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ABSTRACT

The drying of wheat using solid heat transfer media was investigated in this study. A batch dryer and a continuous flow dryer were used with hot sand as one of the heat transfer media. Comparative performance tests of other solid heat transfer media and different sand textures were carried out in the batch dryer. Thermal disinfestation and roasting studies using hot sand were also investigated in the batch dryer and in the continuous flow dryer.

Experiments using the batch dryer showed that hot sand can be used to dry wheat from 17.0 to 14.5 percent moisture content without damage to milling quality of the grain. A residence time of two minutes was found optimum and no benefit was gained by drying for a longer time. Sand to grain mass ratios ranging between 3:1 to 5:1 were found to be effective in removing moisture from wheat. Sand temperatures ranged from 90 to 110°C. An increase in sand to grain mass ratio above 5:1 resulted in no significant increase in the quantity of moisture removed. The amount of moisture removed was found to be proportional to the sand temperature used. Germination counts exceeding 90 percent after three days and greater than 95 percent after six days, as compared to the germination count of un-

dried wheat, were found when optimum drying conditions were used.

A sand texture of 20-40 (0.84 mm to 0.42 mm particle size) removed the greatest amount of moisture from wheat and gave the highest drying efficiency of the different sand textures used. Sand was found to be a better solid heat transfer medium for drying wheat than either granular salt or steel balls. Salt displayed drying capabilities superior to sand and steel balls at temperatures above 120°C. The hygroscopic property of salt inhibits its drying capacity at low temperatures. The difference in density between steel balls and wheat resulted in separation and poor mixing in the batch dryer. The high thermal conductivity of steel balls caused rapid and significant heat losses to the machine components and to the air. These two factors contributed to a reduction in the amount of moisture removed.

Thermal disinfestation was found to be effective when infested wheat was dried with hot sand in both the batch and the continuous flow dryer. The feasibility of using hot sand to roast wheat was also demonstrated.

A 4.5:1 sand to grain mass ratio removed more moisture from wheat than either a 4:1 or a 5:1 ratio in the continuous flow dryer. The maximum quantity of moisture was removed at a grain flow rate of 3.0 kg/min. An average drying efficiency of 61.2 percent was obtained for grain flow rates ranging from 2.5 to 3.5 kg/min using a sand to grain mass ratio of 4:1. Reduced drying efficiencies were found when sand to grain mass ratios above 4:1 were used. A maximum fuel efficiency of 40.7 percent was found at a grain flow rate of 3.0 kg/min using a sand to grain mass ratio of 4:1. The specific energy consumption varied from 6.34 to 9.07 MJ/kg of water evaporated. Solid heat transfer media grain drying was found to be superior to conventional hot air drying in both drying and fuel efficiencies.

A 20-40 sand texture was most efficient in drying wheat. Thermal disinfestation and roasting of wheat using hot sand as the heat transfer medium were shown to be feasible.

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LIST OF SYMBOLS

Atm.	Atmosphere.
C	Carbon.
MC	Moisture content.
MC_1	Initial moisture content of wheat (percent wet mass basis).
MC_2	Desired moisture content of wheat (percent wet mass basis).
MGMR	Medium to grain mass ratio.
$\dot{M}_s$	Mass rate of sand, kg/h.
N	Nitrogen.
P	Power consumed in drying wheat, watts.
SGMR	Sand to grain mass ratio.
$\dot{W}$	Mass rate of water removed from wheat, kg/h.
W_w	Amount of additional water for 100 g of dry wheat, g.
c	Specific heat of sand, J/(kg.K).
db	Dry mass basis.
h_{fg}	Latent heat of vaporization of water from wheat, J/kg.
wb	Wet mass basis.
ΔMC	Amount of moisture removed.
ΔT	Temperature change of sand in drying section, K.
η_d	Drying efficiency, percent.
η_f	Fuel efficiency, percent.

CHAPTER I

INTRODUCTION

Artificial grain drying is practiced during grain processing operations and to prevent deterioration of grain quality in storage. Wheat cannot be stored safely at a moisture content greater than about 14.5 percent (Friesen 1973, Inglett 1974 and Simmonds et al. 1953). Therefore, wheat must either stand longer in the field before harvesting or it must subsequently be dried. Allowing wheat to stand longer in the field presents a risk of damage by wind, insects, hail or heavy rain. A delay in the time of harvest will also very often place time constraints on the conduct of post harvest tillage operations on the farm. Thus there is a significant advantage to harvest wheat at a high moisture content and dry it prior to storage.

The major objective of drying cereal grain is to reduce the moisture content so that spoilage will not occur. Damage in storage arises from physical consumption of the grain by weevils, breakdown of kernel tissue by molds, and excessive respiration of the grain as temperature and moisture levels increase around locations infested with weevils and/or fungi (Friesen 1973 and Inglett 1974).

Marketing constraints and limited drying capacities at terminal elevators require that drying be undertaken on the farm in wet harvest seasons.

In some regions of the world drying is accomplished by exposing grain to sunshine (Khan 1973). Alternatively conventional heated air dryers are used to perform the drying operations. Sun drying produces grain fissures (sun checks), requires a large surface area and labor for spreading, stirring and collecting the grain. Unpredictable weather conditions result in poor control of the drying process. During periods of excess rainfall, delays in drying result in grain losses from sprouting, insect infestations and other causes.

In conventional dryers, air is used as the heat and moisture transfer medium because it can be easily handled and does not by itself contaminate the grain. The low heat transfer coefficient of air coupled with the resistance to moisture diffusion out of the kernels results in extended drying times and relatively low drying efficiencies.

Various investigators have explored different methods for improving drying efficiency. A solid - heat transfer medium is one additional method which has been investigated. Sand is a granular solid medium having a low thermal conductivity (0.33 W/(m.K) (Perry et al.

1969)). Its granular texture permits uniform heat transfer to grain kernels. Sand possesses semifluid characteristics which permit easy separation from grain during the drying process. A quantity of sand can be used repeatedly in a continuous drying process. The heat transfer associated with contact between sand particles and grain kernels may enhance the drying rate. Heat energy from the sand mass is transferred directly from the surface of the sand to the surface of the grain. Removal of moisture takes place from the surface of grain kernels by diffusion and convection into the surrounding air.

The overall objective of this research project was to investigate the feasibility of drying wheat using solid heat transfer media. Other specific objectives were:

a. To determine the feasibility of drying wheat using hot sand without reducing the milling quality of the grain. If feasible, then the optimum conditions for using hot sand were to be determined.

b. To evaluate the drying characteristics and performance of drying wheat using hot sand in a continuous flow dryer.

c. To investigate the effects of sand texture on drying characteristics.

d. To explore the use of other solid heat transfer media and to determine their performance in comparison to sand.

e. To investigate the influence on insect control of hot sand drying.

f. To determine the possibility of roasting and puffing wheat using hot sand.

CHAPTER II

PHYSIOLOGICAL ASPECTS OF WHEAT

2.1 Importance and Production

Wheat provides almost 20 percent of the total food energy for the people of the world and is the national food staple in 43 countries. It is harvested from 214 million hectares each year. The estimated production is over 325 million tonnes (Canadian Internation Grains Institute 1975). Wheat provides more nourishment for the people of the world than any other food source (Inglett 1974).

In Canada wheat is grown mainly in the three prairie provinces of Manitoba, Saskatchewan, and Alberta. Over half the crop is produced in Saskatchewan. Since 1946 the wheat growing area fluctuated between 4.9 and 11.8 million hectares. Almost all of the wheat grown is spring wheat. Eighty to 90 percent of the spring wheat consists of hard red varieties and the remainder is mainly amber durum. The variety Neepawa comprised 42.8 percent of the total production of hard red spring wheat in the 1973 crop year (Canadian International Grains Institute 1975 and Pomeranz 1971). The hard red spring wheat grown in Canada is conceded to be the hardest wheat produced in the world.

The kernel of hard red spring wheat is small, red, plump and hard. The wheat has a test weight of 385 to 400 g/0.5 dm^3 at 12 percent moisture content (MC). Protein content is normally 12 to 15 percent. The wheat has good milling characteristics and yields 75 percent straight grade flour containing an ash content of about 0.40 to 0.46 percent. Approximately 10 million hectares are seeded annually in Western Canada and the production is about 18 to 20 million tonnes (Canadian International Grains Institute 1975).

2.2 Kernel Structure and Chemical Composition

The structure of the entire kernel has an influence on the movement of moisture during drying and conditioning. The cross section of a wheat kernel is shown in Figures 2.1 and 2.2. The wheat kernel is composed of more than 20 tissues, some only one cell layer thick. The principal parts of the kernel are pericarp (5 to 8 percent), aleurone layer (6 to 7 percent), endosperm (81 to 83 percent), embryo (1 to 1.5 percent) and scutellum (1.5 to 2.0 percent) (Inglett 1974 and Pomeranz 1971). The pericarp surrounds the entire seed and acts as a protective covering. The seed coat of red spring wheat is considerably modified at the basal tip of the germ, in such a manner that entry of water through it is relatively easy.

