THE UNIVERSITY OF MANITOBA

WHEAT DRYING AND THERMAL CONTROL OF INSECTS USING HEATED SAND

BY

CHIMANLAL MISTRY

A Thesis

Submitted to

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ABSTRACT

Investigations were carried out to dry wheat from 19 percent initial moisture content in a continuous flow dryer using sand as a heating medium.

The maximum moisture expelled was 2.5 percent in one drying pass when the sand temperature did not exceed 105°C, the sand to grain mass ratio was 5:1 and the wheat flow rate was 3 kg/min. Further moisture expulsion of 1 to 1.2 percent was achieved during cooling of the grain using a forced circulation of ambient air. The maximum moisture reduction during the two stage drying process was 4.1 percent. The optimum tempering time between the two stages of drying was observed to be two hours.

The drying of wheat from 19 percent initial moisture content using hot sand as a heat transfer medium was not accomplished without a slight decrease in baking quality. The germination quality of wheat dried with sand at 105°C was reduced from 98.7 to 88 percent.

Complete extermination of adult and larvae stages of the red flour beetle was achieved. Almost all saw toothed grain beetle adults were killed during the drying of wheat using sand heated to 105°C. A control sample contained 885 larvae of rusty grain beetles inside grain kernels but only 72 and 20 were observed in samples passed through the dryer.

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c	Specific heat of sand, J/^{o}C.kg.
ΔMC	Change in moisture content.
Δt	Change in temperature of sand, ^{o}C.
h_{fg}	Latent heat of vaporization of water from wheat, J/kg.
MC	Moisture content (wet mass basis).
MC_1	Moisture content of grain prior to conditioning (wet mass basis).
MC_2	Moisture content of grain after conditioning (wet mass basis).
MC_i	Initial moisture content of grain.
MC_f	Final moisture content of grain.
MC_{ff}	Moisture content of grain after external cooling.
M_w	Mass of water, kg.
η_d	Drying efficiency.
η_f	Fuel efficiency.
SGMR	Sand to grain mass ratio.
t_{gi}	Grain temperature before drying, ^{o}C.
t_{gf}	Grain temperature after drying, ^{o}C.
t_{gff}	Temperature after external cooling, ^{o}C.
t_{sf}	Final sand temperature, ^{o}C.
t_{si}	Initial sand temperature, ^{o}C.
W	Mass of water evaporated, kg.
W_g	Mass of grain, kg.
W_s	Mass of sand, kg.

CHAPTER I

INTRODUCTION

Ever since man began cultivating land to produce grain, storage has been an essential requirement. The main reason for storage is that grain production is seasonal and consumption is continuous. In modern times, storage is utilized to carry over grain for periods ranging from a few months to several years. For any storage period, the grain must be held with no appreciable deterioration of quality or quantity.

Wheat can be stored safely at moisture contents below 14.5 percent. It is not always possible to allow the crop to stand in the field until full maturity is reached and when the harvested grain will be at a safe moisture content for storage. During wet harvest seasons wheat is sometimes harvested at moisture contents as high as 20 percent. Losses due to shattering of grain in the field and due to wild life can be reduced by harvesting grain at damp and tough moisture levels. Grain drying enables earlier harvesting which in turn provides for a longer harvesting season and also more time for post harvest tillage (Friesen 1973).

Damage to grain during storage occurs due to interaction among physical (temperature, moisture content), chemical (oxygen content) and biological (respiration, post harvest maturity and sprouting) variables (Sinha 1972). Among these, temperature and moisture content combinations are critical in determining safe storage life.

Excessive moisture content coupled with high temperatures cause higher respiration rates in grain kernels and in the micro-organisms present in grain. Thus an environment is provided for insects and bacteria to flourish and further damage the grain bulk.

It is essential to dry grain to safe moisture levels so that storage without deterioration in quality will be assured. Solar drying is one of the oldest methods used to reduce the moisture content in grain and the system is still being employed in many developing countries. This system has a high labor requirement for spreading, stirring and collecting the grain. Control over the drying process is poor due to unpredictable weather conditions. Long rainfall periods or high ambient humidity over an extended period can cause a delay in drying. Such conditions, unfortunately, also encourage insect and mold growth as well as sprouting in grain (Khan 1973).

Alternatively, heated air drying has been used in the United States for over a hundred years (Foster and Peart 1976). In air dryers, the driving force in drying is the difference between the partial pressure of water vapor in the grain and in the drying air. These are of forced convection type with air being used to convey heat to the grain and to remove evaporated moisture. The low coefficient of heat transfer between air and the grain kernel results in extended drying times and in relatively low drying efficiencies.

Numerous methods have been tried by investigators to improve drying efficiency. Conducted heat drying using a granular medium is one of the methods that has been investigated. In this method a heated solid granular medium is used to transfer heat to the grain. A granular medium can be easily mixed and separated from the grain since it has semifluid characteristics. Its granular texture enables uniform heating of kernels. The granular material as an alternative to air provides an improved heat transfer coefficient while maintaining uniformity of heating and non contaminating characteristics to the grain (Raghavan et al. 1974).

One of the solid heat transfer mediums for drying grain is sand (Raghavan et al. 1974, Lapp et al. 1975, Manchur 1975, Mittal 1976). In addition to its low thermal conductivity (0.33 W/m^{o}C) (Parry et al. 1969), its granular texture provides uniform heating by effecting many point contacts with the kernels. The semifluid property enables thorough mixing and effective separation. A quantity of sand can be re-cycled repeatedly which conserves the unused portion of heat in the medium. This, coupled with the higher heat transfer coefficient between sand and grain was found to improve the overall efficiency (Mittal 1976). Moisture is removed from a grain kernel through diffusion and into the surrounding air by forced circulation.

Mittal (1976) investigated the feasibility of drying wheat at an initial moisture content of 17 percent using sand as the heat transfer medium. The overall objective of the current project was to investigate the use of sand as the heat transfer medium to dry wheat from initial moisture contents above 17 percent. The specific objectives were as follows:

1. To determine the temperature and sand to grain mass ratio for drying wheat at an initial moisture content of 19 percent without damaging baking and milling qualities.

2. To assess the effectiveness of using heated sand for thermal control of insects in wheat at the temperature and sand to grain mass ratio used for wheat drying.

3. To assess the effect of solid media drying on the germination of seeds.

CHAPTER II

REVIEW OF LITERATURE

2.1 Wheat Drying-Theory and Systems

2.1.1 Grain Drying Theory

Grain drying usually implies the removal of a relatively small amount of water from grain kernels. It is a process of simultaneous heat and mass transfer. Hygroscopic material such as grain contain moisture which is held within the material by physical and chemical forces.

The exact mechanism which is operative in holding water in the colloidal material of the grain kernel is not fully understood (Johnson and Dale 1954). According to Henderson (1952), the predominant fixing mechanism is adsorption, although solution, hydration, chemical combination and capillary forces are factors which may be present.

The grain drying process which usually reduces the moisture content to the range of 12-14 percent apparently involves the removal of both free and bound water. Bound water may exist under several conditions; liquid water in very fine capillaries exerting an abnormally low vapor pressure because of high concave curvature of the water surface, moisture in the cell or the fibre walls may suffer a vapor pressure reduction because of solids dissolved in it, water in natural organic structures in physical and chemical combination. The difficulty with which the water can be removed from the kernel will vary with the nature and moisture content of the solid. Free water on the other hand, exerts full vapor pressure and it is largely held in the voids of the kernel.

The transfer of moisture from the interior of the kernel to the drying medium surrounding it involves two steps; first the transfer of moisture as either liquid or vapor from the interior to the surface and second, the transfer of water vapor from the surface of the kernel into the mainstream of the drying medium (Badger and McCabe 1936).

When a kernel is at high moisture content the rate of drying is constant, until a definite moisture content is reached, after which the rate of drying steadily decreases and approaches zero at zero true moisture content. This behavior of the drying rate suggests the division of the process in two parts;

1. Constant rate period
2. Falling rate period.

The moisture content at which the constant rate period ends and the falling rate period starts is known as the critical moisture content. The falling rate of drying is observed in most cases during grain drying (Hukill 1954). The falling rate process can further be divided into two phases:

(i). When the moisture is steadily available on the surface for evaporation. In such a case the rate of drying is controlled by the availability of heat for moisture evaporation. The availability of heat in turn is mainly controlled by the difference in temperature between grain and the heating medium and the heat transfer coefficient between them. The rate of moisture removal can be increased in this phase of drying by increasing the temperature of the heat transfer medium.

(ii). When the moisture has to migrate from within the kernel to the surface by capillary movement or diffusion. As this process offers more resistance, the rate of drying is controlled by the rate of moisture movement to the surface.

The driving force in moisture migration during grain drying is the difference in vapor pressure. Grain can be dried in three different ways depending upon the method of providing heat (Oxley 1948).

(I) Ambient air and unheated grain.

(II) Heated air drying.

(III) Heated grain and ambient air.

(I) Ambient air and unheated grain.

This is a drying process by forced circulation of dry air. When the air is at a relative humidity below the equilibrium moisture content of the air and grain, it will pick up moisture when forced through the grain. But as grain and air are at the same temperature, very little potential for moisture migration exists. Thus this is a very slow process. This can be considered to be a forced ventilation process rather than drying.

(II) Heated air drying.

This is one of the most common methods of drying. The incoming hot air heats the grain through which it passes and the air leaving at the higher temperature can carry much more moisture than the ambient air entering the system; thus the air acts as a medium to supply heat as well as to carry away moisture. When ample heat and air are available, there is no limit to the amount of drying that can be carried out in a single stage. In this method of drying, since the air must supply heat to the grain, the grain is always cooler than the air and a temperature gradient develops from the centre of the grain kernel to the surface. A steeper temperature gradient is created within the grain mass between the points of entry and exit of drying air. In ordinary dryers, since relatively high temperatures are used, steep temperature gradients could be a source of trouble as moisture may be deposited in the grain as the drying air approaches the exit. These gradients can be reduced by having thin layers of grain and high air velocity. The arrangements are such that the air does not reach the thermal or humidity equilibrium with the grain so that the evaporation continues throughout the thickness of the grain mass. This results in very rapid drying but the thermal efficiency is very low.

(III) Heated grain and ambient air.

This is an alternative method of using heat for the drying of grain. The grain is dried very rapidly until it is cooled. Unfortunately due to the low specific heat of wheat, 0.46 cal/g^{o}C, at 19 percent moisture content (Disney 1954) grain carries so little heat it is not practical to remove much water in a single stage of drying.

It is possible to use heat very efficiently by applying it to the grain and not to the air. Here much of the heat is used to evaporate the moisture, though a small fraction is used in increasing the temperature of grain. This process was studied by Kelly (1941). He found that the greatest quantity of water that could be removed without exceeding the safe temperature limit was less than two percent. He also found that for each depth and temperature of wheat there is an optimum rate of air flow, which if exceeded, results in heat being wasted in warming up the air.

2.1.2 Conduction drying of grain.

The grain can be heated for drying by numerous methods, one of which is by using conduction as a mode of heat transfer. One of the popular and successful grain dryers is the radiator type. Grain to be dried passes over a series of hot metal surfaces and meets a counter current of unheated air (Oxley 1948). Since the grain kernels are warmed several times by the radiator surface and cooled by air, the process can be considered to be multi-stage drying. The air is also warmed by the radiators so that at the location where the grain enters the dryer, the conditions are those of the hot air and cold grain process.

Dermott and Evan (1978) have referred to heating by circulating the grain over coils of steam pipes for disinfestation in Australia from 1917 to 1919. Tests were carried out by Kelly (1941) to dry artificially heated wheat with unheated air. The wheat at approximately 16.6 percent was heated in a revolving drum to temperatures ranging from 50 to 68.9^{o}C. It was then dried using unheated air for 12 minutes. Moisture removal was 0.8 to 1.4 percent, increasing as the temperature of the wheat increased. It is interesting to note that in each test of drying 57 to 60 percent of the total moisture loss took place in the first minute of drying. On the other hand only 43 percent of the temperature drop occured during the same period.

Hall and Hall (1961) utilized conduction heating to dry corn from 35.8 percent moisture content. The shelled corn was dried on a 1 mm thick steel plate suspended above an electric hot plate. The plate temperatures of 40, 62.2, 87.2, and 109.5^{o}C, were used with air velocities of 0.126, 0.252, and 0.505 m/s delivered from an air compressor and natural convection of air. They observed that the rate of drying increased with an increase in temperature up to 110^{o}C. It was also observed that the natural convection of air was sufficient to carry away moisture evaporated from the corn dried on a heated plate.

Finney et. al. (1963) carried out a laboratory study of conduction drying of shelled corn. Investigations were conducted to determine the drying curves for shelled corn heated by conduction to kernel temperatures of 43.3, 60 and 76.7°C. Efficiency tests were conducted at 76.7°C with 3 different air flow rates:

(i) Normal convection currents 0.05 m/s,

(ii) A forced air velocity of 0.381 m/s and

(iii) A forced air velocity of 0.762 m/s.

They observed that the drying rate increased with the increase of temperature from 43.3 to 76.7°C. They found that the average efficiency of conducted drying decreased from 70 to 30.4 percent as the air flow passing through the drying unit increased from 0.05 to 0.762 m/s. Chancellor (1968a) constructed a simple rice dryer using conducted heat which consisted of a horizontal metal plate over a fire pit. The grain on the plate was stirred by a rotating arm for uniform heating of the grain. Tests were conducted using three depths of grain at approximately 12, 25, and 50 mm and three hot plate temperatures at approximately 71, 100 and 127°C. He reported that the rate of drying doubled with every 11°C increase in temperature. Although the rice dried by conduction had its germination destroyed, the process was found to produce a greater proportion of whole rice than was obtained from sun dried samples. Chancellor (1968b) found that the rate of moisture loss from grain was dependent upon the net rate of energy entry into the grain. In conduction drying the rate at which energy enters into the grain is expected to be much faster than conventional heated air drying. If this is true, the rate of drying will be much faster. But when this method was used, Chancellor observed that overheating occurred on some kernels which were in contact with the heated plate. He suggested that granular media could be used to uniformly heat the grain.

