation has been considered to be one of the most promising methods of insect control.

Studies on thermal disinfestation of stored grains have been conducted using convective heat transfer (Dermott and Evans, 1978; Evans et al., 1988; Fleurat-Lessard, 1985), high frequency waves at 10-100 MHZ (Nelson and Kantak, 1966), microwaves at 300-3000 MHZ (Locatelli and Traversa, 1989), or infrared radiation at 100-100,000 GHz (Kirkpatric and Tilton, 1972; Tilton et al., 1983) to heat the grain. Thermal disinfestation by convective heat transfer using fluidised beds (Dermott and Evans, 1978; Evans et al., 1988; Fleurat-Lessard, 1987) and spouted beds (Claflin et al.1986) has been thoroughly studied and found to be very effective (Fields, 1992).

Conduction drying in a bed of heated granular medium has been studied (McBratney et al., 1989; Raghavan et al., 1988) and shown to exhibit more efficient heating than convective methods (Richard and Raghavan, 1980; Raghavan and Harper, 1974; Khan et al., 1973). However, this technology has not yet been tested for disinfestation of stored grain.

In particulate medium heating, hot granular particles are in close physical contact with the grain and heat transfer occurs mainly by conduction. A bed of heated granular medium also offers the possibility of disinfestation at low grain temperatures to prevent loss of marketable weight by overdrying. The low airflow inherent in the immersion of grain into a bed of heated particles coupled with the use of a non-hygroscopic medium will provide an environment conducive to disinfestation with minimal effects on the grain.

This study was conducted to evaluate the effectiveness of the method in thermal disinfestation of wheat. The test insect used in this study was *Sitophilus granarius*, commonly known as granary weevil. Infestation by *S. granarius* usually causes a reduction in grain quality primarily through weight loss. Further losses resulting from secondary invasion of seeds by fungi and bacteria, and occasional grain heating is also common.

S. granarius thrives mainly in countries with a cool temperate climate such as the northern part of North America and Russia. It is a cold-hardy pest, particularly in areas that have a high relative humidity for part of the year. This insect feeds on whole stored cereals such as wheat, barley, rye, corn, sorghum, rice, cowpeas, accorns, chestnuts, sunflower seed, and bird feed.

Seed damage can be recognized by small circular holes in seeds through which the adult emerges. The insect develops inside the kernel, where temperature and relative humidity are approximately 30°C and 70% respectively. It consumes 64% of the kernel, destroying all the germ and a large part of the endosperm.

Sitophilus granarius have a 100-day lifetime and multiply at an optimum temperature of 27°C. The life cycle, from egg laying to adult emergence, ranges from 28 to 40 days under favourable conditions. Adults of this insect are considered to be the hardiest stage. The lengths of exposure to extreme temperature necessary to give complete kill of adults varies from about 1 day at -15°C to 58 days at 0°C. However, it is less tolerant of short exposures to temperatures over 40°C, unless it is acclimatised for several generations at 30°C.

7.2 Preliminary Study

7.2.1 Objectives

This study was conceived as a preliminary investigation to evaluate the potential of particulate medium thermal treatment as an alternative disinfestation method. The basic concept of the study was to determine the effect of different medium temperatures and exposure times on the mortality of adult insects. The test insect was *Sitophilus Granarius*, a common pest in grain storage and processing centers.

Specific objectives of the study were:

1. To rear healthy, mature insects for controlled infestation of feed grade wheat in the laboratory.

2. To study the mortality of the test insect when exposed to heated salt at 5 levels of temperature and 5 exposure time.

3. To evaluate the magnitude of heating required to achieve total insect kill.

4. To conduct a similar heating process in the Processor and evaluate the energy requirement of the process.

7.2.2 Materials and Methods

a. Design of experiments

To achieve the objectives in the preceding section, thermal disinfestation experiments were conducted on feed grade wheat infested with granary weevil. The tests were performed using the laboratory scale adiabatic mixer used in the preliminary drying experiments. The heating medium used was salt. A 4:1 medium-to-grain mass ratio was used since it has been found to result in adequate heat transfer. 800 g of salt and 200 g of wheat was used in the experiments to achieve the desired ratio while maintaining the mass of the mixture within the holding capacity of the mixer. Mixing speed was kept at 35 rpm to ensure uniform and adequate mixing of the medium and the grain.

Combinations of 5 temperatures and 5 exposure durations were used in the treatments. All treatment combinations were replicated 3 times. Further, an untreated control group was maintained for each treatment combination.

b. Materials

The wheat used in the experiments was destined for animal feed and was purchased from Belcan Agrocentre Inc. It contained some impurities so it was cleaned and there stored at ambient conditions for a month before the experiments. Moisture determination tests were performed and the samples were found to have 8-9% moisture content (w.b.).

Culture of the test insect, *Sitophilus granarius* (Curculionidae: Coleoptera) was obtained from the Agriculture Canada Research Station in Winnipeg, Manitoba. It was reared in the laboratory on wheat at 27.0± 2°C and 65±5% RH. All stages of the test insect were available during the tests. However, only adult insects that were 24 h old were used in the experiments because they were considered to be the hardiest stage of *S. granarius*.

The heating medium used in the experiments was table salt. The salt was of a uniform particle size, averaging 0.358 mm in diameter. It was heated to the initial temperature using a Fisher Model 230F electric convection oven.

The adiabatic mixer constructed for the laboratory drying experiment was used in the thermal disinfestation experiments. The mixer is described in detail in the preceding chapter on grain drying. It was driven by a variable speed motor and was operated at 35 rpm to ensure adequate mixing of the particulates.