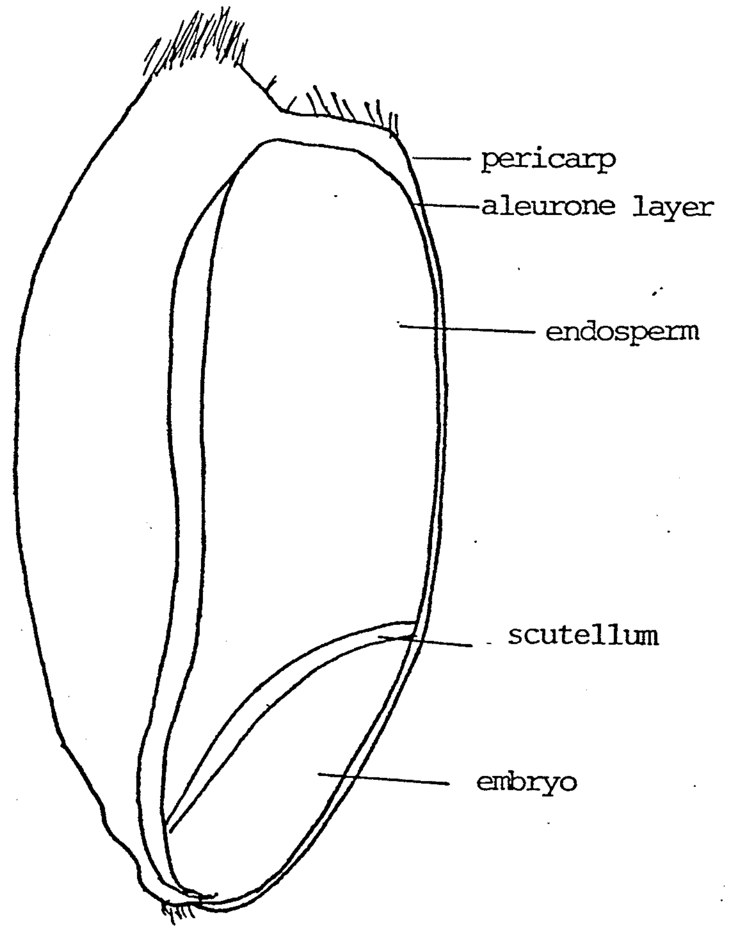


Fig. 2.1 Wheat Kernel Bisected Longitudinally Through the Crease (After Pomeranz 1971)

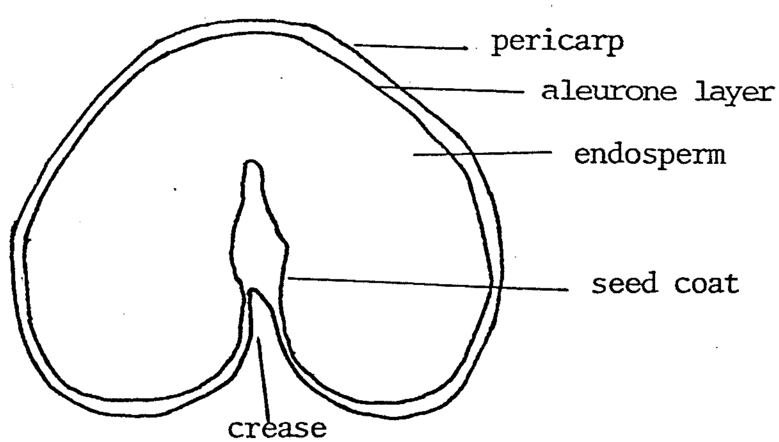


Fig. 2.2 Transection Through a Wheat Kernel above the Embryo (After Pomeranz 1971)

The bran of the flour normally comprises the outer structure of the kernel including the aleurone layer. The starchy endosperm is the source of flour. Its cells are packed with starch and protein. There is usually an outer vitreous portion of the starchy endosperm and an inner floury portion, commonly called horny and floury endosperm respectively.

The embryo is the essential part of the seed and consists of living cells which are very sensitive to heat (Canadian International Grains Institute 1975 and Pomeranz 1971). Thus a kernel is a living organism having a colloidal capillary porous body. It contains a large amount of micro and macro-capillaries, along which moisture can move from the inside to the surface and vice versa. Evaporation of moisture as well as penetration of moisture into the grain occurs mainly through the embryo or close to it. (Gerzhoi and Samochetov 1961).

The chemical composition of wheat is given in Table 2.1. The embryo and aleurone layer are high in oil, non gluten protein and certain vitamins. The embryo contains 26 percent protein and the aleurone 24 percent protein. From the endosperm a water insoluble protein fraction called gluten can be isolated. When hydrated it is an elastic substance particularly important for its functional proper-

Table 2.1 Proximate Chemical Composition of Wheat*

Component	Wheat	
	Whole grain (percent)	Germ only (percent)
Crude protein (Nx5.7)	13.9	26.6
Fat	2.0	10.9
Minerals	1.7	4.3
Fiber	2.3	2.5
Other carbohydrates	68.1	44.2
Water	12.0	11.5

*(Canadian International Grains Institute 1975)

ties in bread making (Canadian International Grains Institute 1975 and Inglett 1974). Other physiothermal properties of wheat are recorded in Table 2.2

2.3 Influence of Heat on Quality

During the drying process the quality of grain undergoes certain changes. In studies of the biochemical changes in dried wheat it has been shown that the specific tensile strength of the gluten is considerably reduced after drying

Table 2.2 Physio-thermal Properties of Wheat

No.	Property	Value	Reference
1.	Bulk density (kg/m^3) at MC(%wb)	784.9 752.9 720.8 11.0 14.1 17.1	Mohsenin 1970
2.	Kernel specific gravity	1.3 at 9.8% MC	ASAE Yearbook 1976
3.	Voids (%)	42.6 at 9.8% MC	-Do-
4.	Angle of repose	28^{o}	-Do-
5.	Specific heat J/(kg.K)	1673.6 at 15% MC 2175.7 at 22% MC	Hall 1957
		$c = 4.184 \times 10^3 (0.262 + 0.00967\ MC(\%db))$	Muir and Viravanichai 1972
6.	Thermal Conductivity W/(m.K)	0.150 at 12% MC 0.154 at 20% MC	Hall 1957
7.	Diffusivity (m^2/h)	4.14×10^{-4} at 9.2% MC	ASAE Yearbook 1976
8.	Heat of vaporization (J/kg)	2.42×10^6 at 15% MC, $65^{o}C$ 2.72×10^6 at 11% MC, $65^{o}C$	Thompson and Shedd 1954
9.	Average net heat of desorption (J/kg)	1.63×10^5 (from 17 to 14% MC)	Becker and Sallen 1956

at grain temperatures above 60°C. The rate of denaturation of the proteins increases considerably in relation to the moisture content of grain (Gerzhoi and Samochetov 1961).

The proteins of wheat are hydrophilic colloids. The swelling capacity of grain and flour proteins plays an important part in the germination of seeds, in the process of milling and in the making of dough. Under the influence of high temperatures, the proteins are subjected to denaturation and coagulation. As a result, the water absorbing and swelling capacities of proteins decrease.

Below 60°C the quality of starch (carbohydrate) does not change appreciably. At higher temperatures and especially at high moisture levels dextrinization and partial decomposition of the starch may occur leading to the formation of dextrins. This causes deterioration in the quality of grain. There is a decrease in germination ability, a change of color and a deterioration in baking value.

Fats are insoluble in water and less affected by heat. But at higher temperatures (70°C and above) fats may also undergo a partial decomposition with the acidity of the fats increasing. The activity of enzymes increases with the rise of temperature up to 50°C. Above 50°C their activity begin to fall and ceases completely at about 80 to 100°C. The lowering of enzymatic activity at a high temperature is related to the denaturation of the proteins of the enzymes. Vitamins are also destroyed at higher temperatures (Gerzhoi and Samochetov 1961).

Adequate germination is a measure of the capability of a kernel to produce a normal seedling. Germination damage by heat is distinct from flour quality damage and occurs over a lower range of temperatures. Delayed germination is also considered a sign of heat damage (Brooker et al. 1974 and Hutchinson 1944).

2.4 Quality Evaluation

Quality in wheat is a relative term. No sound wheat can be judged either good or poor except in comparison with some specific standard or evaluated for some definite use. No wheat has all the characteristics that might be desired. The quality characteristics desired by the miller are based on the physical and chemical composition of wheat. The protein and starch are of greatest importance (Swanson 1938).

Both protein quantity and quality are considered. The quantitative expression of crude protein is related to total organic nitrogen in the flour. Quality evaluations relate specifically to physiochemical characteristics of the gluten forming component (Pomeranz 1971). The proteins of gluten are the basis of the unique ability of wheat flour to be baked into leavened bread. The rubber like cohesive properties of gluten are essential for retaining the bubbles of carbon dioxide generated during fermentation in leavening (Inglett 1974).

Quality is appraised by subjecting the flour to several physical testing devices which measure various rheological characteristics. They characterize the gluten portion of the protein by measuring such factors as extensibility, resistance to extention of doughs at rest, hydration time, maximum development time and tolerance or resistance to breakdown during mechanical mixing. Recording dough mixers such as a Mixograph or a Rheograph are used (Pomeranz 1971).

CHAPTER III

GRAIN DRYING THEORY, PRACTICES AND SYSTEMS

3.1 Grain Drying Theory

Drying is a process of simultaneous heat and mass transfer. It involves the vaporization of water from the liquid state, mixing the vapor with the surrounding air and removing the vapor by the induced flow of the air-vapor mixture. Mass transfer by diffusion is the transport of one component of a mixture due to a concentration gradient (ASHRAE 1972). The necessary heat of vaporization can be provided by conduction from a solid surface, convection from hot air or radiation (Parry et al. 1969).

Grain drying is considered a thermo-physical and physio-chemical process the kinetics of which are determined by the laws of heat and mass transfer inside and outside the substance. Drying takes place when the vapor pressure of grain moisture is greater than the vapor pressure of the surrounding air. The rate of drying increases as the differential of these two vapor pressures becomes greater (Bunn 1970). A study of how a solid dries may be based on the internal mechanism of liquid flow or on the effect of the external conditions. Internal liquid flow may occur by several mechanisms depending on the structure of the solid. Some of the mechanisms are diffusion, capillary flow, shrinkage and gravity.

In the drying of a solid body a molecular diffusion of moisture takes place, both in the liquid and vapor phase. Liquid transfer by capillary action is conditioned by the change of the capillary potential and by the presence of captive air in the capillaries.

In kernels above the critical moisture point, water is evaporated at a nearly constant rate. The temperature rise during this rapid rate of evaporation is very slow. Temperature is held down by the utilization of the latent heat of vaporization to evaporate moisture which tends to cool the product. Below this critical moisture point or falling rate period moisture evaporation is much slower and more difficult to accomplish. The cooling tendency is greatly reduced allowing the temperature of the grain to rise rapidly. Below the critical moisture content slow drying occurs with a long retention time resulting in uniform drying (Bunn 1970, Gerzoi et al. 1961, Hall 1957 and Mounfield 1943).