2.1.3 Grain drying using granular media.

Benson (1966) used agitated beds of heated salt to rapidly heat and puff cereal pieces in 20 seconds. Khan (1973) used heated sand to rapidly dry rice paddy at the same time accomplishing a parboiling effect. Sand temperatures ranged from 190 to 240°C, residence time was 15 to 60 seconds and 20:1 sand to rice mass ratio was used. Like Chancellor (1968a), he observed that viability of paddy seeds was destroyed. He concluded that increasing moisture removal beyond 2 to 3 percent per pass in this type of dryer would adversely affect the milling quality of paddy.

Mittal (1976) has referred to Iengar et al. (1971) who developed a continuous flow dryer using hot sand as a heating medium. In this dryer, sand was heated through a heat exchanger by burning paddy husks and other agricultural wastes. Simultaneous parboiling and drying occured when paddy was mixed with sand at 150^{o}C for 20 minutes.

Raghavan et al. (1974) reported in the study of heat transfer using fluidized beds,that particle to particle conduction accounted for 80-95 percent of the heat transfer; whereas the gas phase contributed very little. Fluidized beds produce better heat transfer coefficients than air. However, they lack uniformity in residence time control, and require special means to separate the granular heating medium from the grain being dried. Conduction drying involves heat transfer from particle to particle and differs from fluidized bed heat transfer since it does not involve air as a fluidizing medium. Particle to particle heat transfer can exchange large quantities of heat economically, uniformly and without producing contamination.

Raghavan and Harper (1974) constructed a continuous flow corn dryer. The dryer consisted of a rotary drum 61 cm in diameter with a length of 76 cm. A perforated helix inside the drum conveyed the product through the drum towards the open end. The relatively small particles of salt mixed with the product, and fell back through the perforations of the helix due to the inclination of the drum. The variation of drum speed varied the residence time for the product from 3 to 32 seconds. The product emerging from the drum was dropped into a forced air cooling unit. The cooling unit consisted of a drum, fabricated from wire mesh, driven by a variable speed motor. A blower was used to force the air through the drum to carry away moisture.

The temperature of salt ranged from 134.4 to 274.5°C and the residence time varied from 4.20 to 21.83 seconds. The feed rate of corn was from 10.96 to 2.68 kg/min. They concluded that a drying temperature of 232.3°C during 13 to 20 seconds residence reduced the moisture level from a range of 15 to 21 percent to a range of 12 to 14 percent. This drying was accomplished without substantial damage to grain quality.

Lapp (1973) reported on experiments which were initiated in 1972 to investigate the feasibility of using heated solid granular media to effect the rapid expulsion of moisture from rapeseed. Fine textured sand and steel balls of approximately 0.91 mm in diameter were used. Sand was heated to the required temperature in an electric oven and mixed in definite sand to grain mass ratios and placed in a bench dryer for timed intervals, then removed and separated by hand screening. Sand heated to 232.3°C was mixed in sand to rapeseed mass ratios of 2.5:1, 5:1 and 8:1 and placed in the model dryer for a residence time of two minutes. It was reported that a sand to rapeseed mass ratio of 2.5:1 reduced the moisture content of rapeseed from 17.6 to 13.3 percent, the ratio of 5:1 from 19.0 to 12.0 percent and 8:1 from 16.0 to 9.3 percent.

Initial successful trials led to construction of a prototype continuous flow dryer (Lapp and Manchur 1974). Oilseeds at initial moisture contents ranging from 11.5 to 15.0 percent were reported to have undergone moisture reductions from 3.0 to 4.5 percent during a residence time of

30 seconds. Sand entered the dryer at 157°C and left at 85°C. It was concluded that the drying of oilseeds using hot fine textured sand was effected rapidly at efficiencies ranging from 45 to 55 percent. Manchur (1975) reported that the viability of rapeseed was completely destroyed by various heat treatments during drying trials. The optimum sand to rapeseed mass ratio was found to be 3:1 with the sand temperatures ranging from 130 to 190°C. The drying of rapeseed was accomplished with the efficiencies up to 65.5 percent during these experiments.

Lapp et al. (1975) used heated sand as the heat transfer medium to accomplish gelatinization, drying and parching of wild rice. Encouraging results were observed when sand to rice mass ratios of 8:1, 16:1, and 24:1 were employed with the sand temperatures ranging from 150 to 250°C. Excessive quantities of popped and hollow kernels were observed following the drying trial runs at high temperature and high sand to rice mass ratios. Lower temperatures and reduced sand to rice mass ratios were used to reduce the occurence of popping and hollow centres. Wild rice was dried from 70 percent to 10 percent in six stages with sand heated to 150°C and sand to rice mass ratio of 16:1 in a bench model dryer.

Mittal (1976) carried out extensive experiments to determine the feasibility of drying wheat from 17.0 to 14.5 percent moisture content using sand as the heat transfer medium. He used both a batch loading bench model dryer and the prototype continuous flow dryer and concluded that:

i. It is technically feasible to dry wheat from approximately 17 to 14.5 percent moisture content using sand heated to 100°C and with a sand to grain mass ratio of 4:1 in two minutes.

ii. The quantity of moisture removed in solid media drying was proportional to the initial temperature of sand.

iii. The grain dried using sand to grain mass ratios less than 5:1 and temperatures below 105°C did not show a serious reduction in germination.

iv. A sand texture of 20-40, i.e. passing through a 20 mesh and retained on a 40 mesh sieve, removed a greater amount of moisture from wheat than sand textures of 12-30, 30-50, 40-60 and 60-100. The 20-40 texture sand also gave the highest drying efficiency of the different sand textures used.

v. A drying efficiency of 61.2 percent was reported for grain flow rates ranging from 2.5 to 3.5 kg/min using a sand to grain mass ratio of 4:1.

2.2 Safe Temperatures for Wheat Drying

It has been concluded by scientists and engineers conducting grain drying research that the efficiency and rate of drying increases with an increase in temperature. Wheat dried at a high temperature becomes case hardened and is more difficult to mill than normal wheat (Hukill 1954). The major parameters affecting the extent of heat damage in cereals are elevated temperature of the drying medium, the duration of exposure and the initial moisture content of the grain. An increase in any one of these factors will increase the probability of damage. Dermott and Evans (1978) reported that wheat at 12 percent moisture content could be held for up to 60 minutes at 64°C and for up to 24 minutes at 68°C before germination was impaired. Frost et al. (1944) found that the maximum temperature at which wheat could be heated without injury to either the milling or baking quality was 82.2°C.

During the drying process, the quality of grain undergoes certain changes. Gerzoi and Somochelov (1958) studied biochemical changes in dried wheat and found that the specific tensile strength of gluten was measurably reduced after drying at grain temperatures above 60°C. The rate of denaturation of protein increases considerably when grain was at an elevated moisture content level.

When grain is at a very high moisture level, at 30 percent or more in corn, high temperatures can be used for initial drying. The kernel temperature is held down by the rapid evaporation of moisture. But as the rate of evaporation decreases, the temperature of the drying medium must be reduced to avoid overheating of the grain kernels (Bunn 1970).

Bakker-Arkenna and Green (1977) reported that wheat at 17 and 19 percent moisture content can be heated to the temperatures of 60° and 64°C respectively without damaging the baking quality.

2.3 Thermal Control of Insects

2.3.1 Thermal death point of insects

The temperature at which an insect can no longer survive for a given duration of exposure varies from species to species. The temperature which an insect can resist is complicated by several factors, including humidity of ambient air, rate of ventilation, thermal history of the insect, size, age and stage of development.

In nature, an insect has a tendency to cool itself by evaporation. In humid air, the rate of evaporation is reduced affecting a lesser temperature depression and the insect can survive to a lower ambient temperature. This ability to survive is related to the size of the insect. Small insects have a very small volume to surface ratio and these insects cannot lose enough water to lower their body temperature appreciably. Thus for short duration experiments, say up to one hour, the humidity may not cause a significant difference in the lethal temperature. But for the experiments of longer duration, say up to 24 hours, the humidity level may have a definite affect. The insects may die of dehydration when the rate of evaporation is high. Therefore, during long exposures insects may resist higher temperatures longer in moist air than in dry air (Wigglesworth 1972).

It has long been recognized that the range of heat tolerance is subject to change, according to the insect's acclimation to their ambient temperature. Baldwin (1954) determined the tolerance limits of the parasitic insect Dahlbominus fuscipennis reared at 17, 23, and 29°C. He found that the 50 percent mortality point for insects reared at 29°C was significantly higher than for those reared at 17°C and 23°C. He also found that the insect's resistance to higher temperatures declined with age. The temperature rise of insects is associated with an increase in the rate of their metabolism. The rate at which oxygen is consumed indicates the rate at which the food reserves are expended. Thus, at elevated temperatures, starvation could be the cause of insect death (Bursell 1970). The increase in rate of air flow over the insects also increases the thermal death point of insects (Baldwin 1954).

2.3.2 Elevated temperatures as a means of disinfestation

The use of high temperatures for extermination of insects is a very ancient process accomplished during solar drying. In some areas of the world a large concrete slab is placed near the site of grain storage and used for solar drying of crops.

Dermott and Evans (1978) have referred to disinfesting wheat of rice weevil (Sitophilus oryzae) and other pests in Australia from 1917-19. They recommended that wheat should be heated uniformly to the range of 60-66°C and held at these temperatures for at least 3 minutes. The wheat was circulated over coils of steam pipes in a continuous flow machine. The average residence time was 15 minutes and wheat was discharged at 60°C. Kirkpatrick and Tilton (1973) have referred to utilization of elevated temperatures to control insects in a flour mill. Hot air recirculated from steam radiators maintained the temperature of the flour mill at 49-51°C for 10-12 hours. This method was found to be economically feasible and the heat had no adverse affect on the baking quality of wheat flour.

The majority of recent work on thermal disinfestation of grain and cereal products is through radiant heating process such as microwave, infrared and dielectric heating (Frost et al. 1944, Kirkpatrick and Tilton 1973, Kirkpatrick 1975a, Kirkpatrick 1975b and Watters 1976). It appears that the cause of insect death as a result of exposure to infrared and microwave radiation is due to an increase in body temperature (Frost 1944). In most of these processes, infested grain is heated to the range of 48 to 85°C within intervals of a few seconds to about 3 minutes and then allowed to cool at a slow rate. Thus, although the insects were subjected to the maximum temperature for a brief interval, they were subjected to a considerable period of above optimum temperatures during the passive colling period (Dermott and Evans 1978).

Kirkpatrick and Tilton (1973) conducted a study to determine the effect of a 4 days exposure to adult rice weevils (*Sitophilus oryzae*) and lesser grain borer *Rhyzopertha dominica* of known age to temperatures of 39±1 and 42±1°C. Different relative humidities were maintained in the range from 50 to 75 percent. They have reported that little or no mortality has occured for rice weevils at 39±1°C and 75 percent relative humidity. When the relative humidity was lowered to 60 percent, they reported that, 100 percent control was obtained. In the case of lesser grain borer only 8 percent mortality was effected at 39±1°C and 60 percent relative humidity. Temperatures ranging from 42 to 44°C with 50 percent relative humidity were maintained to achieve 99.7 percent mortality of lesser grain borers. Further investigations were carried out by Kirkpatrick and Tilton (1973) to determine the effect of 39±1°C and 60 percent relative humidity on various stages of development for rice weevils and lesser grain borers. In rice weevils, 100 percent control of both the egg and larval stage was reported. Lesser grain borers were less susceptible to these conditions as 9.5 percent of the eggs, 0.9 percent of the larvae and 35 percent of the pupae and pre-emerged adult stages survived.

Watters (1976) determined the susceptibility of confused flour beetles (*Tribolium confusum*) to microwave energy. Wheat at 15.6 percent moisture content was exposed for 105 seconds to achieve complete control of confused flour beetles. The temperature of 60°C caused the death of all life stages of the confused flour beetle. He also reported that wheat at a higher moisture content absorbs heat at a faster rate.

Dermott and Evans (1978) evaluated the fluidized heating of wheat as a means of disinfestation. Wheat at 14 percent moisture content containing all immature stages of rice weevil, lesser grain borer and angonmois grain moth were exposed to air at 60,70, and 80°C flowing at the rate of 0.15 m^3/s at 1.6 m/s velocity. Exposures for 4, 6, and 12 minutes, respectively, produced the grain surface temperatures of 59, 62 and 65°C respectively. This gave almost complete disinfestation and the process did not adversely affect the baking quality of wheat.

Mittal (1975) investigated the feasibility of using heated sand as an insect control media. Grain infested with ruty grain beetles (Cryptolestes ferrugineus) was tested at temperatures ranging from 100 to 105°C with residence time of one and two minutes. The tests were carried out in a batch dryer with 4:1 and 4.5:1 sand to grain mass ratios. A 50 g sample of infested wheat was mixed with 450 g of wheat at 17 percent moisture content. He reported that almost complete control of all stages of rusty grain beetle was achieved. In the continuous flow dryer, 50 g of grain containing all stages of rusty grain beetles was placed in cloth bags and sealed. These bags were introduced at the inlet of the drying section while the dryer was in operation. A sand temperature of 105°C and sand to grain mass ratio 4:1 and 4.5:1 were used. The effects of both single and two stage drying were observed. An experiment was also carried out at 115°C with 4:1 sand to grain mass ratio. He concluded that one stage heating at 105°C was effective for killing adults but not effective in killing immature stages. One stage heating at 115°C was as effective as two stage heating at 105°C, which caused a significant decrease in the population of immature rusty grain beetles.