Temperature measurements used to monitor and control the operation of the mixing equipment were obtained with a Cole Parmer thermocouple thermometer. The data were transferred to a Packard Bell personal computer for processing.

c. Methods

The test insect was reared on wheat in plastic containers and stored in a controlled environment chamber at 27°C and 65% relative humidity. Prior to each experiment, adult insects were sieved and released on a tray so that their activity levels could be observed. The most active individuals were selected for the trials and handled using an aspirator. Individuals that were sluggish or had any physical disabilities were discarded. Each batch of 50 adults selected was released into a 200 g lot of clean, feed grade wheat kept in plastic containers with screened caps and held for 24 h. After this period, it was expected that the test insect has infested the grain sample, knowing that it has only a 100 day lifetime.

The salt was heated in the oven to the initial temperature prior to the tests. While the salt was being heated, the mixer was turned on and the cylinder wall was heated to the initial temperature of the medium. Heating of the cylinder was terminated at the instant the medium was loaded. Once the salt reached the desired temperature, 800 g was placed in the mixer and the insect-grain mixture added. The motor was turned on and mixing was carried out for the required exposure time. The salt-grain mixture was then removed from the mixing cylinder into an insulated catch pan. The salt was screened out and the insect-grain mixture transferred to a plastic container and held for 24 h. Insect mortality was recorded at the end of the holding period. The 24 h holding period serves to eliminate bias owing to possible temporary or delayed effects of the treatment. The tests were replicated 3 times.

During the grain-medium mixing process, the temperature of the mixture was monitored using thermocouples installed inside the mixing cylinder. The grain temperature before loading into the mixer was taken using a thermocouple probe placed inside the container. Grain temperature after mixing was taken using the same probe when the insect-grain mixture was transferred to the plastic container for the 24 h holding period.

7.2.3 Results and Discussion

a. Heat Utilization

The use of particulate medium in thermal disinfestation of grain requires that a certain amount of heat be transmitted to the grain to inhibit the growth or continued presence of the insect on the grain. The quantity of heat required and the duration of exposure to attain 100% mortality of the test insect can be determined by evaluating the temperature of the medium-grain mixture.

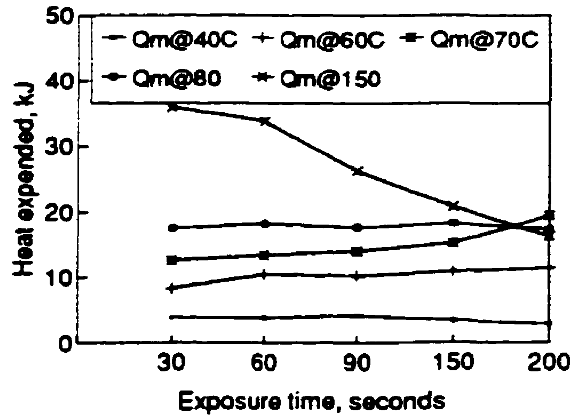

Figure 7.1 Heat input by the medium

Figure 7.1 shows the amount of heat expended by the medium. It shows the amount of heat given off by salt at 5 different exposure periods. At temperatures between 40°C and 80°C, the amount of heat expended was relatively the same over the 5 exposure periods. However, at 150°C, the medium had its peak heat output at 30 s and a significant drop in the amount of

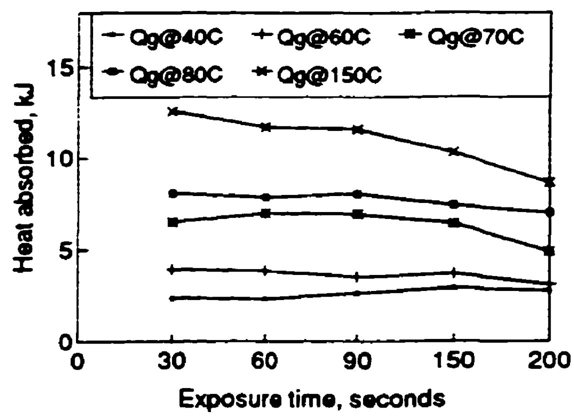

Figure 7.2 Heat absorbed by the grain

heat given off on longer exposure durations can be observed. This result was unexpected since at high initial medium temperature the grain attains maximum achievable temperature very quickly and prolonging contact between the two materials would have resulted in grain-medium temperatures approaching equilibrium. A higher heat transmission was expected in such conditions. The final temperature of the mixture averaged 135°C for a 30 s exposure. For longer exposures lasting 300 s the average value dropped to 98°C.

The amount of heat absorbed by the grain showed a similar trend with the amount of heat expended by the medium (Figure 7.2). This was expected since the mixing equipment was considered adiabatic and heat loss to the environment was minimal. Even the maximum temperature attained by the grain showed the same trend (Figure 7.3). At the highest initial medium temperature of 150°C the maximum grain temperature was only 67°C, showing that particulate medium thermal disinfestation can be used for seed quality grains since seed viability is still considered good at such a temperature.

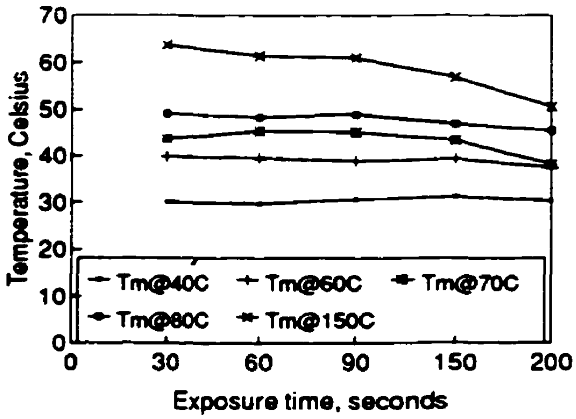

Figure 7.3 Max. grain temperature

Based on the heat expended by the medium and the heat absorbed by the grain, the efficiency of heat transfer between the salt and wheat was calculated. Figure 7.4 shows a plot of the heat transfer efficiency at each temperature over the five exposure