The falling rate period of drying is controlled largely by the grain properties and often can be divided into two stages. The two stages are: (i) unsaturated surface drying and, (ii) drying where the rate of water diffusion within the product is slow and therefore becomes the controlling factor to the rate of drying. These stages are sometimes called the first falling rate period and the second falling rate period respectively. There are generally more than two falling rate periods.

Factors to be considered in selecting drying regimes include the temperature of the drying medium, the maximum allowable temperature of the grain and the duration of the heating interval. The temperature of the drying medium may be raised within certain limits if there is a simultaneous shortening of the drying time. With the correct combination of these three basic drying parameters, it is possible not only to preserve but even to considerably improve the quality of grain by drying. Several passes through the dryer are sometimes required to reduce the moisture content of the grain to a desirable level. Drying can give a reduction in acidity of the flour, an improvement in the baking qualities, an increase in elasticity of the dough and an increase in the sprouting capacity of the grain kernels (Gerzhoi and Samochetov 1961 and Mounfield 1943).

A maximum grain temperature of 43°C is usually recommended for drying wheat that is to be used for seed. For milling purposes temperatures above 60°C should be avoided. For feed grains 88°C is considered the high temperature limit although much higher air temperatures are used. The recommendations for temperature limits to avoid deleterious effects are usually given on the basis of drying air temperatures, whereas the important consideration is the temperature of the kernel. Furthermore, the temperature effect is coupled with the time of exposure to that temperature (Brooker et al. 1974, Stansfield and Cook 1929 and 1932).

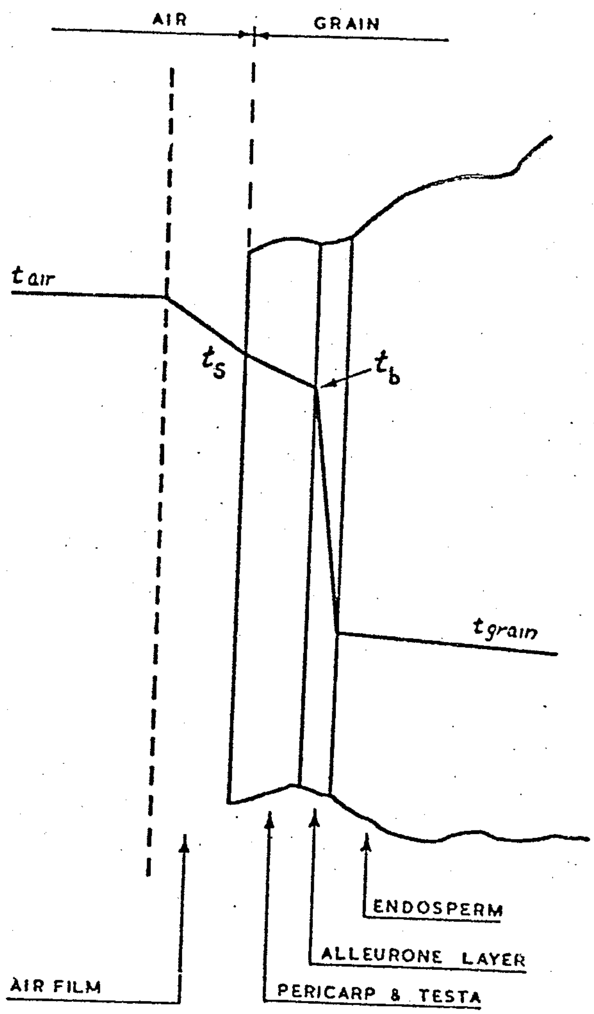
Johnson and Dale (1954) reported that grain moisture content during drying had the greatest effect on heat requirement. The other factors such as temperature of the drying medium and residence time were of minor significance. The average drying curve for wheat showed a heat requirement of 2.51×10^6 J/kg of water at a 14 percent MC dry mass basis (db). Mathematical models for mass diffusion and simultaneous heat and mass diffusion have been derived by various workers using numerical techniques (Husain et al. 1973 and Young 1969).

3.2 Drying of Wheat

Wheat grain behaves in many respects in the same manner as an inert nonliving material which obeys the semilogrithmic drying law. But wheat is a living substance in which physical and chemical changes are continually taking place. During the drying process the free water is removed from the grain, but if the grain remains exposed to continuing drying conditions it adjusts to the environment. It may adjust by undergoing physical changes in the colloidal materials in the cells or as a result of chemical reactions which produce other substances to reduce the loss of moisture e.g. by synthesis of carbohydrates or proteins as reported by McEwen et al. (1954).

It has been established by many investigators that water enters most readily at the embryo end which is the only part of the kernel not protected by the aleurone layer. These results suggest that the resistance to water penetration and the reverse process of water removal or drying is almost entirely concentrated in the aleurone layer which is not on the outside of the kernel but lies at the base of the pericarp or skin. This implies (i) that the rate of drying depends on the resistance of the aleurone layer in the kernel surface and (ii) that the resistance to movement of water in the interior of the kernel is negligible in comparison. These assumptions lead to the semi-logarithmic drying law. Figure 3.1 shows the temperature gradient for drying a wheat kernel.

The rate of drying depends solely on the properties of the kernel at the drying air temperature. The drying rate increases with an increase in air temperature and the



t_{air} = temperature of the air

t_s = temperature at the surface of the wheat

t_b = temperature at the top of alleurone layer

t_{grain} = temperature in the endosperm

FIG. 3.1 Temperature Gradients for Drying a Wheat Kernel (McEwen et al. 1954) equilibrium moisture content drops accordingly. The drying rate was found to be inversely proportional to the mean grain diameter. The rate of drying of a single kernel layer of wheat has been investigated by McEwen et al. (1954) and found to be independent of air velocity but it was greatly dependent on the air temperature. The rate was only slightly diminished by a four-fold increase in drying air humidity. The drying rate was found to be proportional to the moisture content of the grain, and the grain temperature was related to the moisture content at any given stage in the drying process.

A method was proposed by Simmonds et al. (1953) for predicting the rate of drying of wheat in shallow beds for different air velocities and temperatures. The experiments were conducted on a batch dryer in which hot air was circulated through the bottom of the dryer. The zone of vaporization extended throughout the bed of grain and the bottom was never completely dry. At the same average moisture content the spread of moisture throughout the bed increased with the depth of bed, but it was rapidly reduced as the average moisture content dropped. The drying of grain in a deep layer can be thought of as several thin layers in which the humidity and temperature of the air entering and leaving each layer varies with time depending on the stage of drying. Additional moisture will be removed from the dry layer until the equilibrium moisture is reached (Hall 1957). McEwen et al. (1954) found that an increase in bed depth or a decrease in either the porosity of the bed or the size of the kernels caused an increase in the observed pressure drop. Of the three variables considered, under similar drying conditions, the bed porosity had the greatest influence on the pressure drop.

Gerzhoi and Samochetov (1961) suggested that the use of intermittent (multistage) drying may improve the drying process. Increasing the temperature of the drying medium in the second stage provides the possibility of more intensive heating of the grain and better conditions for the movement of moisture from the inner grain layers to the surface. Variable temperature heating has been suggested to accelerate the drying process while preserving the quality of grain. An increase in the drying efficiency was found by successively heating and cooling the grain.

3.3 Drying Using a Solid Heat Transfer Medium

Attempts to use a solid as a drying medium date back to 1948 when Dexter and Creighton (1948) were searching materials for desiccant drying of grain. Porous materials such as sand, wood, corn cobs and straw were impregnated with solutions of calcium chloride, magnesium chloride or other desiccants. Such impregnated materials were found to be effective in removing moisture from hay or grain in mows or bins. Dexter et al. (1969) mixed salted sawdust with high moisture content corn and beans and placed the mixtures in storage. The salt took up moisture to form a saturated solution which was held by the sawdust, consequently molding of the grain was avoided. Gerzhoi et al. (1961) reported drying by placing grain in contact with the outer surface of heated tubes, the moisture evaporated and was absorbed by the surrounding medium. The resulting drying was found to be uneven and inefficient.

Many researchers have investigated conduction heat transfer as a means to increase the efficiency of grain drying. Some of these results are summarized in Table 3.1. G. Hall and C. Hall (1961) determined the characteristics of conduction drying by heating thin layers of shelled corn on a steel plate heated to a temperature of 100°C. Conduction drying was found to be faster than conventional air drying and natural convection was sufficient to carry away the evaporated moisture. The rate of drying was proportional to the plate temperature. Similar studies were made by Finney et al. (1963) to investigate the drying efficiency of conduction drying of shelled corn. Drying rates

Table 3.1 Summary of Work Done on Drying and Processing Grains Using Solid Heat Transfer Media by Various Investigators

Investigator(s) (1)	Grain type (2)	Heat transfer device (3)	Initial temp. of device (°C) (4)	Results (5)
G. Hall & C. Hall (1961)	Shelled Corn	Heated Steel Plate	100	(i) 70% efficiency (ii) Faster drying than conventional
Finney, et al. (1963)	Shelled Corn	-Do-	38-77	Faster and more efficient
Chancellor (1968)	Paddy Rice	-Do-	93	24 to 14% MC in 4 hours
Benson (1964)	Cereal Pieces	Heated Salt Bed	Different temp.	Continuous process for puffing in 20 sec.
Bateson & Harper (1970)	Pieces of Food Product	Heated Granular Bed	-Do-	-Do-
Raghavan & Harper (1973)	Shelled Corn	Heated Salt Bed	232	21 to 14% MC in 30 sec.
Iengar, et al. (1971)	Paddy Rice	Heated Sand	150	(i) Drying and parboiling in 20 min. (ii) Moisture reduced 30 to 16%
Lapp (1973)	Rapeseed	(i) Fine hot sand (ii) Steel ball (0.91 mm ϕ)	232	(i) 4.3 to 7.0% MC reduction in 2 min. (ii) Varying SGMR (2.5:1 to 8:1)
Lapp & Manchur (1974)	Rapeseed	Hot Sand	157	(i) 3.0 to 4.5% MC reduction in 30 sec. (ii) 45 to 55% efficiency (2.5:1 to 4:1 SGMR)
Khan, et al. (1974)	Paddy Rice	Heated Sand	150-180 204	65% efficiency in continuous dryer. 30 to 14% MC in 15 sec. with 20:1 SGMR.
Lapp et al. (1975)	Wild Rice	-Do-	150	Six stage, 16:1 SGMR with 2 min in each stage 70 to 10% MC
Manchur (1975)	Rapeseed	-Do-	130-190	3.7 to 5.8% MC reduction with 3:1 SGMR, 64.5% efficiency

and kernel damage were determined for temperature ranges from 38 to 77°C. They concluded that the drying rate could be defined by Newton's equation as in the case of conventional air drying. An average drying efficiency as high as 70 percent was obtained when forced air was passed over the heated grain to remove the evaporated moisture.