CHAPTER III

EXPERIMENTAL METHODS AND MATERIALS

3.1 Batch Loading Bench Model Dryer

3.1.1 Description of the bench model dryer

A batch loading bench model dryer was constructed by Lapp et al. (1975) to investigate the feasibility of drying, gelatinization and parching of wild rice using a solid heat transfer medium.(Figure 3.1) The main component of this dryer was an aluminum bucket 29.3 cm inside diameter and 22.9 cm deep. The inside volume of the bucket was approximately 0.0154 m^3. This bucket had a removable lid and was equipped with quick release clamps on the outside to facilitate rapid placement and removal of the lid during the drying trials. The entire bucket was enclosed with a 5.1 cm thickness of high density asbestos thermal insulation. The insulation was protected on the exterior by a covering of galvanized sheet metal. Two 1.3 cm diameter vents located radially from centre were placed in the lid to permit the escape of moisture. One of these vents was also used to insert a small propane torch for preheating the drying bucket. A third hole in the centre of the lid carried a glass thermometer to measure the temperature inside the bucket.

The bucket assembly was mounted on a supporting yoke carried by a floor stand 0.9 m high. The yoke had an angular

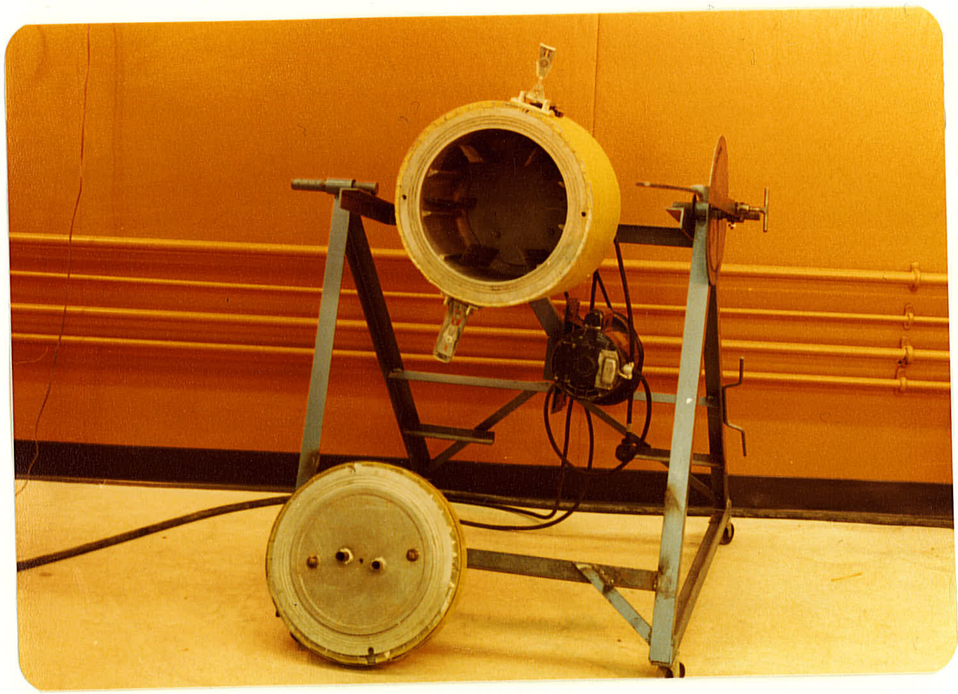


Figure 3.1 Bench Model Batch Dryer Using Sand as a Heating Medium

adjustment with a control quadrant to permit selected positioning of the bucket from vertical for loading, to horizontal for operating and to a steep downward tilt for emptying. A 186 Watt, gear head electric motor transmitting power through a matched pair of three-step pulleys provided rotating speeds of 24, 32, and 40 rev/min. A cage containing six mixing blades extending 3.8 cm from the wall and 22.8 cm long was fabricated and installed inside the drum to improve the mixing action of sand and rice.

3.1.2 Testing procedure of batch dryer

Silica sand having 20:40 texture (0.84 to 0.42 mm particle size) was used in the drying trials on the batch dryer. Sand having 20:40 texture means sand having particles which pass a 20 mesh (20 openings per 2.54 cm length) screen and retained on a 40 mesh (40 openings per 2.54 cm length) screen.

Auxillary laboratory equipment used to conduct the experiments included a sieve for separating grain and sand, thermometers, a mettler balance, a propane torch, an electric oven, enamel sand trays, asbestos gloves, petri dishes and a stop watch.

Experimental procedure.

A 500 g mass of wheat conditioned to the required moisture content was taken as a base. The mass of sand was varied to achieve the required sand to grain mass ratio. The predetermined weight of sand was then poured into an enamel tray and placed in an electric oven for heating to a selected temperature. It was observed that water accumulated on the bottom of the drying bucket while the drying bucket was preheated with a propane torch, installed to discharge heat through one of the ventilating holes provided in the lid. Moisture produced during the combustion of propane was condensing on the inner surface of the drying bucket. To avoid this problem, sand heated to 110^{o}C in the continuous flow dryer was used to preheat the drying bucket. Approximately 3 kg of heated sand was poured into the bucket while it was in a vertical position. The lid was then replaced and the bucket was allowed to rotate for 3 minutes, in a horizontal position, prior to discharging the sand.

Sand heated to the selected drying temperature in an electric oven was then placed in the drying bucket. The 500 g mass of conditioned wheat was then added and the lid was quickly replaced and clamped into position. The bucket was then moved to the horizontal position and the drive motor was switched on. The stop watch was started as soon as the bucket was turned to the horizontal position and the drive engaged. After allowing the bucket to rotate for the required time, it was turned to the vertical position to allow the lid to be removed and then tilted to discharge its contents into an enamel tray. The sand and grain were separated using a hand sieve and the temperature of each was measured. The moisture content of the dried wheat was determined following each trial (Mittal 1976).

3.2 Continuous Flow Wheat Dryer Using Sand as a Heating Medium.

3.2.1 Description of the continuous flow dryer

The continuous flow dryer used for conducting experiments consisted of a 3.05 m length of a rotating drum having 43.2 cm inside diameter (Figure 3.2). The length was divided into a 1.22 m insulated drying section, a 0.61 m screened separating section and a 1.22 m cooling and delivery section. The motion was transmitted through a small pinion gear meshing with a large ring gear welded to the outside of the cylinder. The rotating speed of the cylinder was varied using a variable speed reduction system driven by a 250 Watt electric motor. The drum rotated on six 7.6 cm diameter calsonite rubber castors. The castors supported the rotating drum through three roller guides. Adjustment bolts were provided on the roller guides to align the three roller guides and the ring gear into the same cylindrical plane. This would enable the ring gear to run true and mesh with the pinion gear while the roller guides were in contact with the rubber castors. The pinion gear was mounted on rubber to allow for deflections which would occur if any eccentricities remained in the system.

The screened separating section consisted of 10 mesh galvanized steel wire cloth having a wire diameter of 0.6 mm. The sand after being separated, was recirculated through a 3.05 m bucket elevator and a 15.2 cm diameter fibreglass insulated pipe to the sand heating hopper. A special high

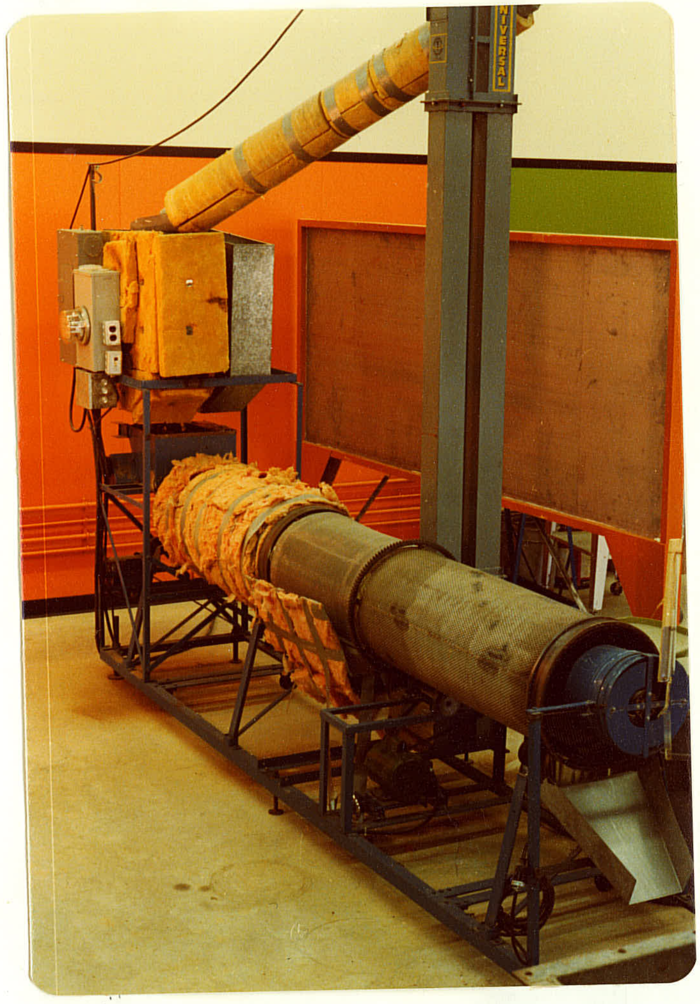
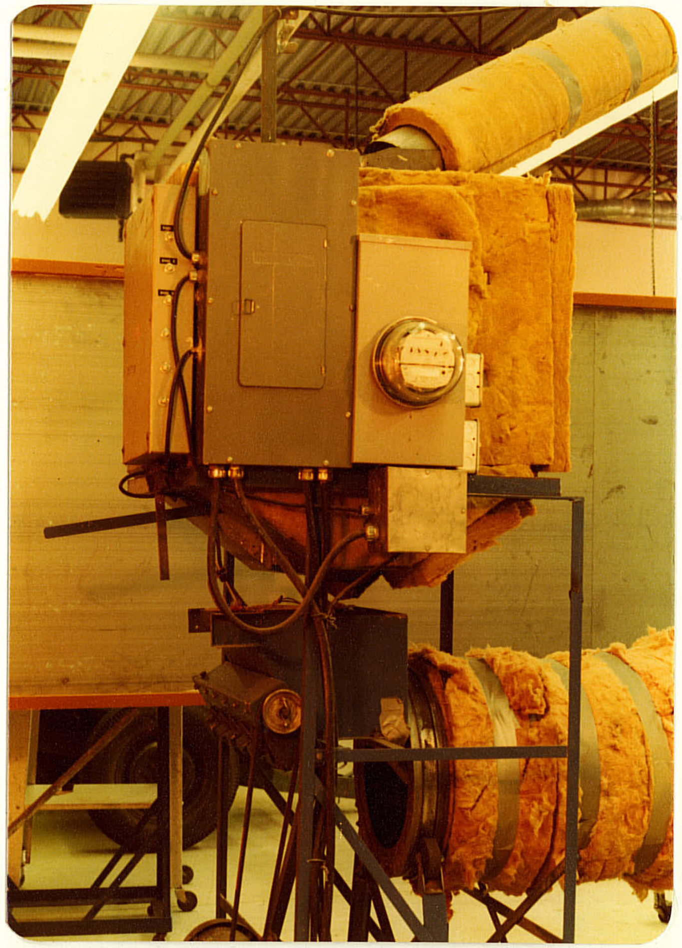


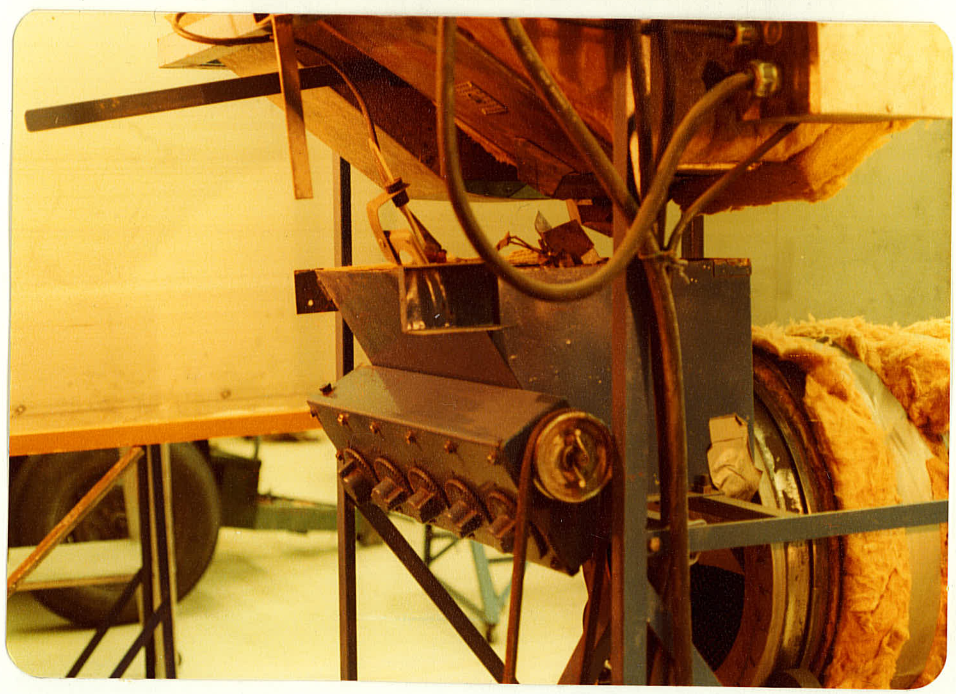
Figure 3.2 Continuous Flow Dryer Using Sand as a Heating Medium

temperature resistent belt was used in the elevator leg because of high sand temperatures.

Two hopper bottom tanks were mounted at the inlet of the drying section, one for damp grain and one for hot sand. The capacities of these grain and sand tanks were 1.32 and 0.84 m^3 respectively. The hoppers delivered sand and grain into a mass and volume feed mixing metering head. The sand tank was insulated with a 5.1 cm thickness of rigid fibreglass. Ten 230V, 2 kW calrod heating elements were installed in the sand tank to provide energy for heating the sand. The heating elements were connected in four separate circuits having one, two, three and four heaters in each circuit. Each circuit had a separate circuit breaker. This arrangement permitted the selection of the required number of heaters from one to ten. A thermostat switch was installed to avoid overheating of the sand. It switched off the circuit having four heaters if the temperature of the sand exceeded the preset temperature. The sensor for the thermostat switch was installed in the section of the metering head which received sand from the sand tank.