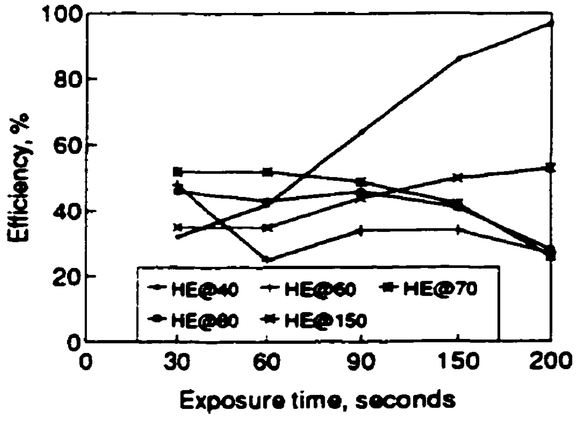

Figure 7.4 Heating efficiency

periods. Exponential curves adequately fit ($R^2 \geq 0.94$) the efficiencies at 40°C and 150°C. The efficiency at both temperatures exhibited an increasing trend. Also, the temperatures between the two (60, 70, and 80°C) fitted an exponential curve. However, the efficiency trend was decreasing.

b. Insect Mortality

Mortality of adult insects was plotted against exposure time for each temperature and is shown in Figure 7.5. Since there was no mortality in the control batches (untreated and held for 24 h), the data presented were not corrected for base mortality. The lines were generated using a non-linear curve fitting routine based on the model:

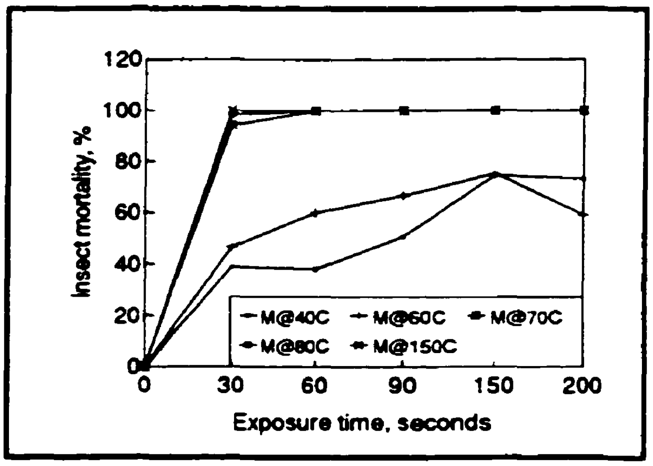

Figure 7.5 Insect mortality

$$M = a + b\,(t)^c \qquad (7.1)$$

Where:

M = mortality, %

a,b and c = constants

t = time of exposure, s

The constants a, b and c best fitting the data at each temperature are presented in Table 7.1. For 80°C and 150°C, the values for a and c are near zero and the values of b are 98.5 and 100, respectively.

As can be seen in Figure 7.5, 100% mortality occurs within 30 s for a medium temperature of 80°C and above. At 70°C mortality was about 95% in the first 30 s and reaches 100% at an exposure time between 30 and 150 s. At temperatures below 70°C, a logarithmic relationship was observed. At lower temperatures of 24, 40 and 60°C maximum mortalities were 50, 75 and 80% respectively. Whether this was sufficient to ensure

Table 7.1 Values of the constants used in the model

Temperature, °C	a	b	c
24	0.307	12.653	0.270
40	0.394	7.356	0.440
60	-0.074	18.677	0.280
70	-0.001	87.108	0.028
80	-0.001	98.477	0.003
150	1e-16	100.00	2e-17

protection of the stored wheat depends on the level of damage to the reproductive functions of the surviving insects. However, reproduction after-treatment was not measured.

c. Grain Quality

The above results clearly indicate that mixing of infested grain with pre-heated particulate medium can be an effective method of disinfestation. However, in achieving the primary objective of disinfesting the grain, the effects of the heat treatment on quality of the grain should be considered (Ghaly and Taylor, 1982). Although higher temperatures provide rapid disinfestation, the nutritional characteristics of the grain may be altered. Previous studies on thermal disinfestation clearly demonstrated that the relationship between mortality and temperature is complex and that the heat dosage required to achieve a particular level of mortality cannot always be achieved within the constraints related to grain quality as advocated by Vardell and Tilton (1981a and b). In this respect, the particulate medium method provides an opportunity to exploit the effect of the heated media to achieve adequate insect mortality.

A visual inspection of the wheat samples after treatment showed no burning or discolouration resulting from any of the treatment combinations. Moisture content was not determined in this test since the grain was not exposed to air after treatment. Therefore, it was assumed that minimal moisture reduction took place during the entire thermal treatment process. From the other studies, such as the laboratory scale drying tests, moisture reduction was only around 3% (w.b.) in the absence of aeration.

7.2.4 Conclusion

Effects of the thermal treatment on adult *Sitophilus granarius* were found to be a function of the initial temperature of the medium as well as the duration of exposure. Significant insect mortality was achieved at lower temperatures. However, at temperatures above 70°C insect kill was almost instantaneous. A mortality rate of 100% was attained at the lowest exposure time of only 30 s with an initial temperature of 150°C.

Evaluation of the thermal process showed the most effective temperature-time combination for particulate medium thermal disinfestation was a moderate (70, 80°C) or high (150°C) temperature treatment over a short exposure period. This combination ensures a high thermal efficiency while achieving total insect kill. With this finding, it can be concluded that thermal disinfestation using a heated particulate medium can be used to efficiently disinfest grain without adversely affecting grain quality.