A conduction dryer composed mainly of a horizontal metal surface placed over a hot fire pit was reported by Chancellor (1968a, b). He dried 455 kg of paddy rice (Oryza sativa L.) from 24 to 14 percent MC in four hours when the metal surface heated to 93°C. Excessive localized heating of kernels at the point of contact with the steel plate was a problem. Chancellor suggested a granular medium such as sand to reduce excessive localized heating on the kernels. He concluded that this method of grain drying was a process in which heat energy entered individual kernels and water vapor evaporated. The rate of moisture loss was dependent upon the net rate of energy entry into the grain. Drying was independent of diffusion and drying rates were found to exceed those of heated air dryers.

Khan (1973) reported that hot sand has been traditionally used for uniformly roasting rice, wheat and corn in the Indian subcontinent. The use of hot sand for partial drying of rice during the parboiling process was an ancient practice in India. Laboratory studies concluded that the simultaneous parboiling and drying of paddy rice was feasible. Due to gelatinization more rice yield and less broken kernels were obtained after hulling. Optimum results were obtained using a 20 to 1 sand to grain mass ratio (SGMR) with a sand temperature of 204°C. These conditions reduced the MC of paddy from 30 to 18 percent in 15 s.

A continuous flow dryer using the above principle was also developed by Khan et al. (1974). They extracted 9.7 percent moisture from paddy at a paddy feed rate of 146 kg/h using a SGMR of 10.3:1 and a sand temperature of 204°C. The drying efficiency was 55 percent and increased to 65 percent if the moisture removed during the cooling of the grain was also considered. A sand temperature of 150 to 180°C produced the most desirable color for milled rice.

A small continuous flow dryer was built by Raghavan and Harper (1974) using heated granular salt. The dryer consisted of a rotary drum 61 cm in diameter and 76 cm long, fitted with a perforated helix inside the drum for conveying and separating the grain from the salt. Corn was dried from 21 to 14 percent MC in 20 s in a salt bed maintained at 232°C. Benson (1966) used an agitated bed of heated salt to rapidly heat and puff cereal pieces in 20 s. Bateson and Harper (1973) developed an apparatus and described a continuous process for puffing pieces of food products with heated granular materials.

Raghavan et al. (1974) reported that fluidized beds produce better heat transfer coefficients than air. However, they lack uniformity in residence time control and require special means to separate the particulate matter being processed. Drying by conducted heat differs from the heat transfer in a fluidized bed since it does not involve a fluidized medium and the main mode of transfer is by contact between the solid medium and the grain kernels. Particle to particle heat transfer can exchange large quantities of heat economically, uniformly and without product contamination. Raghavan et al. (1974) also found that the heat transfer coefficient per impact was larger for coarse particles than for fine particles of salt. Although the heat transfer per impact was less for fine salt, the product of the number of impacts and the heat transfer per impact was greater.

A continuous dryer using hot sand was developed by Iengar et al. (1971) in which sand was heated through a heat exchanger by burning paddy husks and other agricultural wastes. By mixing paddy with sand heated to 150^{o}C for

20 min simultaneous parboiling and drying occurred.

Lapp (1973) initiated bench experiments beginning in 1972 using heated fine textured sand and steel balls approximately 0.91 mm in diameter to investigate the feasibility of obtaining efficient moisture removal from rapeseed. In initial drying trials SGMR of 2.5:1, 5:1, and 8:1 with sand heated to approximately 232°C were used. The residence time of the samples in the bench drum dryer was about two minutes. Trials with initial MC of rapeseed at 19.0, 17.0 and 16.0 percent yielded MC after drying of 13.3, 12.0 and 9.3 respectively. Initial laboratory success led to further investigations which resulted in the construction of a prototype dryer with which Lapp and Manchur (1974) reported moisture reductions ranging from 3.0 to 4.5 percent in 30 s using a sand temperature of 157°C. Drying of oilseeds using hot fine textured sand was achieved at drying efficiencies ranging from 45 to 55 percent. Manchur (1975) reported reducing the MC of rapeseed by 3.7 to 5.8 percent using a SGMR of 3:1 with initial sand temperatures ranging from 130 to 190°C with an average drying efficiency of 64.5 percent.

Lapp et al. (1975) applied the heated solid medium principle to accomplish gelatinization, drying and parching of wild rice (<u>Zizaria aquatica</u> L.) in laboratory trials.

A six stage experiment using a sand temperature of 150°C and a SGMR of 16:1 was conducted to dry wild rice. Samples were dried for two minutes in each stage and the six successive stages reduced the MC of the wild rice from 70 percent to less than 10 percent. The dried rice had a low percentage of popped and hollow-centered kernels ranging from 3 to 5 percent and possessed a dark color which is desirable for wild rice.

CHAPTER IV

DRYING INVESTIGATIONS USING A SMALL BATCH DRYER

4.1 Description of the Batch Dryer

A model batch dryer was constructed for use in this investigation (Figure 4.1). The main component of the model was an aluminum drying bucket 29.3 cm inside diameter and 22.9 cm deep. The net volume was approximately 0.0153 m^3. The bucket was equipped with a removable lid (Figure 4.2). 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. Quick release clamps were installed on the outside of the bucket to facilitate rapid placement and removal of the lid during drying trials. Two 1.3 cm diameter vents to permit the escape of moisture were provided in the lid. They were located 2.5 cm radially from the center. One of these vents was also used to insert a small propane torch for preheating the drying bucket. A third hole in the center of the lid carried a glass thermometer to measure the temperature inside the drying bucket (Lapp et al. 1975).

The bucket assembly was mounted on a supporting yoke carried by a floor stand 0.91 m high. The yoke had an angular adjustment with a control quadrant to permit select-

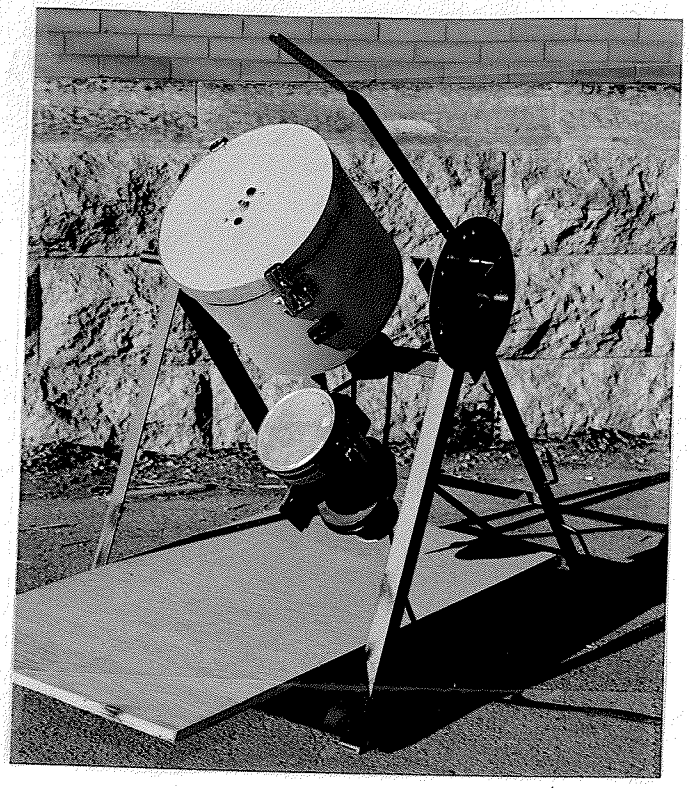


FIG. 4.1 Front View of Small Solid Heat Transfer Medium Batch Dryer

FIG. 4.2 Inside View of Drying Bucket of Small Batch Dryer

ed positioning of the bucket. The bucket was normally positioned upward for loading, horizontally for drying and inclined downward for dumping. 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 (Figure 4.3). A cage containing six mixing blades extending 3.8 cm from the wall and 22.9 cm long was installed inside the bucket to improve the mixing action of the sand and grain (Figure 4.2).

4.2 Operation of Dryer

Silica sand having a 12-30 texture (0.589 to 1.651 mm particle size) was used. Sand having a 12-30 texture means grain sizes which pass a 12-mesh screen (12 openings per 2.54 cm length) and retained on a 30-mesh screen (30 openings per 2.54 cm length). Auxiliary laboratory equipment employed to conduct the experiments included a sieve for separating grain and sand, thermometers, a balance, a propane torch, electric ovens, enamel sand trays, asbestos gloves and a stop watch.