The metering head was a component of a conventional livestock feed ration mix mill (Figure 3.3 and 3.4). It was driven by a separate 250 Watt electric motor. The metering head was calibrated to deliver the required amount of sand and grain into the drying section so that the required sand to grain mass ratio could be maintained. Adjustable legs were mounted on the frame of the machine to control the inclination of the





Figures 3.3 and 3.4 Inlet End and Metering Head of the Continuous Flow Dryer

rotating cylinder. The frame was also provided with castors for moving the dryer from place to place.

The residence time in the drying section could be controlled by varying the slope of the rotating cylinder, the rotational speed of the cylinder and the feed rate. Mixing and axial movement of sand and grain was assisted by small, gently curved spiral flights attached to the interior of the cylinder in both drying and cooling sections. A fan having a capacity of 17 m^3/min was installed at the end of the cooling section. The fan supplied air to carry away the moisture expelled in the drying section and facilitated cooling of grain in the cooling section. Two semi-circular metal sheets were provided at the inlet section of the fan to regulate the air flow (Lapp and Manchur 1975, Manchur 1975, Mittal 1976).

The sand used as a solid granular medium for drying wheat was of 20:40 texture. 20:40 texture means the sand passing through 20 mesh sieve but retained on a 40 mesh sieve. The sieve analysis of sand used is indicated in Appendix 1. The fineness modulus of sand was 2.29.

This investigator designed and installed a cooling system on the machine to accomplish more effective grain cooling along with further moisture removal (Figure 3.5). The main component of the unit consisted of a 20 cm diameter cylinder 100 cm high. It had a false conical bottom fabricated from galvanized steel wire cloth of 10 mesh and 0.6 mm wire diameter. The cooling air entered the cylindrical section 30 cm above the

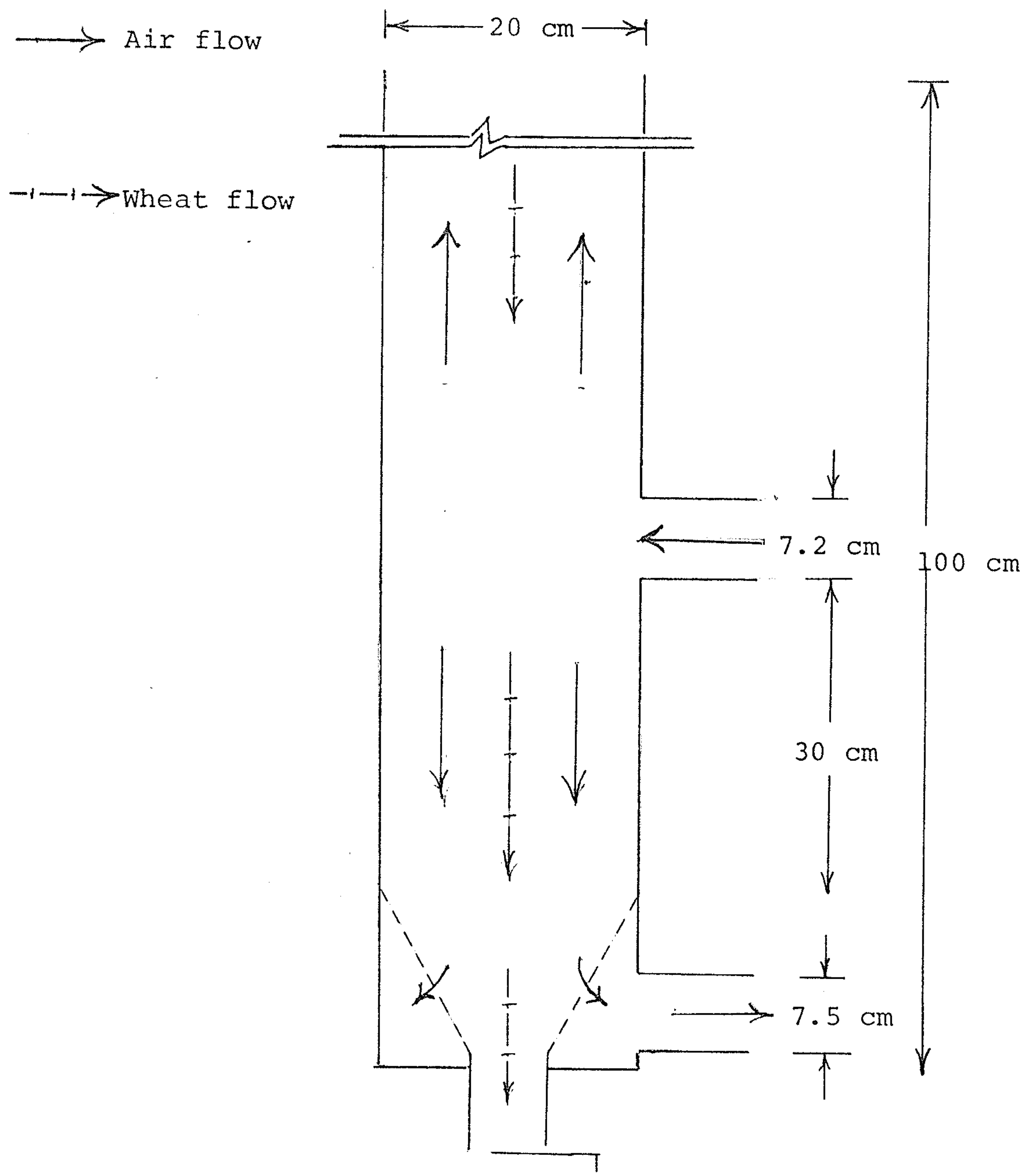


Figure 3.5 Schematic Diagram of The Additional Cooling System

top of the false conical bottom. A sliding gate at the bottom of the unit controlled the rate of wheat flow. The grain coming out from the rotating cylinder was elevated and discharged into the cooling unit through an auger.

3.2.2 Testing procedure for the continuous flow dryer.

The adjustable legs on the frame of the dryer were set for a drop of 6 cm in the 305 cm length of frame. The cylinder slope was approximately 1.13 degrees. This setting gave a residence time for the sand and wheat mixture in the drying section of approximately one minute when the cylinder was rotated at 11 rpm.

The metering head had four openings. Two were used for sand, one for grain and one was blocked off. This enabled individual control of the sand and grain flow rate. The metering head was calibrated by weighing the amount of sand or wheat delivered over a period of one minute. The calibration curves were found to be linear as shown in Figure 3.6 and Figure 3.7. The gear settings to achieve the desired flow rates of grain and sand were determined from these calibration curves.

Some of the heaters were switched on to preheat the sand to the desired temperature. The required flow rate was set and the dryer was operated so that the hot sand could circulate to preheat the dryer prior to drying trials (Manchur 1975). The damp wheat was then metered into the throughput flow at the desired rate and the desired parameter

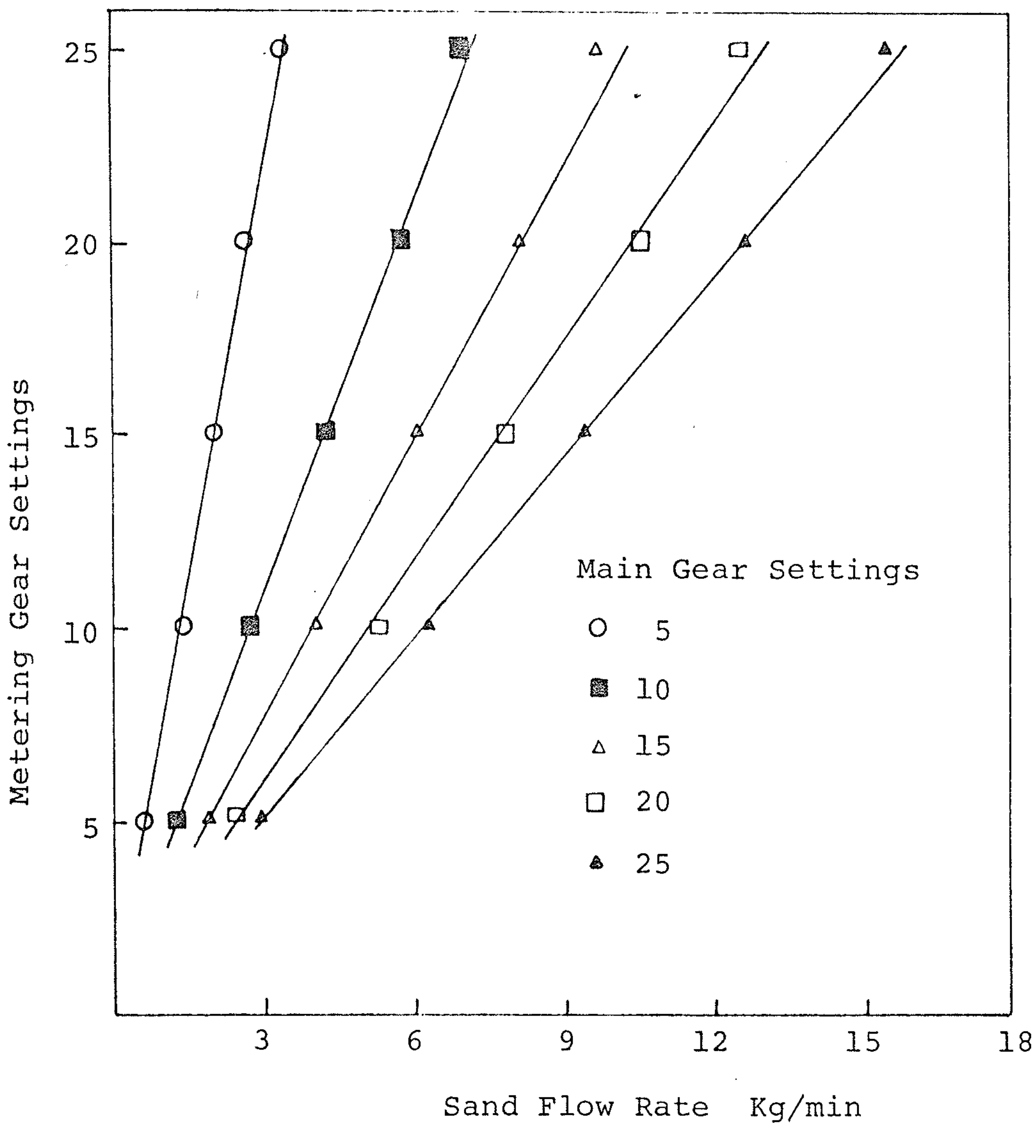


FIG. 3.6 Flow Rates of Sand (20:40) for Various Settings of the Metering Head and the Main Gear

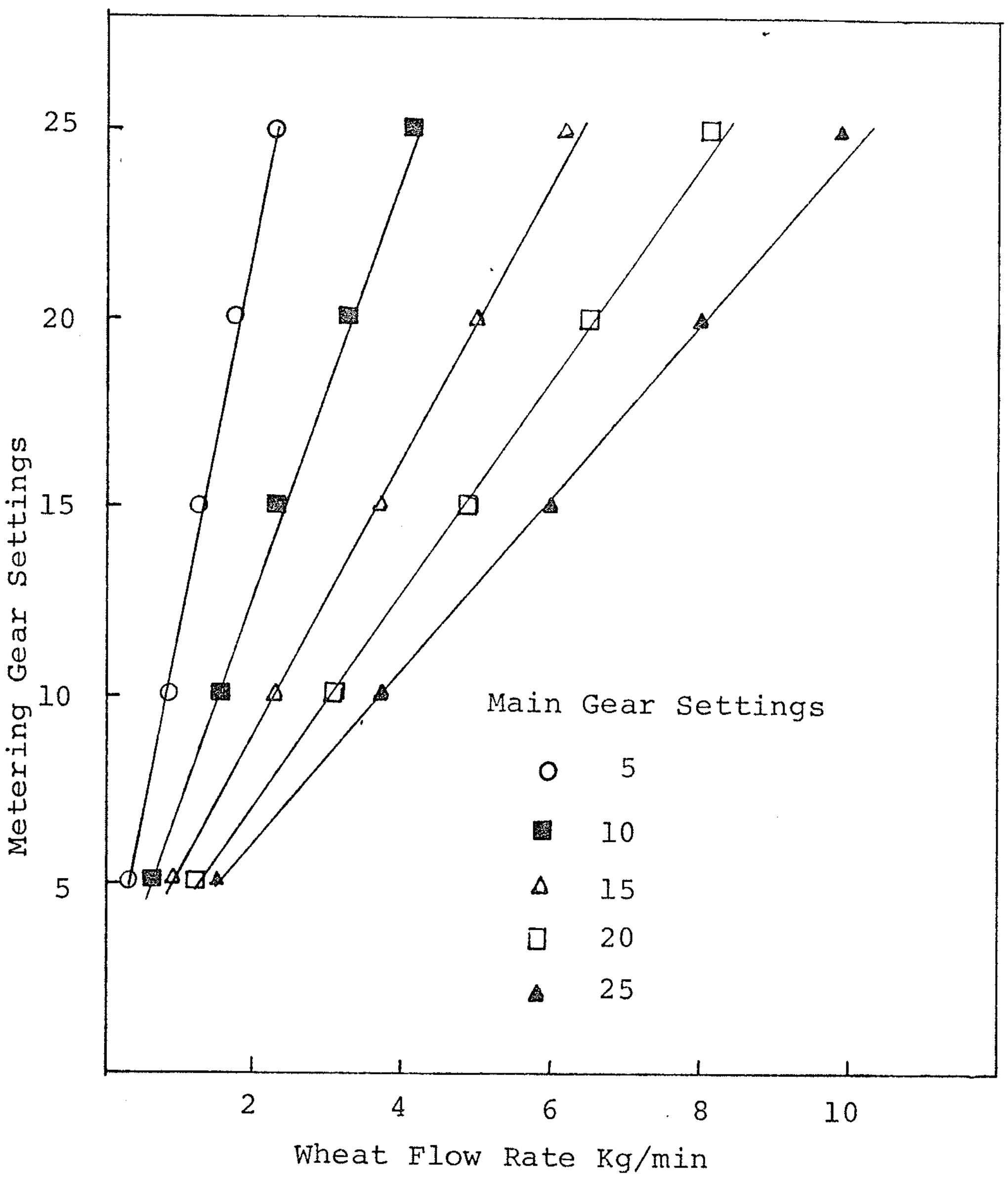


FIG. 3.7 Flow Rates of Wheat (18.8% MC) for Various Settings of the Metering Head and the Main Gear

values were measured or determined.