7.3 Thermal Disinfestation Using the Processor

7.3.1 Objectives

In the preliminary study on thermal disinfestation, it has been established that at temperatures over 80°C, 100% mortality of adult *S. granarius* was achieved almost instantaneously. At temperatures below 70°C, mortality was a function of exposure time to heated particulates. Using this information, a test was conducted to determine the operating parameters in the Processor which will yield temperature and exposure times necessary for 100% mortality. Since the tests using the Processor were performed in a continuous mode, it was impractical to use actual insect infested samples. Instead, temperature-time values from the preliminary experiments were used as a guide.

Specific objectives of the study were:

1. To determine the energy requirements necessary to achieve the temperature-time combinations which resulted in total insect kill using the Processor.

2. To determine the thermal parameters and grain flow rates the machine is capable

of processing.

3. To compare the operating efficiency of the Processor in thermal disinfestation with those achieved in the convection/particulate medium study.

7.3.2 Materials and methods

a. Design of the study

To determine the performance of the Processor in disinfestation of grains, two tests were conducted. These tests were performed using wheat at a moisture content of 14% (w.b.). The use of the Processor required a large volume of material since the unit was designed for a rated capacity of 3 t/h. In order to perform these experiments at a reasonable rate, it was decided to operate the machine at 1 t/h. Based on the convection/particulate medium tests, the machine attains stable operating conditions after a warm-up period of 10 to 15 min. Therefore, 500 kg of wheat were prepared for the study to get at least 15 min of useful data. Since the grain was kept in cold storage before the experiments, its temperature was raised to ambient temperature of about 20°C before the experiments.

Contact time between the grain and the medium is controlled by the rotational speed of the mixing auger. Since the mixing auger is driven by a stepless variable speed motor, the contact period can be varied from a low of around 15 s to a high of 15 min. Consequently, the flow rate of grain through the mixer can also be varied. Practical use of the unit requires that a high grain flow rate be used at short contact times rather than at longer exposures.

As the results of the preliminary study pointed out, total insect kill is achieved at initial medium temperatures as low as 80°C and a 30 s exposure. To achieve a much higher assurance of total insect mortality the tests were conducted at two temperatures with an exposure time of 60 s. A test at 100°C and at 110°C was conducted. To reduce the warm-up period of the Processor, the medium was heated to its initial temperature prior to the introduction of grain into the mixer, unlike in the convection/particulate medium study where grain was simultaneously loaded when the medium was being heated. Since the process controller was active in the PID mode, temperature stabilization was achieved at the point of grain loading into the mixer. The tests were carried out for 30 min or until all of the wheat samples were consumed.

b. Materials

The material used in thermal disinfestation using the Processor was wheat. The grain was purchased from the same supplier of grain in the other processing experiments. The wheat was destined as animal feed and has a moisture content of about 14% (w.b.). It was stored in a cold area for two weeks prior to the actual experiments.

The medium used in the tests was table salt. The salt has the same quality as those used in the preliminary thermal disinfestation experiments.

c. Methods

Prior to the experiments, the feed auger was calibrated to determine the actual flow rate of wheat through the machine. It was necessary to recalibrate the feed auger every time a test was conducted because a small change in grain moisture content tends to alter the auger feed rate. Flow rate of salt through the Processor was also calibrated to give a mass ratio of 4:1. This flow rate stays constant as long as the amount of salt in the heater was around 175 kg. Any change in media flow rate was made solely by adjusting the rotational speed of the heater. The speed of the heater was usually synchronized with the speed of the mixer to ensure a steady flow of particulates through the machine and prevent starving or bottlenecks in any component of the Processor.

While the flow rate of wheat and salt was being calibrated 1000 kg of wheat was equilibrated to room temperature. Two-30 min heating tests were conducted. One experiment was conducted at an initial medium temperature of 100°C and another at 110°C. In order to maintain a stable contact temperature between the wheat and salt, the process controller was set to monitor and control initial medium temperature with the probe corresponding to the outlet medium temperature of the heater. To avoid problems associated with storing heated wheat after treatment, the cooling cylinder of the Processor was calibrated and set to cool grain for 3 min. After cooling, the grain was placed in plastic containers and stored in the cold storage.

During the experiments, temperature monitoring was done using the thermocouples installed in the Processor. Two probes monitor inlet and outlet temperature of the salt in the heater, two probes measure the inlet and outlet temperature of grain in the mixer, one probe measures grain and salt temperature at the outlet of the mixer, and one probe measures the final grain temperature after aeration.

7.3.3 Results and discussions

During the experiments an initial period of adjustment lasting 5 min was observed. The process controller which regulate the medium temperature was adjusted until the temperature of the medium stabilized without the aid of the auxiliary burner. This was necessary in order to monitor the actual amount of energy the burner was feeding the machine. With the auxiliary heater cycling on and off to stabilize the temperature, no fixed energy input can be accounted for during the heating process.

a. Operating temperatures

Figure 7.6 shows the temperature profile generated with the medium at an initial temperature of 100°C. **Tmi** and **Tmo** plots the initial medium temperature and the medium temperature at the outlet of the mixer. **Tgi**, **Tgo**, and **Tga** shows the initial grain temperature, grain temperature at the outlet of the mixer, and its temperature after aeration, respectively. Although the medium was pre-heated to a value higher than the desired contact temperature, the Processor took 5 min to stabilize all its operating temperatures. The grain initially went up to a temperature over 80°C before dropping to a stable temperature around 70°C. The average grain temperature was 72.9°C with a standard deviation of 1.8°C. This value is 8°C higher than the desired grain temperature of 65°C where germination rate of the seed is not affected by the thermal treatment. The 8°C difference shows that a much higher flow rate could be accommodated by the Processor at

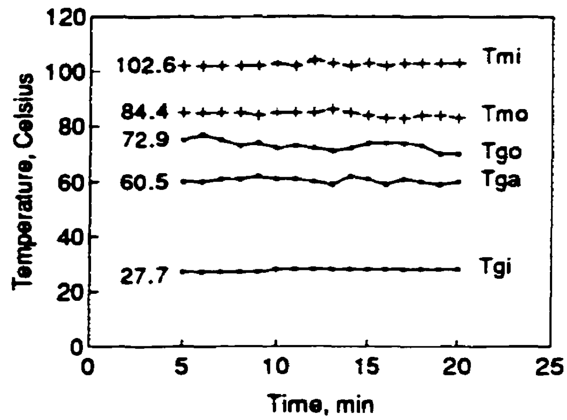

Figure 7.6 Temperature profile @ 100C

the machine settings used in the experiment.