4.2.1 Grain conditioning

The desired initial moisture levels were achieved by adding a measured quantity of water to the wheat. The

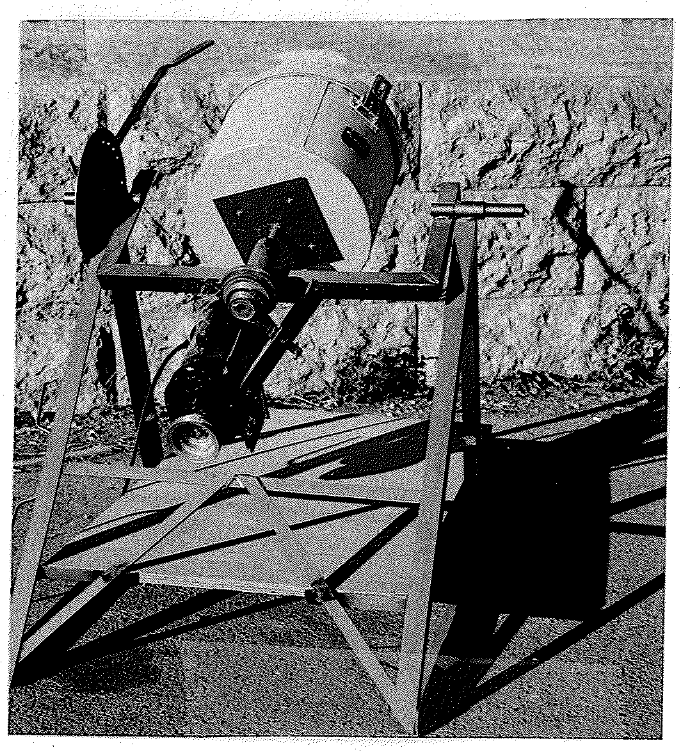


FIG. 4.3 Backview of Small Batch Dryer Driving Mechanism

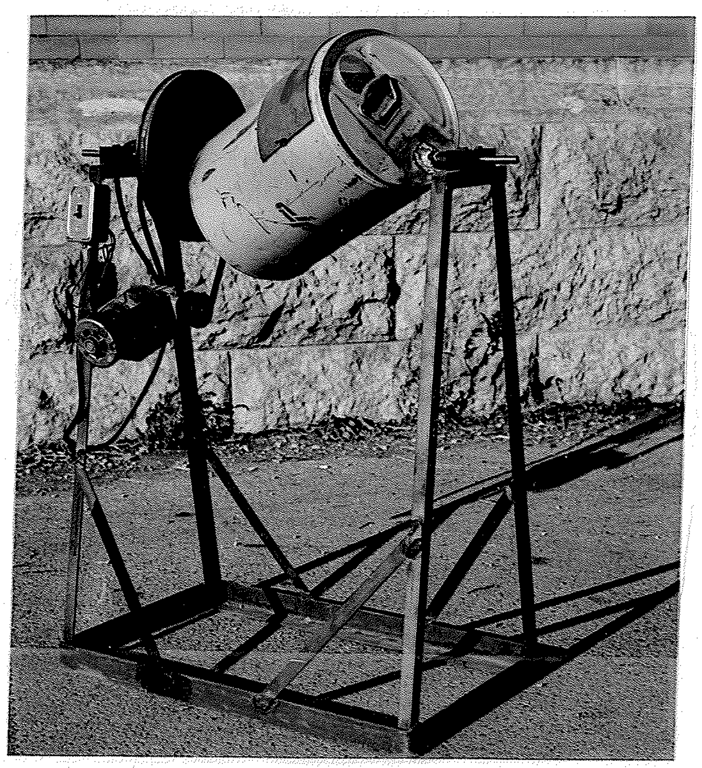


FIG. 4.4 Grain Conditioner

amount of water to be added was calculated as noted below:

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

A moisture conditioner was fabricated as illustrated in Figure 4.4. The main component of the unit was a metal drum 28 cm in diameter and 38 cm long mounted on a suitable yoke. The drum was mounted diagonally on a horizontal shaft driven by a 95 watt electric motor. It accomplished mixing by rotation. The measured quantity of water for a given grain sample was mixed in the rotating drum for 30 min. After mixing the wheat was stored for at least four days in a refrigerator. This procedure as described by Ghaly et al. (1973) and Warner and Browne (1962) insured uniform moisture throughout the grain sample. The grain was removed from the refrigerator and held at room temperature for 24 hours prior to drying.

Artificial dampening has sometimes been criticized since the grain is not typical of freshly harvested grain. Nevertheless, grain as received at the dryer from a combine may be extremely variable in MC. Grain dampened by the above standard procedure is at least consistent. The results obtained by drying field harvested and conditioned grain justified the use of dampened grain in test dryers as observed by Aykroyd and Joyce (1970) and Hustrulid (1963).

4.2.2 Testing procedure

A 500 g sample of Neepawa wheat was selected as a base and the mass of sand was varied to give the desired SGMR. The predetermined mass of sand was poured into an enamel tray and heated in an electric oven to the required temperature. The drying bucket was preheated to the desired temperature using a small propane torch prior to each set of drying trials.

The wheat and the sand were put into the bucket while the bucket top was in a vertical position. The mixture of sand and wheat was emptied from the bucket when the desired time had elapsed. The wheat and sand were then separated and the temperature of the wheat was measured.

4.2.3 Grain moisture measurement

The moisture content of the grain was measured with a Halross moisture meter model 919, which has an accuracy of ±0.10 percent using a 150 g grain sample. The oven drying method was used for checking the meter accuracy, according to ASAE standard (ASAE Yearbook 1976) by keeping the oven temperature at 130^{o}C for 19 h.

4.2.4 Quality testing

Dried wheat samples were sent to the Grain Research Laboratory of the Canadian Grain Commission in Winnipeg to assess the effect of drying on the gluten quality for baking purposes. This was assessed by the Mixograph test in which the resistance during mixing was recorded. The moving and mixing parts contain two pairs of pins supported and geared to describe a planetary motion. The resistance of the dough when pulled by the upper pins against the fixed pins tends to thrust the bowl on its support (Quisenberry and Reitz 1967 and Swanson 1938). The curves obtained yield information about changes in the rheological properties during mixing. The curves normally consist of a rising part showing an increase in resistance with mixing time, followed by a more or less slow decrease in resistance. The records are usually interpreted in terms of dough development time and subsequent breakdown time (Pomeranz 1971).

4.2.5 Curve characteristics

Characteristics of quality curves were described by Pomeranz (1971), Quisenberry and Reitz (1967) and Swanson (1938) as discussed below.

A. Dough development time:-As soon as the flour particles are wetted, gluten develops accompanied by an increase in resistance imparted to the moving upper pins which is displayed by the recording pen moving away from the lower side of the chart. The resistance which is small at first increases rapidly and the pen moves out nearly in a straight line. The rate at which dough develops has been found to be a quality characteristic.

B. Absorption protein factor:-The height of the curve is influenced by the stiffness of the dough because of the greater twist given to the bowl by the movement of the pins through the dough. The height is also influenced by the amount of protein since the density of the three dimensional gluten network of the dough is a function of protein content. However, the quality of the protein will also influence the height of the curve since this is a factor in the strength of the gluten filaments.

C. Peak elasticity:-The resistance is greater when a pair of the moving pins moves away from one of the fixed pins than when the moving pair approaches a fixed pin. The recording pen oscillations and the amplitude of this movement or the width of the curve is due to elastic properties of the dough. Variation in this elasticity is apparently due to the quality of the protein.

D. Final elasticity:-After the curve has reached the peak which occurs at the point of highest resistance of the dough, the pen oscillations begin to decrease. This is apparently due to the severing of the protein chain links at the point of junction. The occurrence of this decrease depends on the quality inherent in these gluten chains.

Five catagories or standards of quality were used for assessing the Mixograms obtained from the dried wheat samples. The standard curves for the Mixograms (shown in Figures A.1 to A.5) were chosen from all curves obtained and were defined as follows:

Category 0 - quality unchanged

Category 1 - reduced quality

Category 2 - severely reduced quality

Category 3 - damaged quality

Category 4 - severely damaged quality

4.2.6 Germination test

Germination tests were performed using four replications in 9 cm petri dishes. In each petri dish 25 seeds were placed on a pad of two filter papers (Whatman No. 42) wetted with 5 cm^3 of distilled water. Samples were then placed in a constant temperature room at about 20°C. The rate of germination (after three days) and the ultimate germination (after six days) were determined for all treated samples. Results were recorded as a percentage of the untreated controls, which were treated similarly in all respects except drying. This method of germination testing was described by Ghaly et al. (1973) and Warner and Browne (1962).

4.2.7 Experimental design

The selected values of the experimental variables involved in the study were as follows:

i) sand to grain mass ratio 3:1, 4:1, 5:1, 6:1 and 8:1

ii) initial sand temperature 90, 100 and 110°C

iii) residence time 1, 2 and 3 minutes

Factors that were held constant in all experiments were, silica sand having a texture of 12-30, Neepawa wheat initially conditioned to approximately 17 percent MC and a rotating drum speed of 24 rev/min. A randomised experimental design was used. Three replications were used for each set of variables and the average of each was determined.

4.3 Results and Discussion

The results from the drying trials involving variation in temperature, SGMR and drying times are recorded in Table 4.1. The results have been arranged in ascending order of SGMR. Moisture content reductions from the initial MC of about 17 percent ranged from 2.0 to 3.9 percent. The desired reduction of MC (2.5 percent) occurred in many tests. The temperature of the wheat dried with hot sand varied from 50 to 90°C after drying.

The baking quality of the grain must not be reduced by any drying process. Baking quality tests were performed by the Grain Research Laboratory of the Canadian Grain Commission. The results indicated that wheat was dried from 17.0 to 14.5 percent MC without damage to its baking quality as noted in Figure 4.5. The optimum conditions for drying as determined from these experiments are listed in Table 4.2.