The temperature of sand was measured at 3 different locations using mercury-in-glass thermometers. The temperature (t_{si}) of sand entering the drying section was measured by a thermometer installed in the section of metering head controlling the sand flow rate. A thermometer installed in the elevator leg's boot hopper collecting sand from the separating screen indicated the temperature (t_{sf}) of sand upon completion of the drying process. The temperature (t_3) of sand entering the sand tank was measured by the third thermometer. The temperature of grain discharged from the rotating cylinder was measured by placing a thermometer in the bin collecting the dried grain. The temperature and humidity of the ambient air was measured by a wet and dry bulb thermometer installed at the air inlet section of the fan.

The temperatures in the cooling unit were measured at five locations using copper-constantan thermocouples. These temperature measurements included that of the inlet air, exhaust air at the bottom of the tower, grain temperature at the outlet, 30 cm and 60 cm from the bottom of the screen. All thermocouples were connected through a switching box to a model 590 TC Digitec digital thermocouple thermometer. Temperatures were displayed directly in degrees Celcius, with a repeatability and resolution of 0.1^{o}C. The temperature and humidity of the exhaust air at the top of the cooling tower were measured with wet and dry bulb mercury-in-glass thermometers.

Each test through the continuous flow dryer was carried out for approximately 15 minutes. Electrical energy consumption was measured using a watt hour meter. Wheat samples from three locations, entry to the dryer, discharge from the rotating cylinder and discharge from the cooling unit were taken at 5 minute intervals for moisture content and temperature determinations. Each sample was approximately 1 kg mass collected by random sampling during each test. All samples were taken to the Grain Research Laboratory of the Canadian Grain Commission, Winnipeg, for baking quality and protein content determinations. Various parameters controlled were:

(i) Sand temperatures of 100°C and 105°C were maintained during the first stage drying tests while 105°C, 100°C and 95°C were applied during second stage drying trials.

(ii) Grain flow rates of 1.5, 2.5, and 3 kg/min.

(iii) Sand to grain mass ratios of 3:1, 4:1, 5:1 and 6:1.

(iv) Air flow rate of 4.85, 10.17 and 17 m^3/s.

(v) Tempering times of 15 minutes, 2 hours, 1 day, 2 days and 10 days were allowed.

Wheat was conditioned to an initial moisture content of approximately 19 percent, sand used had a texture rating of 20:40 and a residence time of 1 minute was kept constant throughout the trials.

3.3 Grain Conditioning.

The grain was conditioned to the desired initial moisture content by adding a measured quantity of water to the wheat. The amount of water required was calculated using the following relationship:

$$M_w = \frac{(MC_2 - MC_1)W_g}{100 - MC_2}$$

where M_w = Mass of water

MC_1 = Initial moisture content (wet mass basis)

MC_2 = Desired moisture content (wet mass basis)

W_g = Initial mass of grain

The moisture conditioner (Figure 3.8) used for conditioning small quantities of grain for trials using the batch loading dryer was described by Mittal (1975). A metal drum 28 cm diameter and 38 cm long mounted diagonally on a horizontal shaft was the main component of the unit. The shaft was driven by a 95 Watt gear head motor imparting rotation to the drum and mixing of the grain inside. The calculated mass of water required to raise the moisture level of the grain mass was added to the wheat in the drum and allowed to mix for 30 minutes. As suggested by Ghaley et al. (1973) and Warner and Brown (1962), the wheat after conditioning was stored in sealed plastic bags in a refrigerator for at least four days to insure a uniform moisture distribution throughout the grain sample. The grain was removed

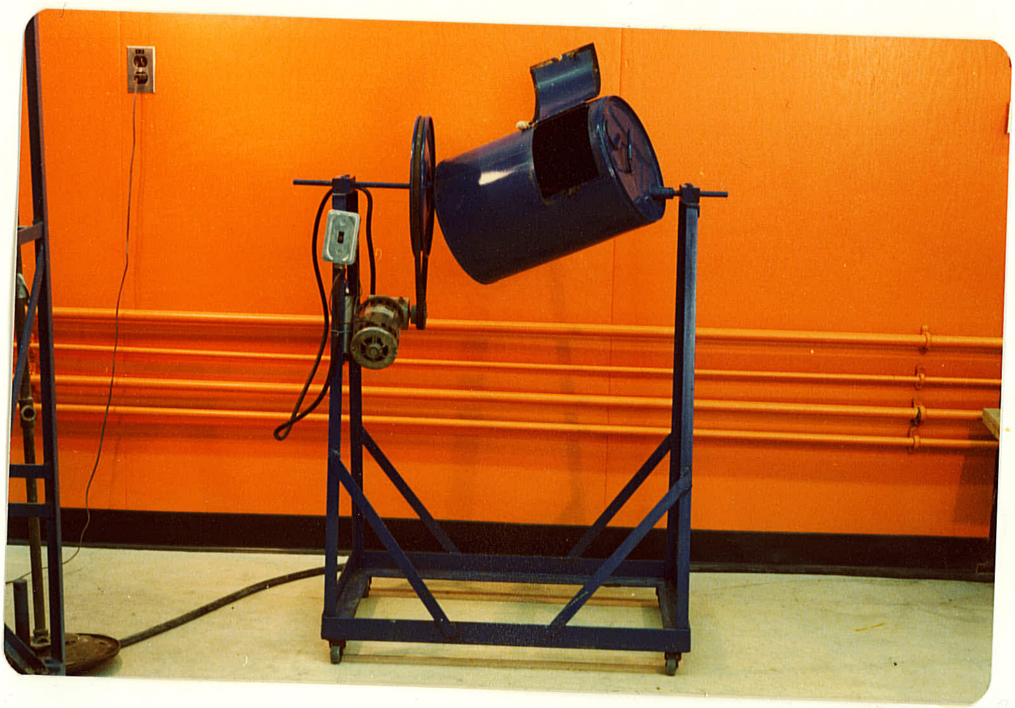


Figure 3.8 Grain Conditioner to Obtain Desired Moisture Levels for the Bench Model Batch Drying Trials

from the refrigerator and held at room temperature for at least 24 hours prior to drying (Johnson and Dale 1954).

The grain for the continuous flow dryer was conditioned using a small concrete mixer of approximately 0.23 m^3 capacity. A 20 kg mass of wheat was placed in the mixer and the calculated amount of water was added in two to three parts at 5 minute intervals while the mixer was in operation. The mixer was allowed to run for approximately 30 minutes. The conditioned grain was then placed in 40 kg capacity drums and stored at room temperature for at least 5 days. The grain was mixed for a brief interval daily to ensure uniform distribution of moisture.

Artificial moistening of grain has sometimes been criticized since the grain is not typical of freshly harvested grain (Mittal 1976). The naturally moistened wheat received for drying may be extremely variable in moisture content, whereas wheat dampened by the above described procedure is at least consistent. Studies conducted by Hustrulid (1963) indicated that there was no significant difference in drying rates of naturally moist and remoistened grain.

3.4 Grain Moisture Measurement

Moisture contents are reported on wet mass basis in this thesis. The moisture content of grain was measured with a mini Protimeter. This moisturemeter had a readability of 0.1 percent and accuracy of ± 0.2 percent. The meter was checked for accuracy according to ASAE standards (A.S.A.E. Yearbook, 1979) by maintaining the sample at 130°C for 19 hours in an electric oven and the calibration was checked prior to each test run. To ensure continuing accuracy, the meter was checked periodically during experiments against the oven drying method.

3.5 Quality Tests

Quality in wheat or flour is a relative term. Wheat or flour can be judged good or poor by comparing with some specific standard. No wheat has all the desired characteristics, so the term quality is used to describe the suitability of wheat or flour to produce specific end products such as bread, pastry, cakes, macaroni or crackers (Pomeranz 1971). Hard red spring wheat was used for all experiments conducted for this thesis. The quality was evaluated for milling and baking properties that determine the suitability of wheat for bread production. Good baking quality for bread is due to retention of carbon dioxide in cells resulting from yeast growth. This gas retention in turn is due to gluten formation properties of protein in wheat flour (Swanson 1938). When wheat is heated above 60°C, the protein is subjected to denaturation and coagulation. As a result, the gluten formation quality of protein declines (Pomeranz 1971).

A mixograph was used in the Canadian Grain Commission's Research Laboratory to assess the quality of the dried wheat samples. The mixograph, a physical dough testing instrument, measures the plasticity and mobility of dough that is subjected to prolonged relatively gentle mixing at a constant temperature. Resistance offered by the dough to mixing blades is transmitted to a pen that traces a curve on the chart.

Samples of wheat subjected to solid media drying were submitted to the Grain Research Laboratory of the Canadian Grain Commission for evaluation of the gluten damage that may have occurred. Wheat samples were air dried if necessary and tempered to 15.5 percent moisture content. A 150 g sample was milled using an Allis Chalmers Laboratory mill. The flours were evaluated using the Swanson Mixograph procedure using 35 g of flour and 21.7 ml of water.

A comparison of the shape of curves obtained from the mixograph using flour from the dried samples was made with the curve of an undried control sample. The extent to which dough consistency was reduced and peak time increased was equated with the degree of drying damage.

For this series of tests, seven categories were used:

1. Satisfactory (no change)
2. Satisfactory, but slightly changed
3. Satisfactory but changed
4. Quality reduced
5. Seriously reduced
6. Damaged
7. Severely damaged.

3.6 Germination Test

The germination tests were conducted in 9 cm plastic petri dishes. One Whatman filter paper (No. 3) was placed in each petri dish, 5 ml of water was then added, and 25 plump, mechanically sound seeds were added to each petri dish. Three replications were repeated for each sample. The petri dishes were then sealed in a plastic bag and stored at room temperature. Each germination test of the samples of dried wheat was accompanied by a test using undried grain from the same source as the dried samples. The germination count for each test was computed as a percentage of the corresponding control sample. The germination counts were made after 3 and 6 days for determination of the rate of germination and ultimate germination respectively (Ghaley et al. 1973, Watson 1970, Warner and Brown 1962).

3.7 Thermal Disinfestation

3.7.1 Materials and equipment

Sand, the solid granular medium used for drying wheat, was evaluated with respect to its potential to accomplish thermal disinfestation. Wheat infested with rusty grain beetles, Cryptolestes ferrugeneus, saw-toothed grain beetles, Oryzaephilus surinamensis, and red flour beetles, Tribolium castaneum, was used for the thermal disinfestation trials. The cultures of rusty grain beetles on wheat were maintained at

$30^{\circ}C$ and 70 percent relative humidity for 21 days in an incubator, at the Winnipeg Research Station, Agriculture Canada, to obtain larvae in all stages.

Cylindrical containers made out of wire cloth were used to expose adult and larval stages of insects to heated sand during the drying of wheat (Figure 3.9). For larvae and adults of red flour beetles and adults of saw-toothed grain beetles the containers were made from 60 mesh brass wire cloth. The containers were 2.5 cm diameter and 20 cm long. Adult rusty grain beetles escaped from the 60 mesh containers, therefore 100 mesh stainless steel wire cloth was used for their containers. These cylinders were 2.5 cm in diameter and 10 cm long. In both types of cylinders, one end was sealed using the same mesh wire cloth while a copper ring 2.5 cm in diameter was soldered at the other end to hold a number 6 rubber stopper. This facilitated the loading and unloading of the infested wheat during the course of the tests. Twenty cages of each type were constructed so that an adequate number of replications could be used during each test.

3.7.2 Testing procedure

A 30 g sample of wheat infested with rusty grain beetle adults and larvae was placed in each stainless steel wire cloth container and was firmly closed using a rubber stopper. Ten adults each of saw-toothed grain beetle and red flour beetle and 10 larvae of red flour beetle were put in

Figure 3.9 Wire Mesh Containers Used for Thermal Disinfestation Tests

each brass wire cloth container which was then tightly sealed with a rubber stopper. The cages were loaded at the Winnipeg Research Station, Agriculture Canada. A thermocol box was used to transport containers from the grain dryer to the research station.

The dryer was set to dry wheat at an initial moisture content of 19 percent. The temperature of the sand was maintained at 105°C for Experiment 1 and at 100°C for Experiment 2. The flow rate of wheat was 3 kg/min and the sand to grain mass ratio was 5:1. The residence time of the cages in the drying zone of the cylindrical sand dryer was approximately 1 minute.

The dryer was operated for 10 minutes prior to the start of each thermal disinfestation test to stabilize ambient drying conditions. The containers were then placed in the drying cylinder at the inlet end, one at a time and at one minute intervals. The containers were ejected from the dryer with the dried wheat. Alternate cages were retrieved from the dried wheat and sealed in the thermocol box. The other cages were allowed to remain in warm wheat for 24 hours. The count of live and dead adults of the three species and live larvae of red flour beetles was made after 24 hours. The population of live larvae of rusty grain beetles was estimated from the adults that emerged weekly for six weeks.