With the process controller maintaining an almost constant initial medium temperature at around 102°C, all other temperatures maintained their readings. A 15°C difference in temperature exists between the salt and wheat as they exit from the mixer. A much higher feed rate could have lowered the temperature difference between the two particulates. However, since the salt was recycled after mixing the excess heat carried by the media was totally recirculated into the system thereby preventing any heat loss in the exiting media. The wheat experienced an increase in temperature of over 40°C, which was similar to the results of the treatment combination of 150°C-30 s in the preliminary study. After cooling in the aerating cylinder, the grain was unloaded from the Processor at 60°C.

At 110°C initial medium temperature, the Processor also showed stable operating temperatures after 5 min of operation (Figure 7.7). Although there was no change in the flow rate of the medium and the grain, it can be seen that there was a much bigger reduction in medium temperature. Furthermore, the final temperature of wheat after mixing was almost the same as those in the 100°C tests. Even the average increase in grain temperature was similar to that of the first test. The average grain temperature was 69.8°C with a standard deviation of 2.4°C. These results were unexpected since increasing initial medium temperature was supposed to further increase the final temperature of the grain. However, a detailed analysis of the chart showed initial grain temperature in the second experiment was around 4°C lower than the 100°C experiments. This factor may have affected the heating process. This effect could be better evaluated with the analysis of the heat utilization in the Processor.

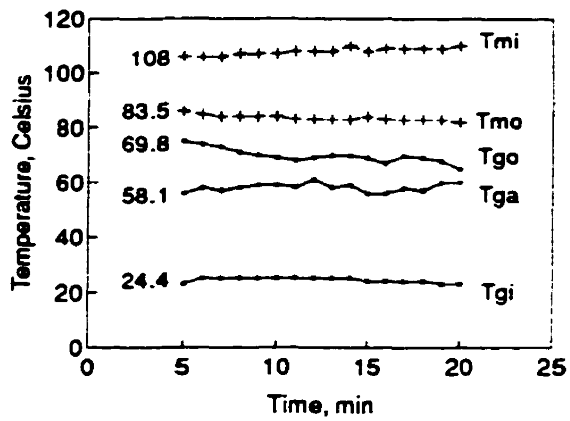

Figure 7.7 Temperature profile @110C

b. Heat utilization

Average operating temperatures were calculated by removing data from the initial 5 min of warm-up time and another 5 min before the machine was stopped. In the 100°C initial medium temperature, a drop in salt temperature of 18°C resulted in an increase in grain temperature of 45°C. While for an initial medium temperature of 110°C, the drop in medium temperature of 24°C resulted in an increase in grain temperature of 45°C. In both tests, the average increase in temperature was almost the same. As mentioned earlier, this could be the effect of lower initial grain temperature of the wheat in the second experiment.

The heat absorbed by the grain was calculated using the actual increase in grain temperature as the basis. With the known grain flow rate through the mixer and the specific heat of wheat at 14% (ASAE, 1989) which was 2.026 kJ/kg.K, the heat absorbed by the grain is 25.44 kW in the first test and 25.55 kW in the 110°C test. In the 100°C experiment, the flow meter setting was at 80 corresponding to a power input into the Processor of 52.5 kW. With this power input the overall heating efficiency was 49%. For the 110°C test, the flow meter was set to 90 corresponding to a power input of 59 kW. At this level of power, overall efficiency was calculated at 43%.

In the calculation of the heat absorbed by the grain, the amount of heat used in evaporating moisture was not included since the actual value taken from moisture determination amounted to less that 1%. The low moisture reduction was due to the lack of air movement inside the mixing chamber. The inlet and outlet spout of the mixer was properly sealed to outside air during mixing such that whatever moisture evaporation from the grain was retarded by the stagnant saturated air inside the mixing chamber.

The overall efficiencies generated in this study were significantly higher than those achieved in the convection/particulate medium study. The results are actually expected since in the former study it was observed that at all three levels of power input (10, 15, and 20 kW) the overall efficiency of the Processor increases with an increase in grain flow rate. This result was especially noticeable in the values for heating efficiencies where the difference in efficiency between flow rates at the same energy input was around 30%.

c. Cost comparison

Several studies on the economics of thermal disinfestation has shown that the cost of using the process was comparable to the current use of chemicals to control insect pests.

Evans (1981) evaluated several methods of thermal disinfestation and found the use of fluidized bed cost between Aus$0.40 to $0.50/t and using RF or microwaves costs around Aus$0.40/t. Thorpe et al. (1984) reported that the operating costs for spouted bed was similar to those of fluidized bed disinfestation which has been estimated at US$0.55/t. Another study conducted by Sutherland et al. (1986) found that fluidized bed using LPG costs Aus$0.75/t while those using natural gas could cost around Aus$0.56/t.

The cost of disinfesting wheat using the Processor was estimated and compared with the previous figures. For the continuous disinfestation at grain temperatures around 70°C, the cost of operating the Processor using Propane as fuel was between CAN$0.39/t to $0.75/t. These costs are comparable to those found using heated air methods such as spouted bed and fluidized bed disinfestors. Further studies should be done to improve this cost performance in disinfestation.