4.3.1 Effect of sand to grain mass ratio

An increase in the SGMR above 5:1 showed no significant increase in the quantity of moisture removed. In some tests the total quantity of moisture removed decreased as noted in Figure 4.6 and 4.7. Higher quantities of sand resulted in increased sand to sand particle contact. When this happened the sand was in contact with sand instead of grain and there was no potential for heat transfer bet-

Table 4.1 Results of the Wheat Drying Using Hot Sand in Batch Dryer

Sand to grain mass ratio	Residence time (min)	Percent moisture reduction (wb)	Sand temp. (°C)		Grain temp. (°C)	
			Initial	Final	Initial	Final
3:1	1	2.00	100.0	56.0	21.0	50.0
	2	2.33	100.5	55.3	20.8	51.5
	1	2.20	120.0	72.0	22.0	65.0
	2	2.45	120.0	69.0	22.0	66.0
	1	2.53	139.0	98.0	22.0	82.0
	2	3.88	138.0	96.0	22.0	90.0
4:1	1	2.20	90.0	58.0	22.0	51.0
	2	2.25	90.0	57.0	22.0	52.5
	3	2.00	90.0	56.0	22.0	52.0
	1	2.31	100.3	64.0	21.4	53.6
	2	2.43	100.3	59.6	21.4	54.3
	3	2.33	102.3	58.2	21.5	53.0
	1	2.43	109.5	66.2	20.3	60.0
	2	2.58	110.0	65.5	20.3	60.8
	3	2.54	110.0	63.7	20.3	58.8
5:1	1	2.20	92.0	59.5	22.0	52.5
	2	2.25	92.0	57.5	22.0	54.0
	1	2.38	101.5	68.3	21.8	60.8
	2	2.50	101.5	68.5	22.0	61.8
	3	2.47	101.2	62.7	22.7	57.5
	1	2.45	112.0	71.0	23.5	62.0
	2	2.55	112.0	70.0	23.5	62.0
	3	2.50	112.0	68.0	23.5	57.0
6:1	1	2.00	89.0	61.0	17.0	54.0
	2	2.10	90.0	62.0	18.3	56.0
	3	2.05	90.0	59.0	17.0	54.5
	1	2.38	100.3	70.5	20.8	62.0
	2	2.47	100.8	70.5	21.4	62.7
	3	2.45	100.7	66.8	20.8	60.5
	1	2.42	109.7	72.3	20.7	65.0
	2	2.50	107.2	72.8	21.5	65.6
	3	2.48	110.5	71.8	20.5	64.9
8:1	1	2.05	91.0	68.5	19.5	60.0
	2	2.25	92.0	69.0	19.5	60.5
	3	2.15	91.0	68.0	19.5	61.0
	1	2.13	100.0	68.0	20.0	60.0
	2	2.33	99.0	68.5	21.2	60.8
	3	2.47	99.0	71.5	21.0	64.8
	1	2.25	110.0	79.0	24.0	70.5
	2	2.55	110.0	77.5	24.0	69.5
	3	2.60	109.5	77.0	24.0	68.0

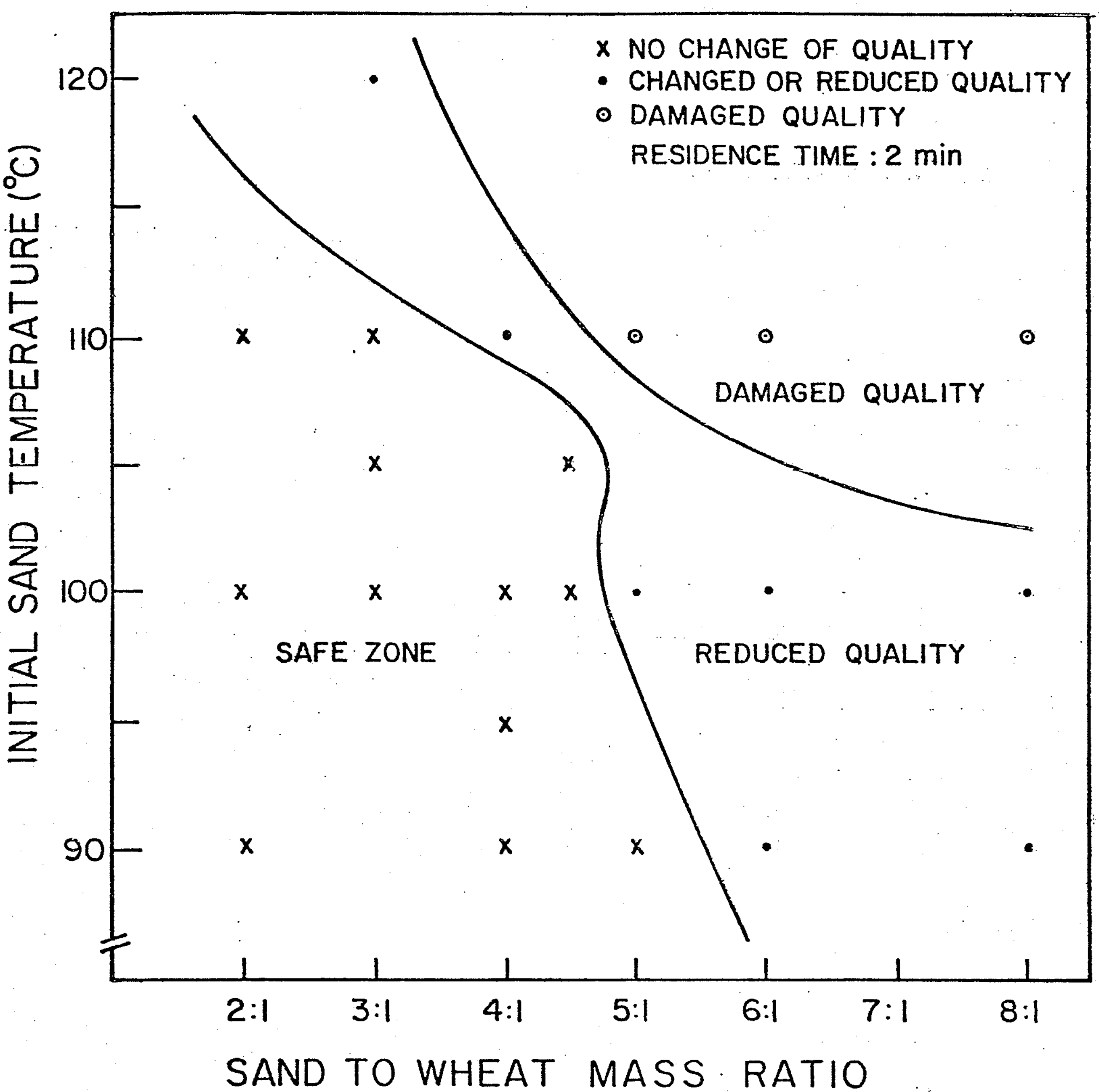


FIG. 4.5 Effect of Drying on Quality of Wheat

Table 4.2 Optimum Drying Conditions for Wheat Using Heated Sand

Sand temp. (°C)	Sand to grain mass ratio	Residence time (min)
100	4:1	2
105	4.5:1	1
90	4:1	2[a]

[a]Two stages - one minute/stage.

ween the sand particles of the same temperature. A lower SGMR allows more sand to wheat kernel contact and provides a potential for heat transfer from the higher temperature sand to the lower temperature wheat kernels. The presence of a large quantity of sand surrounding wheat kernels also provides a physical barrier to the escape of moisture from the kernels.

An analysis of variance showed significant differences among the various treatments at the five percent level (Table B.1). There was no significant difference between different SGMR at initial sand temperatures of 100 and 110°C using a residence time of three and two minutes respectively. A comparison between different treatments also showed significant differences in drying at the five percent level. There was no significant difference in drying between treatments using SGMR of 3:1 versus 8:1, 4:1 versus

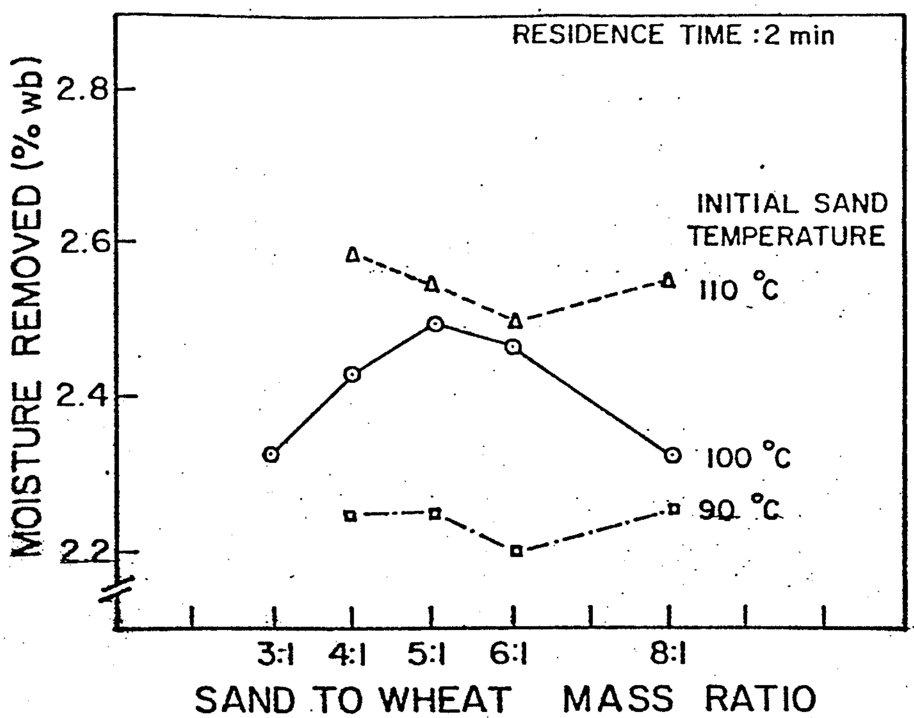


FIG. 4.6 Percent Moisture Removed from Wheat as a Function of Sand to Wheat Mass Ratio for Different Initial Sand Temperatures with Two Minutes Residence Time

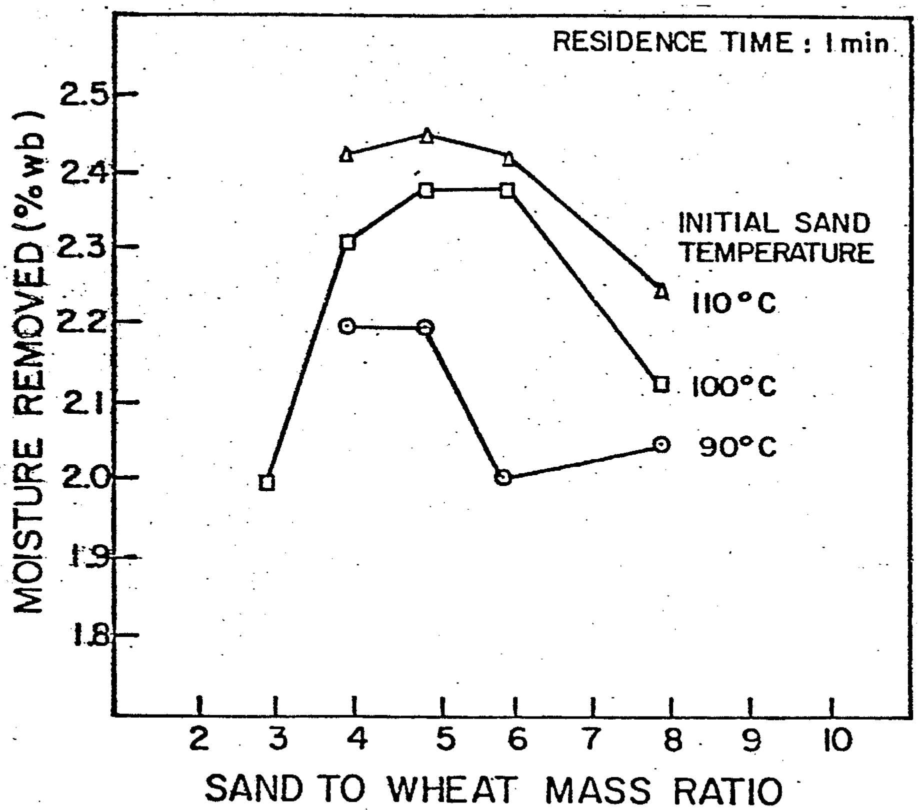


FIG. 4.7 Moisture Removed from Wheat as a Function of Sand to Wheat Mass Ratio for Different Initial Sand Temperatures with One Minute Residence Time

5:1 and 4:1 versus 8:1.