The control samples, taken from infested wheat used for thermal disinfestation tests, were maintained at 30°C and 70 percent relative humidity during the course of experiments.

CHAPTER IV

RESULTS AND DISCUSSION

4.1 Performance of the Batch Dryer

The batch dryer used to complete the tests carried out for this thesis was constructed in June 1975 for drying, parching and gelatinization of wild rice (Lapp et al. 1975). As the conversion of moisture to steam and maintenance of high relative humidity was desired for this process, no provision was made to circulate air to carry away the moisture expelled from the grain. During the tests, very little moisture escaped through the 1.3 cm diameter vents provided on the lid, and water condensed on the interior of the lid and the drying bucket. During some trials, the condensed moisture was observed to be wetting the sand. This condition did not resemble the prototype continuous flow dryer process in which air is forced through the drying cylinder to carry away the evaporated moisture. The drying tests using the batch dryer were therefore discontinued because of dissimilar ambient environment at high humidity and without air circulation.

4.2 Performance of the Continuous Flow Dryer

The results of tests conducted on the continuous flow dryer are presented in Table 4.1. The values in the table are averages of at least 3 trials. The results are arranged in

Table 4.1. Results of Wheat Drying Using Continuous Flow Dryer

Flow rate in kg/min	SGMR	MC_i	t_{gi}	t_{si}	t_{gf}	t_{sf}	ΔMC	Moisture Evaporated kg/min	Δt	Efficiency % Drying	Overall
1.5	3:1	19.4	23	105	26	54	1.2	.0222	51	28.19	13.27
		19.2	21	104	26	53	1.7	.0316	51	40.12	23.38
		18.9	20	105	25	52	1.8	.0333	53	40.68	24.4
	4:1	19.4	23	106	27	58	1.6	.0297	48	30.05	20.91
		19.2	21	104	27	54	1.8	.0334	50	32.44	26.99
		18.9	20	105	28	55	1.8	.0333	50	32.37	22.57
	5:1	19.4	23	105	30	62	2.1	.0389	43	35.15	22.67
		18.9	20	105	30	63	2.2	.0407	42	36.77	21.438
	6:1	19.1	23	105	34	68	2.2	.0408	37	35.70	24.50
		19.0	20	104	33	65	2.2	.0407	39	33.79	24.11
2.0	3:1	18.9	25	105	32	56	1.8	.0444	49	44.04	32.55
		19.3	20	104	27	55	1.6	.0397	49	39.34	35.19
	4:1	18.9	25	105	33	59	1.9	.0469	46	37.13	25.65
		19.2	20	106	31	60	2.0	.0495	46	39.19	31.20
	5:1	18.9	25	105	35	66	2.1	.0518	39	38.70	26.95
		19.0	20	104	34	63	2.2	.0543	41	38.59	27.50
	6:1	18.9	25	105	34	65	2.1	.0519	40	31.50	23.07
		19.2	19	105	36	67	2.1	.0520	42	30.06	20.54
2.5	3:1	19.2	23	107	31	54	1.6	.0495	53	36.28	29.38
		19.1	20	105	31	58	1.7	.0525	47	43.40	31.11
	4:1	19.2	22	104	33	64	1.8	.0557	40	40.57	30.53
		19.3	20	105	31	63	1.7	.0527	42	36.56	27.52
	5:1	19.2	22	105	35	68	2.2	.0880	37	42.88	34.31
		19.0	19	105	35	67	2.2	.0679	38	41.65	29.44
	6:1	19.2	24	105	36	71	2.1	.0650	34	37.14	26.25
		19.0	19	105	38	70	2.0	.0617	35	24.24	21.93
3.0	3:1	19.2	23	105	33	60	1.6	.0594	45	42.7	36.73
		19.3	17	105	32	58	1.8	.0669	47	46.08	35.80
	4:1	19.2	23	107	35	68	1.8	.0768	39	41.59	25.91
		19.4	18	106	34	66	1.9	.0705	40	42.79	31.33
	5:1	19.3	24	103	37	70	2.2	.0816	33	48.0	36.26
		19.1	19	106	38	73	2.5	.0927	33	54.57	40.69
		18.9	19	105	40	72	2.3	.0850	33	50.03	35.55
	6:1	19.3	18	105	40	71	2.4	.0890	34	42.30	29.57
		18.9	19	104	41	73	2.3	.0850	31	42.05	27.98

ascending order of wheat flow rate and sand to grain mass ratio. The initial moisture content of wheat ranged from 18.9 to 19.4 percent. The final moisture contents after one pass through the dryer ranged between 18.2 and 16.6 percent. The lowest moisture reduction was observed with the flow rate of wheat at 1.5 kg/min and a sand to grain mass ratio of 3:1. The maximum moisture reduction of 2.5 percent was recorded with the grain flow rate at 3 kg/min and sand to grain mass ratio of 5:1. Khan et al. (1974) concluded that it was not possible to remove more than 2 to 3 percent moisture without adversely affecting the milling quality of rice paddy.

4.2.1 Capacity of the continuous flow dryer.

The moisture reduction increased with the increase in flow rate of wheat through the dryer for 3:1 to 6:1 sand to grain mass ratios.

At wheat flow rates below 3 kg/min the corresponding sand flow rate was also low. This resulted in a low thermal capacity of the mixture and a higher proportion of the heat was lost to the surrounding air and to machine components. Thus a limited quantity of heat was available for drying wheat which resulted in lower moisture expulsion.

The continuous flow dryer could not be tested for wheat flow rates higher than 3 kg/min because of excessive overflow of sand and grain mixture at the inlet end of the drying cylinder. It was concluded that the maximum drying capacity of this dryer was 3 kg/min of wheat.

4.2.2 Effect of sand to grain mass ratio.

The moisture expelled from wheat at an initial moisture content of 19 percent using sand to grain mass ratios ranging from 3:1 to 6:1 is indicated in Figure 4.1.

It was observed that the amount of moisture removed from wheat increased with the increase in sand to grain mass ratios up to 6:1. As the proportion of heated sand increased, more heat was available for moisture evaporation from the wheat. At sand to grain mass ratios higher that of 5:1, the increase in moisture removal from wheat was insignificant and actually decreased in some trials.

In solid granular media drying, the major mode of heat transfer is conduction. At sand to grain mass ratio 5:1, the grain is fully surrounded by sand providing maximum possible contact between sand particles and grain kernels. Any further increase in proportion of sand will not increase the contact between sand particles and grain kernels. Thus, in spite of an increase in thermal capacity of the mixture, there will not be a significant increase in heat conducted to the grain. In fact, higher proportions of sand would create a physical barrier between the grain kernel and the surrounding air. This would reduce the amount of moisture expelled from the grain (Mittal 1976).

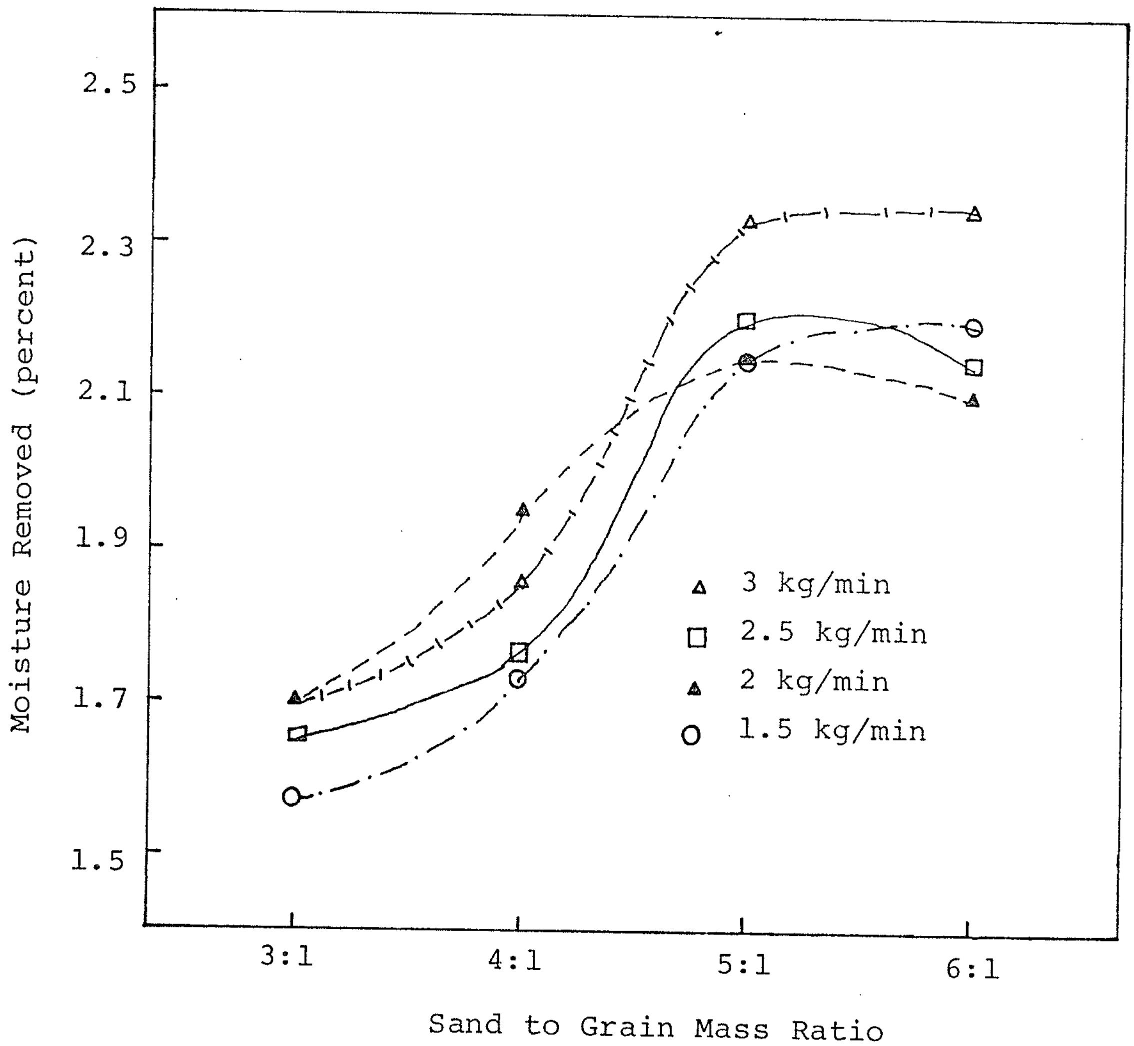


Figure 4.1 Percent of Moisture Removed as a Function of Sand to Grain Mass Ratios for Different Wheat Flow Rates

It was concluded that optimum sand to grain mass ratio for drying wheat at an initial moisture content of 19 percent and the sand temperature at 105°C was 5:1 in the continuous flow dryer.

4.2.3 Effect of air flow rate.

The effect of air flow rate on percentage of moisture removed from wheat is indicated in Figure 4.2. As the air flow was increased from 4.85 to 10.17 m^3/min, the quantity of moisture expelled from wheat decreased. Further increase in air flow resulted in further decrease in moisture removed.

It was expected that an increase in air flow would increase the amount of moisture evaporated from the surface of grain kernels with resultant additional cooling of the grain. On the contrary, the excess amount of air did not enhance the evaporation from grain kernels but carried away heat from incoming heated sand, thus reducing the availability of heat for the evaporation of moisture from the wheat.

It was concluded that 4.85 m^3/min of air was sufficient to carry the moisture evaporated from wheat in the drying cylinder of this prototype dryer.

4.2.4 External cooling of grain.

The wheat coming out of the dryer at the outlet end was at a temperature of 37 to 40°C. It was expected that forced circulation of ambient air would cool the grain along

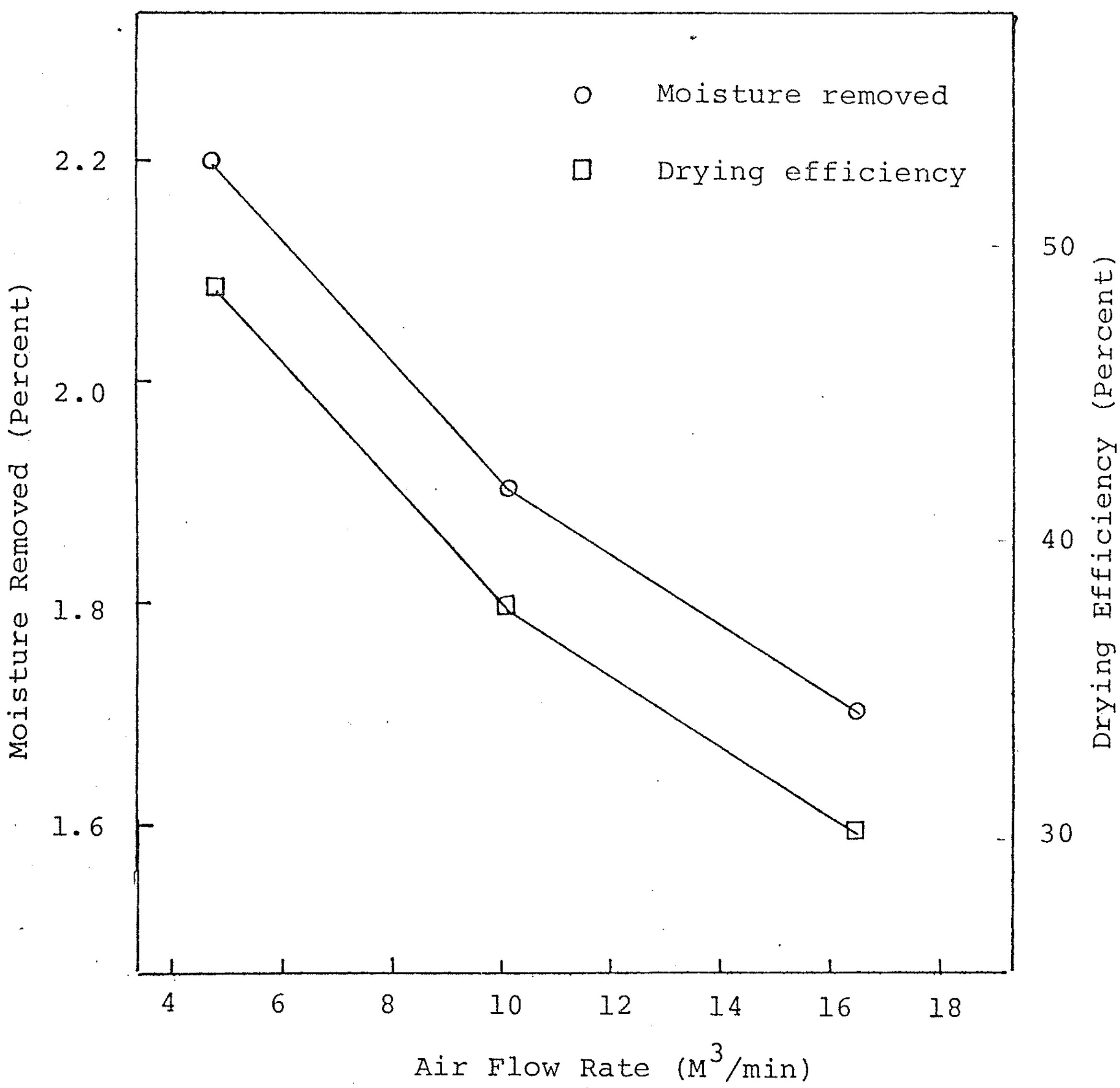


Figure 4.2 Effect of the Air Flow Rate Through the Drying Cylinder on Moisture Expelled During Drying of Wheat in the Continuous Flow Dryer

with further expulsion of moisture. This provision for air circulation and cooling would increase the amount of moisture removed from grain in one pass.