7.4 Conclusions

From the foregoing discussion, it can be concluded that thermal disinfestation of wheat is possible using the Processor. To maintain the viability of the seed and operate at a high efficiency, initial medium temperatures around 100°C were effective.

The two parameters that affected the performance of the Processor in thermal disinfestation were initial medium temperature and mass ratio between the particulates. High thermal efficiencies were achieved by loading the machine at relatively high flow rates to lower the mass ratio, and maintaining a totally closed mixing chamber. The stifling environment inside the closed mixing chamber not only improves the thermal efficiency of the process but may also enhance the disinfesting effect of the method. The overall efficiency of the Processor was shown to be much higher than those achieved in the preliminary disinfestation study as well as the convection/particulate medium experiments. Estimates of the cost of disinfestation using the method showed that it was comparable to heated air thermal disinfestation.

CHAPTER VIII
DE - GERMINATION OF WHEAT

8.1 Introduction

This chapter of the study deals with a special application of the Processor related to Agricultural Processing. It is a response to the need for reducing the proliferation of unwanted seeds in agricultural areas. This need is expressed in policies of Agriculture Canada that regulates the entry of grains and oil seeds into the country.

A special case where de-germination of seeds is required is seen in the bird feed industry. The demand for different varieties of seeds for feeding pet animals has grown steadily. As early as 1980, importation of these seeds has provided a lucrative business for specialty grain dealers. With concern over the entry of unwanted weed seeds into the farm areas, grains and oilseeds were required to be de-germinated before they could be imported into the country. As of this time there appears to exist no de-germination facilities in Canada (Belcan, 1996). Most of the specialty seeds entering the country in commercial quantity go through the United States where they are processed and re-exported here.

Another sector of the grain industry concerned about the control of unwanted seed species is the seed growers. Purity is the primary consideration demanded on seed quality grains. It is affected by the growth of weeds in farm areas cultivating grain destined as seed material. Two sources of unwanted seeds have been identified as major contributors to the proliferation of weeds. One is the airborne source where birds handle and drop seeds while flying, and bird droppings containing undigested seeds.

A much bigger source of weed seeds is animal manure used as a supplement to commercial fertilizer. The annual manure application to fields cultivated for cereal crops spread all of the undigested seeds into the farm. In the absence of processing before manure application, this practice is so far the biggest source of weeds.

With facilities for de-germination, underutilised materials removed as primary screenings in grain elevators can be employed in animal feed as well as bird feed. These screenings contain a mixture of broken grains and other seeds that are smaller than the seeds being processed. They have a very low commercial value. However, when processed properly, they can augment the protein source needed in animal production.

8.2 Objectives

This investigation is a first attempt at evaluating the potential of particle-to-particle heat transfer in the de-germination of grains and oilseeds destined for animal feed. The test material is seed quality wheat. Wheat was chosen because of its high germination capacity and smaller particle size. The high germination capacity of wheat will test the maximum level of temperature where total de-germination is achievable. The small particle size will lower the relative size ratio between the heating medium and the grain which in turn will test the separation capacity of the Processor.

Specifically, the work aimed to:

1. Process seed quality wheat in the Processor to determine seed viability when exposed to temperatures 40, 60, 80, and 100°C for 60 s.

2. Evaluate the effects of the thermal treatment on the seed after 3 days and 7 days in germination pads.

3. Determine any physical damage on the seed that may lower its quality after treatment.

8.3 Materials and methods

8.3.1 Materials

The grain seed used to test the de-germination potential of the Processor was wheat. It was purchased from Belcan Agrocentre located in Vaudreuil, Quebec. The material was clean and was destined for seeding in the next season. Moisture determination tests showed the grain to have a moisture content between 8% and 10% (w.b.).

The medium used in heating the grain was salt. It was of the same quality as those used in the disinfestation study. It has a uniform particle size, averaging 0.358 mm in diameter.

The Processor was modified to accommodate the small relative size ratio between the grain and the medium. Specifically the separation section of the machine was altered to allow the grain to be separated from the medium without any carry over of salt into the aeration cylinder. Further, the inlet chute of the aeration cylinder was modified to prevent the smaller wheat particles from falling through its perforations.

Temperature measurements used to monitor the operation of the Processor were obtained using a Cole Parmer thermocouple thermometer and a SCANLOG software to convert the data into delimited ASCII files. The data was transferred to a Packard Bell personal computer for recording.

8.3.2 Methods

One ton of seed quality wheat was purchased from the supplier. It was passed through an aspirator to remove impurities. The cleaned wheat was stored in a polyethylene bag for one week prior to the tests to equilibrate its temperature to ambient conditions in the room.

While the wheat was being equilibrated to room temperature, the separation section of the Processor was modified. A rectangular trough made of perforated sheet having 2 mm perforations was placed over the existing screen of the separator. The inlet chute of the aeration cylinder was modified by lining the inner surfaces with 0.5 mm thick galvanized sheet.

Before the experiment, the grain feed auger was first calibrated to deliver 500 kg/h with wheat that has been warmed up to room temperature. Then, the mixer was calibrated to a contact time of 60 s. The rotation of the heater was also adjusted to provide heated salt to achieve a 4:1 ratio.

The process controller which regulates medium temperature was set to regulate the outgoing grain temperature to ensure that the seed grain would be exposed to the desired temperature for a pre-determined contact time. This was done by connecting the thermocouple which monitors outlet grain temperature of the mixer to the input of the process controller.