4.3.2. Effect of initial sand temperature

At higher sand temperatures greater quantities of moisture were removed as noted in Figures 4.8 and 4.9. This was also observed by Chancellor (1968), Hall and Hall (1961), Khan (1973) and Manchur (1975) for other grains using solid heat transfer media. Thus the rate of moisture removal from wheat is directly proportional to the net amount of energy entering into the grain. An analysis of variance test (Table B.2) showed significant differences among treatments at different temperatures. There was no significant difference in drying using SGMR of 4:1 with one minute residence time and SGMR of 5:1 with one and two minutes residence times. A comparison between different temperature treatments also indicated the significant differences as noted in Table B.2.

4.3.3 Effect of residence time

An increase in drying time from one to two minutes gave a corresponding increase in the amount of moisture removed. A further increase in the drying time from two to three minutes slightly decreased the amount of moisture removed compared to two minutes residence time as noted in

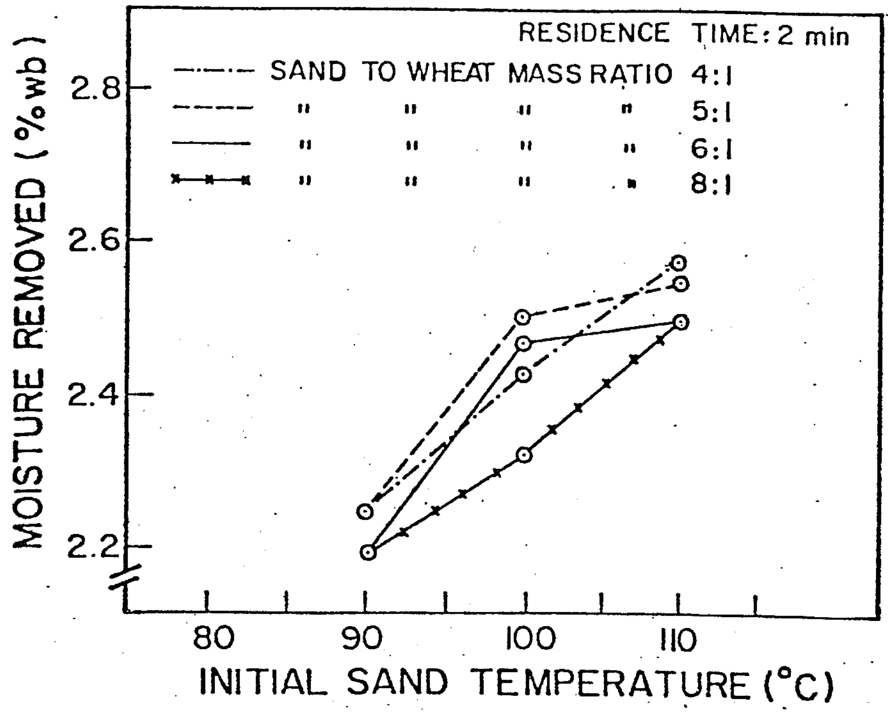


FIG. 4.8 Percent Moisture Removed from Wheat as a Function of Initial Sand Temperature for Different Sand to Wheat Mass Ratios

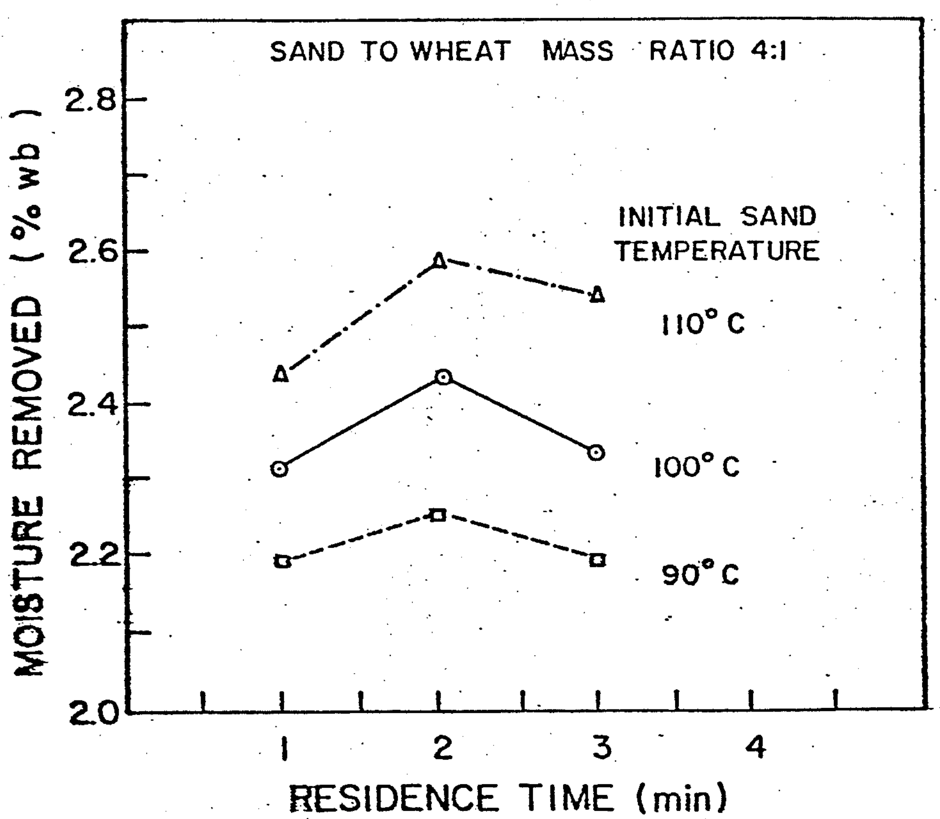


FIG. 4.9 Percent Moisture Removed from Wheat as a Function of Residence Time for Different Initial Sand Temperatures

Figures 4.9 and 4.10. An analysis of variance indicated no significant difference among residence time differences as noted in Table B.3 except for the SGMR of 8:1 at 100°C sand temperature. No significant difference was noticed by making a comparison between different residence time treatments. It was concluded that a two minute residence time was optimum and that no benefit was gained by increasing the residence time further.

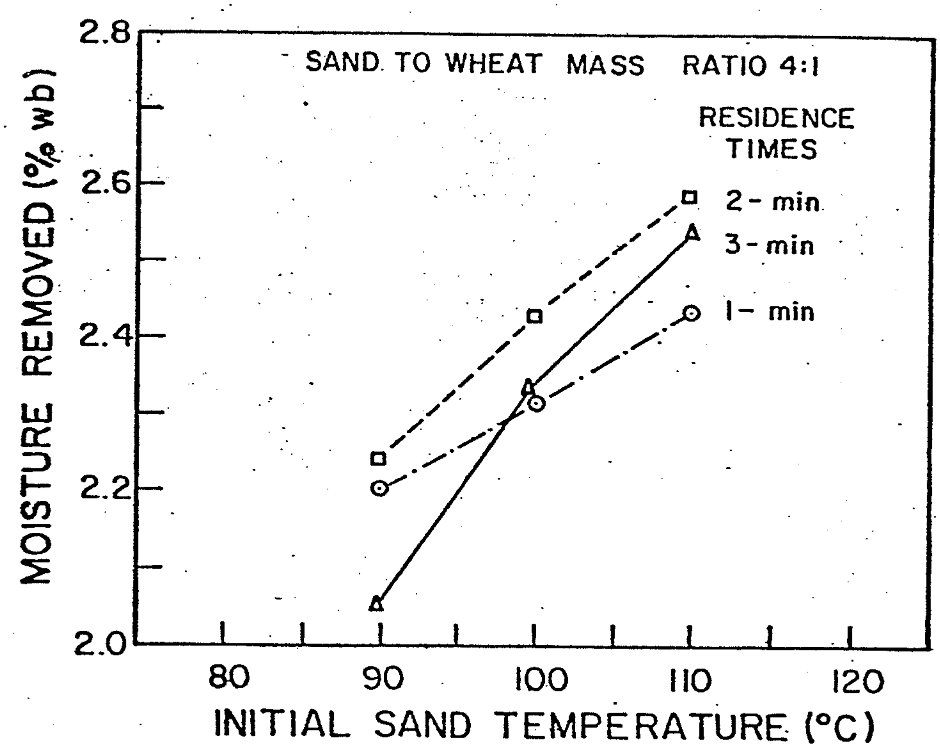


FIG. 4.10 Percent Moisture Removed from Wheat as a Function of Initial Sand Temperature for Different Residence Times

4.3.4 Effect on germination

Germination counts after three days for different drying treatments were recorded and are shown in Figure 4.11. The six days germination counts were also recorded and shown in Figure 4.12. The germination counts showed that samples dried using optimum drying parameters (time, temperature and SGMR), as shown in Table 4.2, did not undergo serious reduction in germination quality. The three day germination count of dried samples had a count in excess of 90 percent of the germination count obtained from the undried samples, while the six day count of the dried samples was in excess of 95 percent of the undried samples. These favorable germination counts were obtained from samples dried using the optimum parameters of temperature, time and SGMR as determined experimentally during the course of this investigation.