The results of tests conducted with the additional cooling system added to the machine are tabulated in Table 4.2.

The exit air flow rate was 0.62 m^3/min at the top and 0.49 m^3/min at the bottom of the cooling system. The residence time of grain in the cooling device was approximately 3 minutes. The moisture reduction was 2.3 to 2.5 percent in the principle drying cylinder of the dryer and the grain temperature averaged 39°C at the outlet. After passing through the cooling system, the temperature of the grain was reduced to 32°C. During the cooling process an additional 1 to 1.2 percent moisture was expelled from the grain. The drying efficiency was 70 to 72 percent when the moisture expelled during cooling was taken into account.

It was concluded that the use of an increased flow rate through the drying cylinder to cool the grain also resulted in removal of heat from the sand and reduced the drying efficiency of the machine. The external cooling system was found to be effective in improving the drying efficiency of the process.

4.2.5 Multistage drying.

The objective of drying grain is to reduce the moisture content of grain to a safe level such that deterioration

Table 4.2. Results of Wheat Drying in the Continuous Flow Dryer Using Hot Sand and an External Cooling System

Test No.	MC_i %	t_{gi} °C	t_{si} °C	t_{gf} °C	MC_f %	Δt	t_{gff} °C	MC_{ff} %	ΔMC %	η_d
1	19.0	21	105	39	16.7	35	32	15.6	3.4	69.9
2	19.1	21	104	39	16.7	34	32	15.7	3.5	74.2
3	19.3	22	106	40	17.1	35	33	15.9	3.4	70.2
4	18.9	21	105	39	16.8	33	33	15.6	3.3	71.2
5	19.0	21	100	37	16.9	32	32	15.9	3.1	69.7
6	19.2	22	101	37	17.0	32	31	15.9	3.3	74.4

will be avoided. This level is considered to be 14.5 percent for wheat. It was not possible to dry wheat from an initial moisture content of 19 percent to final moisture content of 14.5 percent using the continuous flow heated sand dryer in one pass. This led to the application of multistage drying of wheat.

The results of tests conducted are indicated in Table 4.3. The moisture expelled in the first stage of drying ranged from 2.1 to 2.3 percent. The sand temperature was 104 to 106°C with sand to grain mass ratios of 5:1.

Grain drying with heated sand effects very rapid removal of moisture from the surface of grain kernels. No time is available for moisture to migrate from the interior to the surface of the grain kernel. Thus, in multistage drying, it was necessary to allow some time in between stages to establish equilibrium of moisture within the grain kernel. Tests were conducted allowing waiting periods of 15 minutes to 10 days between two stages of drying (Table 4.3). It was observed that a waiting period of two hours was an optimum time to achieve an equilization state for the moisture in grain kernels. There was no further significant increase in moisture removal during the second stage of drying when the grain was allowed to stand more than two hours between the two stages.

It was found that the drying efficiency was maximum at 44 percent when two hours were allowed between the two

Table 4.3. Results of Two Stage Drying Using a Continuous Flow Dryer Employing Heated Sand

	First Stage							Second Stage						Overall		
MC_i	t_{gi}	t_{si}	t_{gf}	t_{sf}	Δt	ΔMC	Tempering Time	t_{gi}	t_{si}	t_{gf}	t_{sf}	Δt	ΔMC	ΔMC	Δt	η_d
18.9%	19°C	105°C	40°C	73	32	2.3%	15 min	40	105	50	77	28	1.2	3.5	60	41.9
19.1	19	104	39	72	32	2.2	15 min	39	105	49	76	29	1.3	3.5	61	41.3
19.1	22	105	40	72	33	2.3	2 hrs	36	105	45	74	31	1.6	3.9	64	43.9
19.0	21	105	41	73	32	2.2	2 hrs	36	104	46	74	30	1.6	3.8	62	44.1
19.4	18	106	39	72	34	2.3	1 day	26	105	38	68	37	1.8	4.1	71	41.7
19.3	19	104	40	71	33	2.2	1 day	25	105	40	71	34	1.7	3.9	67	42.0
19.4	20	106	38	68	36	2.1	2 days	23	104	39	69	35	1.7	3.8	71	38.5
19.4	20	104	40	70	34	2.2	2 days	23	105	41	70	35	1.7	3.9	69	40.9
19.1	19	104	38	70	34	2.1	10 days	19	105	39	69	36	1.7	3.8	70	39.1

drying stages.

4.2.6 Drying efficiency.

When artificial heat is used for drying, efficiency in its use is important. In most grain drying processes heat for vaporization of moisture is supplied by a medium which is heated and passed through the grain. The drying efficiency is expressed as:

$$\text{Drying efficiency} = \frac{\text{heat utilized to remove moisture}}{\text{heat available for drying}}$$

The heat utilized to remove moisture is the product of the latent heat of vaporization of water from wheat and the quantity of moisture removed. The heat available for drying using the solid medium is the product of the mass, its specific heat and the change in temperature. This can be expressed in symbols as:

$$N_d = \frac{W \cdot h_{fg}}{W_s \cdot c \cdot \Delta t}$$

where

N_d = drying efficiency.

W = mass of water evaporated kg.

h_{fg} = latent heat of vaporization of water from wheat J/kg.

W_s = mass of sand kg.

c = specific heat of sand J/kg°C

Δt = change in sand temperature.

A value of 2.56×10^6 J/kg for the latent heat of vaporization of water from wheat (Peart and Lien 1975) and a value of 878.6 J/kg^{o}C for specific heat of sand (Salisbury 1950) was used to calculate the drying efficiencies. Mean drying efficiencies for different grain flow rates and various sand to grain mass ratios are shown in Figure 4.3. The drying efficiency varied from 28.2 to 54.6 percent (Table 4.1). The maximum drying efficiency was achieved at a grain flow rate of 3 kg/min and a sand to grain mass ratio of 5:1.

When the wheat was dried using sand to grain mass ratios greater than 5:1, a decrease in drying efficiency was observed. An excessive mass of sand in the drying cylinder was thought to be creating a physical barrier between the grain kernel and the surrounding air. Although more heat was available for drying, there was a decrease in the drying rate, thus causing a drop in drying efficiency.

At sand to grain mass ratios below 4:1, there tends to be an increase in drying efficiency. Prior to each drying test, sand at 105^{o}C was allowed to run through the dryer for some time to warm up the machine as well as to maintain uniform heat throughout the sand mass. The temperature of the sand and grain mixture in the drying cylinder is estimated to be in the range of 50 to 60^{o}C. When the drying test was started, the machine components were at a higher temperature than that of the sand and grain mixture. It is believed that the machine components may be supplying heat back into the sand and grain

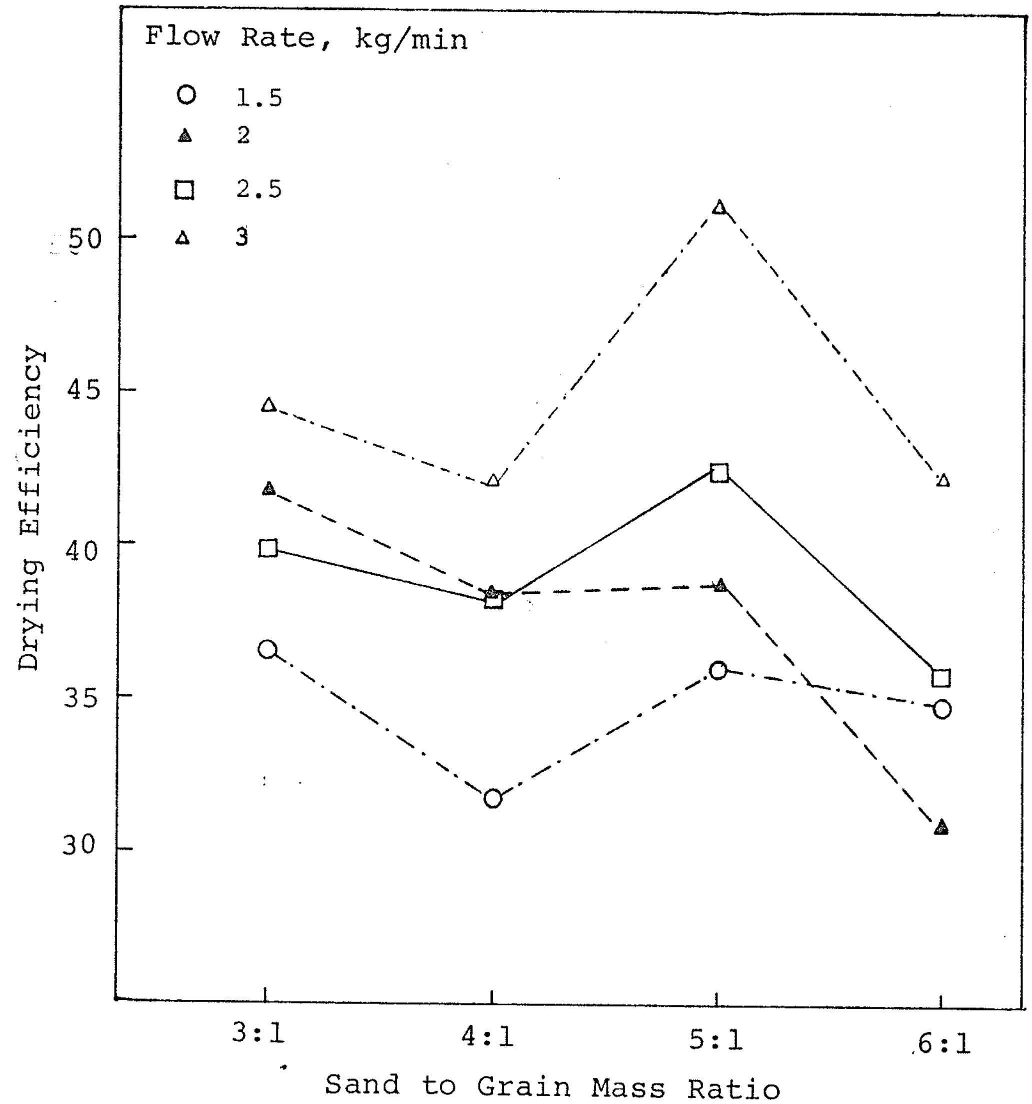


FIG. 4.3 Drying Efficiency as a Function of Sand to Grain Mass Ratio for Different Wheat Flow Rates.

mixture in the beginning of a drying trial. The quantity of mixture at a sand to grain mass ratio of 3:1 was low. Thus the thermal capacity was also low. The heat which was being supplied by machine components was more prominent at low sand to grain mass ratios. This situation could have been avoided by running the tests for a longer duration.

Mittal (1976) reported a maximum drying efficiency for the continuous flow dryer as 62 percent while drying wheat from 17 percent to 14.5 percent. The specific heat of wheat is a function of its moisture content. At a higher moisture content, more heat was utilized to raise the temperature of wheat so less heat was available for the evaporation of moisture.

The maximum drying efficiency obtained for the continuous flow dryer was 54.6 percent. The efficiency can be improved by insulating the machine components more effectively to reduce heat losses to surrounding air. The efficiency of the dryer was found to be 72 percent when moisture expelled during external cooling was considered.

4.2.7 Fuel efficiency.

The increasing cost of energy fuels and the possibility of shortages has increased the need for efficiency in the use of energy for grain drying. The future predictions for increase in fuel costs indicate that energy costs will be a larger proportion of the total cost of drying.

Fuel efficiency is defined as the ratio of energy utilized to remove water and total energy utilized by the dryer. In symbols the fuel efficiency can be expressed as:

$$\eta_f = \frac{W.h_{fg}}{3600P}$$

where

η_f = fuel efficiency of dryer.

h_{fg} = latent heat of vaporization water from wheat J/kg.

P = energy consumed in kW.

W = mass of moisture removed.

In the continuous flow dryer, the total energy consumption included energy required to heat the sand and to operate various electrical motors on the machine. The fuel efficiency of the continuous flow dryer at various sand to grain mass ratios and wheat flow rates are shown in Figure 4.4.