To start the experiment, the data acquisition system was switched on and observed for any unusual readings. As soon as the temperature readings were found to be stable, the process controller was set to the desired grain temperature and the pilot flame of the burner was lighted. Feeding of wheat into the mixer was initiated and the main burner of the heater was fed with propane fuel. As temperature of both the medium and grain increased, it was monitored every minute to make sure no sensing problems occurred. Once the grain attained the set temperature and the process controller started cycling, three samples of 1 kg each were taken every 3 min. Once the last sample was taken for the set temperature, the controller was adjusted to the next higher temperature to be tested. While the temperature of the process increased to the next setting, the wheat samples were cooled down to room temperature. As soon as the next setting was attained and the process controller starts cycling, three samples were once again taken every 3 min and cooled down. The same process was repeated until the last setting of 100°C was attained and samples were taken.

After the last temperature setting was tested, all of the samples were lined up on top of a table for germination testing. From each of the three samples taken in each temperature setting, 100 full-bodied seeds were selected. The seeds were inspected for any damage incurred during thermal treatment. The seeds were spread in groups of ten over the surface of a germination paper. Another sheet of germination paper was placed on top and the sheets were rolled into a cylinder containing equally spaced sample of treated seeds. The cylinder was wetted with lukewarm water and placed inside a stainless steel canister containing a 12-mm level of water. All the other samples were processed the same way. The samples were checked for number of germinated seeds after 72 h of holding time.

Another set of samples was prepared right after the first batch of samples was made for the 72 h holding period. For this batch, the same method was employed to treat the seeds prior to their being held in the stainless steel holding tank. However, this time a 7 day holding period was observed.

The percentage germination was evaluated by counting the number of seeds that sprouted. Since the sample size was 100 seeds per test, replicated 3 times, the actual count showed the percentage of seeds de-germinated by the treatment. All of the counts were recorded and compared with samples for the 7 day holding period.

8.4 Results and Discussions

8.4.1 Process temperature

During the experiments, the performance of the Processor in controlling grain temperature instead of medium temperature was tested. Figure 8.1 shows the temperature profile generated during the test. It can be observed that at the lower grain temperature settings it takes longer for the Processor to attain the desired temperature. At higher temperatures, the setting was attained in a span of a few minutes. It was expected that using grain temperature to control the heating process would result in a larger time lag between sensing and actually regulating the temperature. However, this was expected to be constant over all the temperature settings.

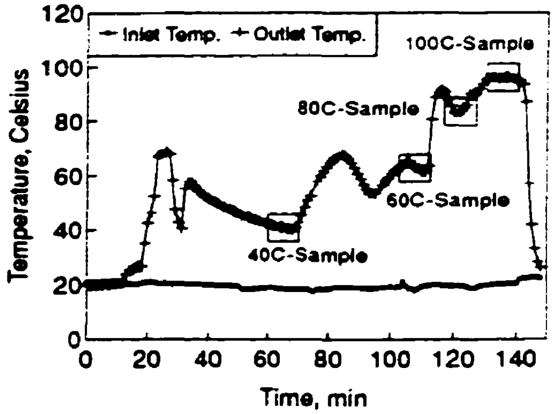

Figure 8.1 Grain temperature

This unusual result can be explained by the fact that the machine components were already heated during the switch to a higher temperature such that a minimal amount of heat was required to raise the operating temperature of each component to arrive at the set grain temperature. This results in more of the heat going toward heating the grain rather than increasing the temperature of the machine components. Although it was expected that higher operating temperatures would mean increased heat loss to the environment, this loss was very minimal as most of the heat input went into raising the temperature of the grain.

The temperature chart also showed a very distinct pattern initially observed in the convection vs. conduction experiments. The temperatures seem to increase to a certain value before it gradually lowers and stabilizes to the pre-set level. These findings show that although the process controller was set to run on Proportional Integral/Derivative (PID) control mode, the controlled parameter tends to overshoot the set value. This is a result of the big mass of medium that absorbs the heat that was consequently transferred to the grain to raise its temperature. The time lag between sensing, control action by the process controller, and the resultant increase in the grain temperature was totally due to the time lag in heating the medium and transferring the heat from the medium to the grain. At higher temperature settings, this time lag was reduced by the frequent cycling of the process controller due to the higher heat demand of the process.

8.4.2 Seed germination

Results of the germination tests on treated and untreated samples are shown in Figure 8.2. Both the result of the 72 h and 7 day holding periods are presented. As can be observed from the chart, the de-germination percentage was lower for the 40°C treatment than those samples that were not treated. It was expected that the seeds would respond otherwise. Even with the 7 day holding period, the average de-germination percentage was still lower at 40°C than the untreated sample. However, at this holding period, the difference was not significant.

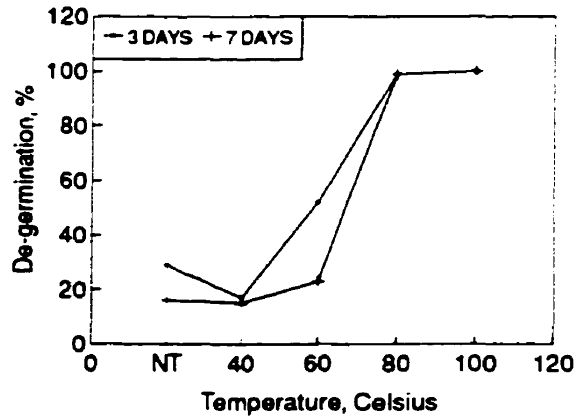

Figure 8.2 De-germination vs. temperature

A search for an explanation to this phenomenon showed that at the lower temperature of 40°C, the heat available was just enough to break the dormancy of the seed yielding a higher germination rate. Light heat treatment of wheat, corn, and legumes has been found to stimulate germination (Mohsenin, 1970). However, such heat treatment will endanger the germination and viability of the seed once the critical temperature or time of heating is exceeded. From the de-germination results seen here, it appears that for a 60 s contact time, the critical temperature for germination and seed viability is between 40°C and 60°C.

It can also be observed that both at 72 h and 7 days, the de-germination rate was the same at 80°C and 100°C, where the latter temperature showing 100% de-germination rate. This showed the Processor to be an effective de-germination tool at 100°C for a contact time of 60 s.

A visual inspection of the wheat seeds processed was also done to check for any discolouration, burning, or cracking of the seed as a result of the heat treatment in a heated bed of salt. The 100 seed samples used in the germination tests were inspected for any such problems and the results showed that no discolouration, burning or cracking occurred during the thermal treatments.

8.5 Conclusions

Based on these results, the following conclusions can be derived:

1. The germination and seed viability of wheat reaches critical temperature between 40°C and 60°C for a contact duration of 60 s.

2. Total de-germination of wheat was achieved at 100°C medium temperature.

3. There was no visual indication of damage to the samples by the thermal treatment to attain 100% de-germination.

It has been shown that the Processor is an effective de-germination tool for preventing the germination of wheat seeds when used as animal feed. Similar studies can be conducted to evaluate its performance on other grains destined for animal feed. Also, varying other operating parameters of the Processor to achieve the desired results at the most economical setting should be further studied.

CHAPTER IX
EPILOGUE

9.1 Recapitulation of the conclusions

This investigation was directed at evaluating the critical parameters involved in particulate medium thermal processing of grains and developing a fully functional continuous-flow particulate medium thermal Processor. The conclusions derived from the results of these study are summarized as follows:

9.1.1 Testing of the Processor

Heating time using the Processor was 5 times faster than a unit using convection heating.

Heating efficiency of the Processor was 87% greater than the convective unit.

Drying efficiency of the convective unit was 95% higher than that of the Processor

Overall thermal efficiency of the Processor was found to be 28% higher than that of the convective unit.

9.1.2 Particulate medium corn drying

Moisture reduction from the grain increased with an increase in initial medium temperature.

High initial moisture content resulted in lower grain temperatures at all levels of initial medium temperature.

A large proportion of the moisture removal in the processor occurs in the mixing section.

The highest value of moisture removal in the Processor was 6.17% (w.b.) with corn flow rate at 500 kg/h, an initial moisture content of 19%, and exposed to salt at 250°C for 60s..

9.1.3 Roasting of soybeans

A significant amount of moisture was removed from the soybean when mixed with high temperature particulate medium.

An average moisture reduction of 4.11% was achieved over 3 different medium temperatures. The moisture reduction was lower than published results by Tromp (14.2%).

The performance of the Processor in roasting soybeans at 500 kg/h was comparable with the capacity of the Roast-a-Tron (340 kg/h) and the Sukup Grain Toaster (364 kg/h).

9.1.4 Thermal disinfestation of wheat

The overall thermal efficiency in disinfesting wheat was between 43% and 49%.

The most important parameter which affected performance of the machine in thermal disinfestation was initial medium temperature.

The efficiency of the Processor was higher in disinfestation than those in the preliminary disinfestation study as well as in the convection/particulate medium experiments.

The cost of thermal disinfestation using the Processor is comparable with heated air thermal disinfestation data published in literature.

9.1.5 De-germination of wheat

The germination and seed viability of wheat reaches critical temperature between 40°C and 60°C for a contact time of 60 s.

Total de-germination of wheat was achieved at 100°C grain temperature.

There was no visual indication showing damage to the samples by the thermal treatment to attain 100% de-germination.

9.2 Contribution to knowledge

This study has made an original contribution to knowledge by analysing the existing body of knowledge on particle-to-particle heat transfer and synthesizing these information to develop a fully functional commercial-scale particulate medium thermal processor. This work has successfully elevated particulate medium heat transfer from a concept to a practical method of thermal processing grains, which to date have not been achieved by other researchers. The knowledge gained and the process involved in the development of the thermal processor constitutes an original contribution to the science of engineering as it responds to the challenge of agricultural processing. The contribution to knowledge can be summarized as follows:

1. The study showed that the Processor is 5 times faster in heating and 28% more efficient than a convective heater. However, it confirmed that limited moisture removal is achievable using salt as particulate medium in drying applications.

2. In a continuous flow particulate medium Processor, the initial grain moisture content and medium temperature influence the drying of corn.

3. Commercial scale roasting of soybeans was demonstrated with results comparable to existing roasting equipment in the market.

4. Thermal disinfestation using particulate medium heating is the most energy efficient application of the thermal treatments tested.

5. Particulate medium thermal de-germination is effective at 100°C initial medium temperature for an exposure time of 60 s.

9.3 Recommendations for further studies

The biggest problem encountered in this investigation was the limited amount grain for processing and the unavailability of freshly harvested grains for extended drying studies. In terms of the process and the equipment tested, the following suggestions should provide for interesting research in particulate medium thermal processing:

1. In this study, the instrumentation used were mostly manually controlled. The use of Programmed Logic Controls (PLC) for monitoring and control of process parameters will test the maximum performance of the processor in all of the intended applications.

2. The use of hygroscopic media should be thoroughly tested in order to improve the drying performance of the method. Use of natural zeolite was attempted but was stopped due to a very high level of attrition of the zeolite samples. A more dimensionally stable zeolite derivative has to be found to benefit from its favourable characteristics.

3. A detailed chemical analysis of roasted grains should be undertaken to determine the different effects of thermal treatment on the nutritional aspects of the grain . Feeding trials should be done to validate the results of lab-scale experiments on the benefits of roasting of animal feed.

4. Long term studies should be conducted on the combined drying and roasting of soybeans destined for animal feed. This aspect of the method's application could save a large amount of energy in storage and processing of soybeans.

5. Comparison of the quality attributes of the grain should be made between the conventional method and those using particulate medium thermal treatment.

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