The fuel efficiency was in the range of 28 to 41 percent. The highest fuel efficiency was achieved at a grain flow rate of 3 kg/min and sand to grain mass ratio of 5:1.

Peart and Lien (1975) have reported the maximum fuel efficiency at 39 percent while drying corn with hot air at the temperature of 105°C. The efficiency of solid medium drying using sand was found to be higher than for air dryers. The fuel efficiency of the sand dryer would be still higher if moisture expelled during external cooling is taken into account.

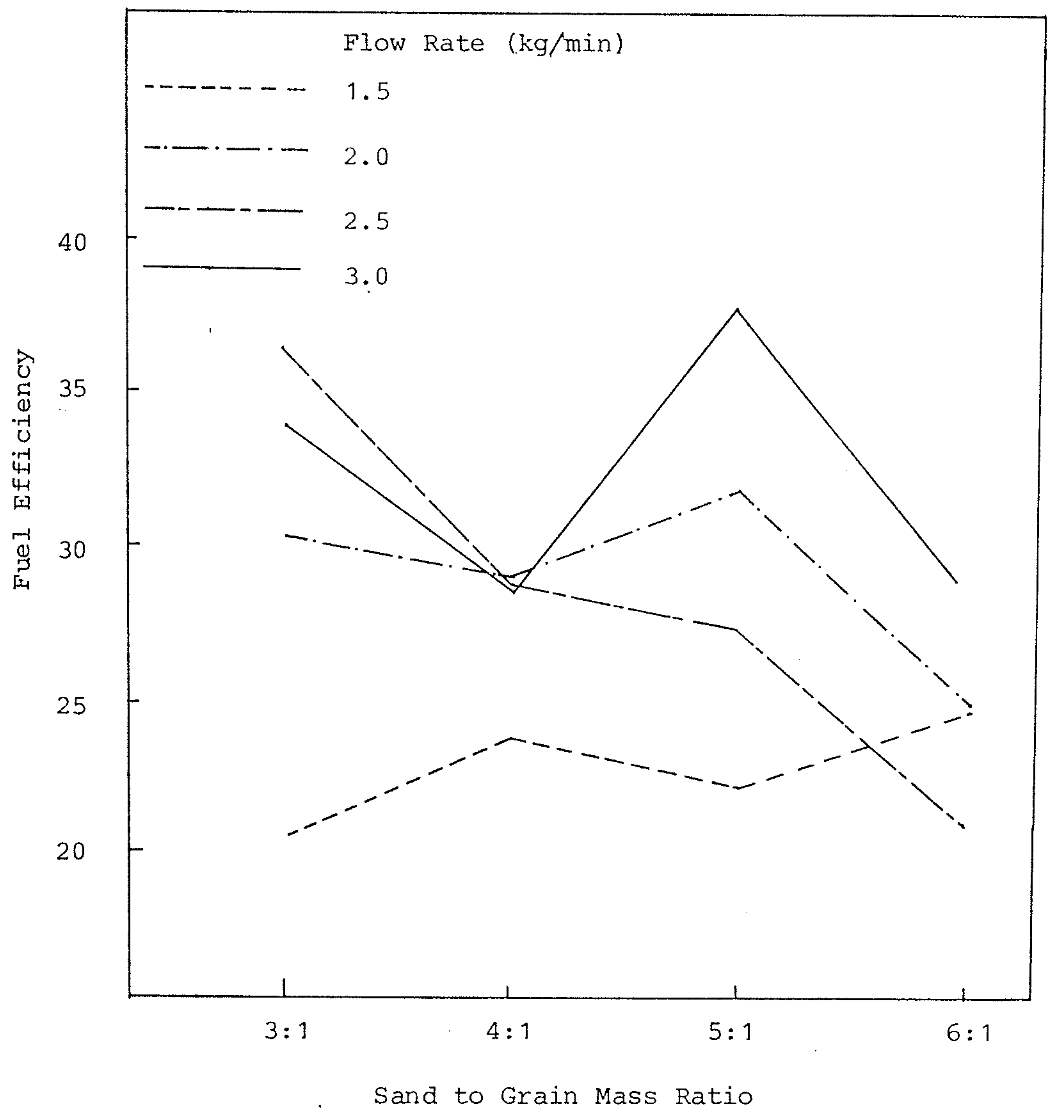


Figure 4.4 Fuel Efficiency as a function of Sand to Grain Mass ratio and Wheat Flow Rate.

4.2.8 Quality of dried wheat.

The baking quality tests on dried wheat were conducted at the Grain Research Laboratory of the Canadian Grain Commission. The results of the quality tests along with the drying conditions are tabulated in Table 4.4.

It was observed that it was not possible to dry wheat from an initial moisture content of 19 percent without a slight change in gluten formation quality of wheat. The rate of denaturation of protein in wheat is a function of grain temperature and moisture content (Gerzoi and Somochetov 1958). Wheat at a high moisture content cannot be subjected to high temperatures for a rapid drying process. Ghaley et al. (1973) have reported that it was not possible to dry wheat of an initial moisture content above 15 percent by spouted bed heating without damaging the functional properties of grain. They dried the grain using heated air at temperatures ranging from 60^{o} to $200^{o}C$.

Warner and Brown (1975) have also reported that as the moisture content of wheat increases, it is more susceptible to drying damage. While drying wheat at an initial moisture content of 19.9 percent at $76^{o}C$ for one hour, the germination quality was reduced to 30 percent, whereas drying wheat from an initial moisture content of 17.9 percent under identical conditions, the germination count was 90 percent.

The author did not succeed in drying wheat from an initial moisture content of 19 percent without slight change in

Table 4.4. Baking and Germination Quality of Wheat Dried in the Continuous Flow Dryer Using Heated Sand

No. of Stages	Test No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	MC_i	19.3	18.8	19.0	19.1	19.1	18.9	19.1	19.3	19.3	19.2	19.1	19.1	19.2	18.9	19.1	18.9
	t_{si}	106	104	104	105	106	105	105	100	101	100	100	101	101	100	102	100
	ΔMC	2.3	2.4	2.3	2.1	2.4	2.1	2.2	2.0	1.9	2.1	2.1	2.2	2.1	2.2	2.2	2.1
	Quality Category	5	2	3	2	5	-	-	-	-	-	-	-	-	-	-	-
	Germination Percentage	49	89	92	88	65	-	-	-	-	-	-	-	-	-	-	-
2	t_{si}	104	105	104	105	104	-	-	90	90	90	95	96	95	100	100	101
	ΔMC	1.2	1.1	1.1	1.2	1.1	-	-	1.0	0.9	0.9	1.1	1.2	1.1	1.2	1.1	1.1
	Quality Category	5	2	4	4	6	-	-	2	2	2	2	3	3	4	4	5
	Germination Percentage	33	84	65	51	7	-	-	84	88	87	88	91	90	61	72	67

baking quality using the continuous flow dryer.

4.2.9 Germination quality.

Germination counts after 3 days for rate of germination and after 6 days for ultimate germination are recorded in Table 4.4. It was found that when wheat was dried with sand at the temperature of 105°C, a wheat flow rate of 3 kg/min and a sand to grain mass ratio of 5:1, the germination count remained above 85 percent.

It was noted that when the baking quality was reduced to category 3 (satisfactory but quality changed), the germination count remained above 80 percent. The baking quality damage was found to occur at lower temperatures than the germination quality. This was also indicated by Warner and Brown (1962), Ghaley et al (1973) and Mittal (1976).

4.3 Thermal Control of Insects

The results of tests conducted to assess the potential of drying with heated sand as a thermal disinfestation process are shown in Tables 4.5 and 4.6. The mortality of adult insects was more than 98 percent when exposed for 1 min. to sand heated to 100°C or 105°C during the drying process. Not less than 97% of the larvae outside the grain kernels were also killed by heat during the process.

The number of larvae of rusty grain beetles inside the grain kernels was observed to be 885 and 976 in the control samples for treatment at 105 and 100°C respectively.

Table 4.5 Results of Wheat Disinfestation Tests Using Sand at 105° C

Stage	Species	Removed After Drying			Cooled 24 Hrs After Drying			Control Sample		
		Live	Dead	Total	Live	Dead	Total	Live	Dead	Total
Adults	Rusty grain beetle	0	160	160	1	163	164	183	32	215
	Saw toothed grain beetle	2	98	100	0	100	100	99	1	100
	Red flour beetle	0	97	97	0	89	89	98	1	99
Larvae	Rusty grain beetle Outside Kernels	6	129	135	0	129	129	68	0	68
	Inside Kernels	68	4	72	19	1	20	880	5	885
	Red flour beetle	0	98	98	0	94	94	84	14	98

Table 4.6. Results of Wheat Disinfestation Tests Using Sand at 100°C

Stage	Species	Removed After Drying			Cooled 24 Hrs After Drying			Control Sample		
		Live	Dead	Total	Live	Dead	Total	Live	Dead	Total
Adults	Rusty grain beetle	0	129	129	5	146	151	133	12	145
	Saw toothed grain beetle	0	99	99	0	99	99	100	2	102
	Red flour beetle	2	96	98	17	80	97	94	4	98
Larvae	Rusty grain beetle Outside Kernels	1	43	44	8	0	8	25	1	20
	Inside Kernels	99	3	102	189	4	193	970	6	976
	Red flour beetle	1	84	85	3	83	86	90	9	99

Only 72 and 102 were counted as dead or alive in samples of infested wheat immediately after treatment in the dryer.

The containers used for exposing larvae and adult insects were made from 60 and 100 mesh wire cloth. The sieve analysis of sand (Appendix 1) indicates that only 0.97 and 0.92 percent sand could have passed through the wire cloth to come in direct contact of infested grain. The mortality of larvae and adult insects was only due to heating of the brass and the stainless steel wire cloth containers.

The cages which were left for 24 hours in warm grain after passing through the dryer with sand temperature of 105°C after disinfestation trials, indicated a more effective control of insects than at 100°C. This indicates that after a short exposure of insects to high temperatures, sustained exposure at moderate temperature increases the effectiveness of thermal disinfestation. Higher survival of insects in samples left in warm grain after passing through the dryer with a sand temperature of 100°C could not be explained satisfactorily.

It was concluded that heated sand treatment can be effectively used to greatly reduce infestations of the red flour beetle, saw toothed grain beetle and rusty grain beetle from wheat. The treatment would eliminate the problem of contamination of grain by chemical pesticides used for insect control.

CHAPTER V

CONCLUSIONS

1. It was not possible to dry wheat from 19 to 14.5 percent moisture in a single pass in the prototype continuous flow heated sand dryer. The maximum moisture that could be expelled was 2.5 percent in one stage of drying when the sand temperature did not exceed 105^{o}C, with sand to grain mass ratio 5:1 and a wheat flow rate of 3 kg/min.

2. An additional moisture reduction of 1 to 1.2 percent was achieved by cooling the grain utilizing forced circulation of ambient air at the rate of 27.7 to 35.0 $m^3/min \cdot m^2$ for 3 minutes.

3. The maximum moisture reduction in two stage drying was 4.1 percent. The moisture reduction of 3.9 percent, found using a tempering time interval between stages of 2 hours, indicated that the interval was near the optimum length.

4. It was not possible to dry wheat at an initial moisture content of 19 percent in the continuous flow dryer using heated sand without causing a slight reduction in baking quality.

5. Maximum capacity of the prototype continuous flow dryer, drying wheat, was found to be 3 kg/min.

6. A sand to grain mass ratio of 5:1 was found to be optimum for drying wheat with a sand temperature of 105°C and using 20:40 texture sand for grain flow rates ranging from 1.5 to 3 kg/min.

7. An air flow rate of 4.85 m^3/min was found to be adequate to carry away evaporated moisture from the drying cylinder for the grain flow rate up to 3 kg/min. An increase in the air flow rate tended to decrease the moisture reduction in the wheat being dried.

8. The maximum drying efficiency was found to be 54.6 percent while drying wheat from an initial moisture content of 19 percent, and the maximum fuel efficiency was 41 percent. The sand was heated to 105°C and the sand to grain mass ratio was 5:1. The drying efficiency increased to 72 percent when moisture expelled during external cooling was taken into account.

9. It is possible to exterminate adults of the rusty grain beetle and saw-toothed grain beetle and adults and larvae of the red flour beetle in one pass in a continuous flow dryer with sand heated to the temperature of 105°C. The larvae of the rusty grain beetle inside the grain kernel were greatly reduced in number but not completely exterminated, perhaps because the heated sand did not come in direct contact with the infested grain.

10. The wheat drying carried out at optimum conditions had no significant adverse effect on the germination quality. The temperatures at which germination quality damage occurred were higher than the temperatures at which the baking quality damage occurred.

RECOMMENDATIONS

1. Investagations should be carried out to dry wheat at 19 percent initial moisture content in a continuous flow dryer using heated sand at temperatures lower than 100°C. The corresponding residence time of grain in the drying cylinder should be more than one minute.

2. The cooling section of the drying cylinder on the prototype should be extended in length for further cooling of grain.

3. A cooling system utilizing forced circulation of ambient air should be integrated with the dryer to cool the grain to ambient temperature along with further expulsion of moisture.

4. The depth of the sand tank should be increased to keep the heaters submerged in sand.

5. Drying tests should be carried out with different sand textures. There may be optimum sand textures for different grain kernel sizes and initial moisture contents of grain.

6. The drying tests should be carried out for a longer duration preferably one to two hours to stabilize the temperature of the machine components and the mixture of sand and grain.

7. Thermal disinfestation tests should be conducted utilizing grain infested in bulk. This will allow the sand to come

in direct contact with different stages of insects and with infested kernels.

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APPENDIX I

Sieve Analysis of 20:40 Texture Sand

Sieve Size	Percent Retained	Percent Coarser
16	1.16	1.16
18	2.15	3.31
30	27.20	30.51
35	27.10	57.61
50	39.45	97.06
60	0.97	98.03
70	1.53	99.56
80	0.42	99.98
100	0.02	100.00
Pan	0.00	