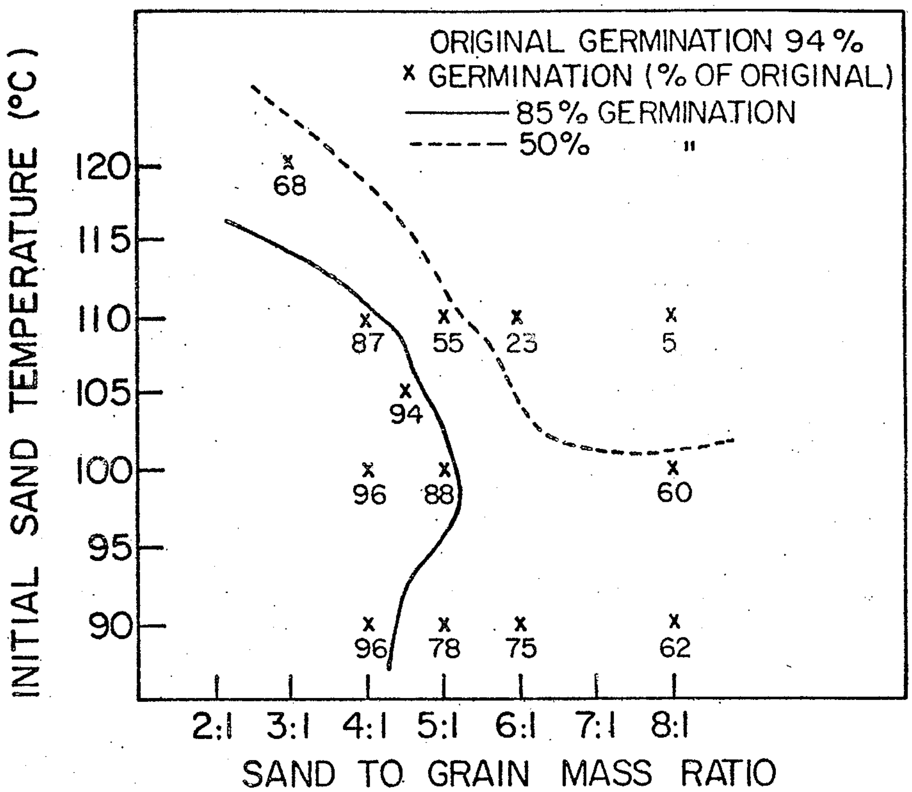


FIG. 4.11 Effect of Drying with Hot Sand on Rate of Germination of Wheat (Three Day Germination Count)

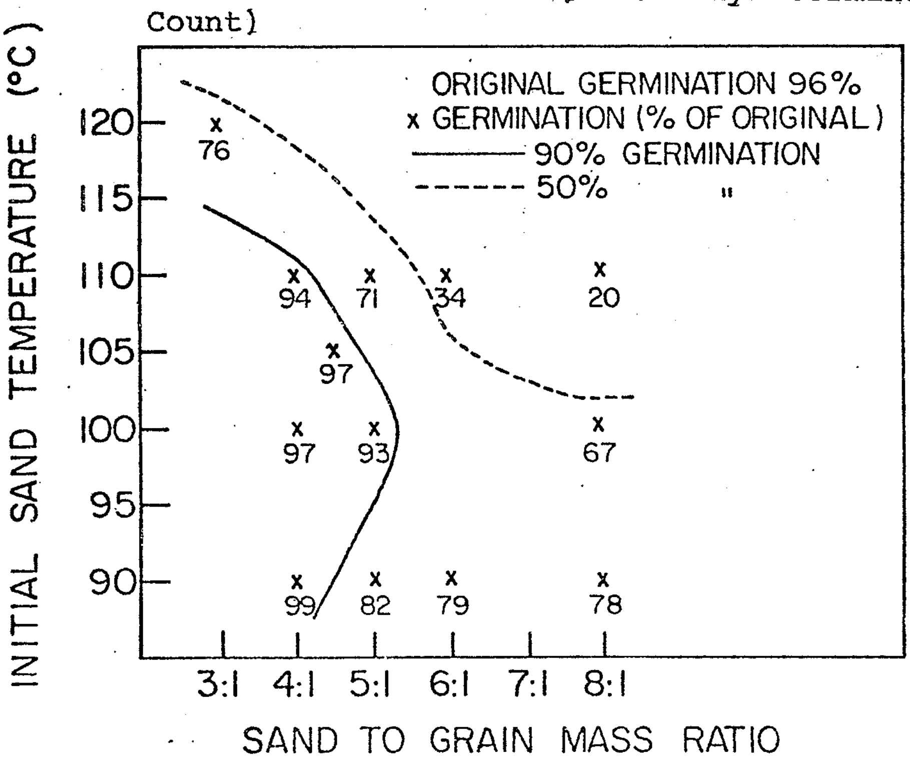


FIG. 4.12 Effect of Drying with Hot Sand on Ultimate Germination of Wheat (Six Day Germination Count)

CHAPTER V

CONTINUOUS FLOW SOLID HEAT TRANSFER MEDIA GRAIN DRYER

5.1 Description of Prototype Dryer

The prototype dryer (Figure 5.1) used for this investigation consisted of a rotating drum 3.05 m long with 43.2 cm inside diameter. 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 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. The rollers on which the drum rotated consisted of six 7.6 cm diameter rubber casters. The casters were in contact with three roller guides attached to the cylinder. The roller guides were adjustable to maintain the alignment. The same adjustment insured that the small gear remained in mesh with the large gear on the cylinder. The small gear was rubber mounted to allow for deflection which would occur if any eccentricities occurred in the system.

Two hoppers one for damp grain and one for hot sand

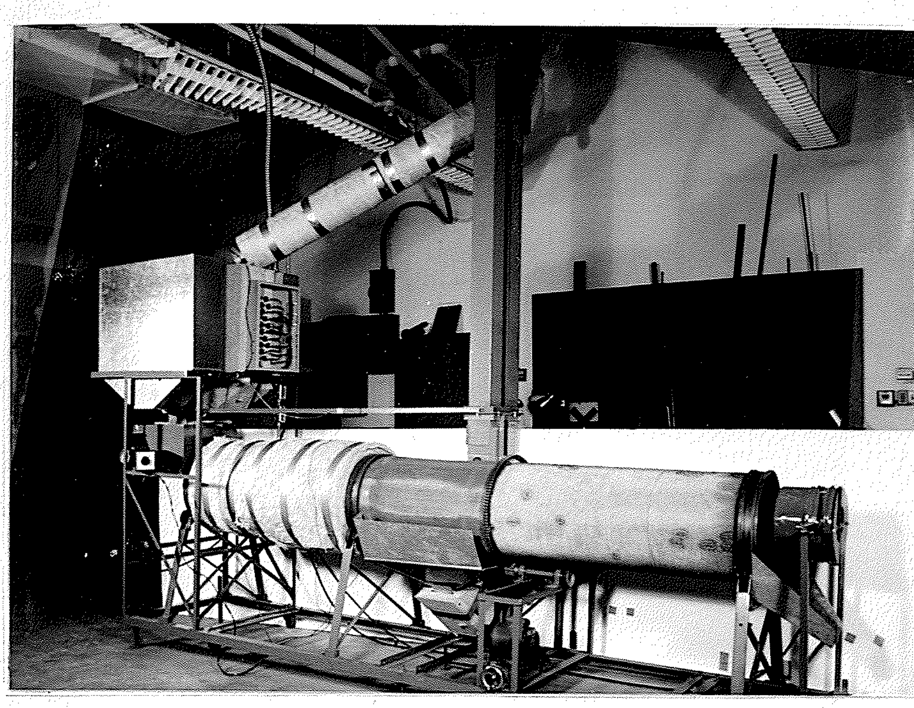


FIG. 5.1 Continuous Flow Prototype Dryer Using Solid Heat Transfer Media

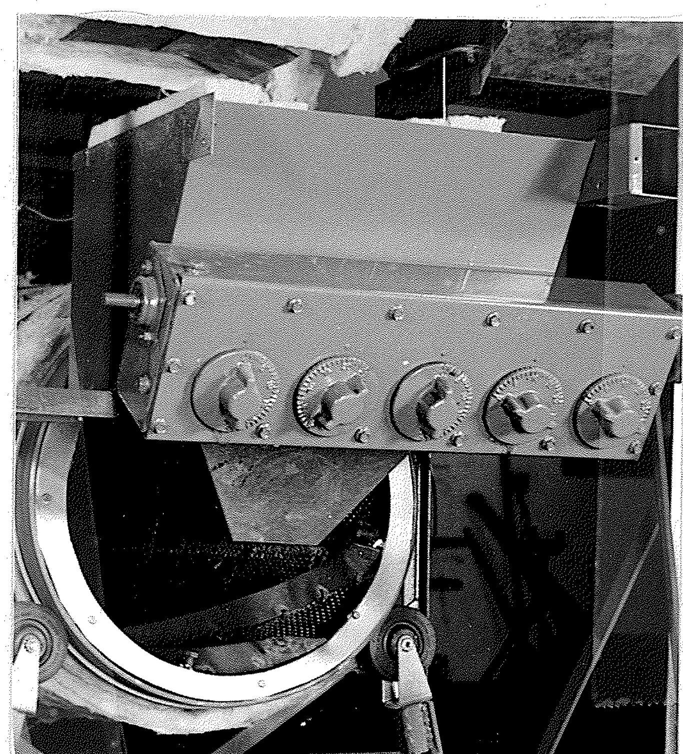


FIG. 5.2 Metering Head for Regulating Flows of Sand and Grain

were mounted above the drying section inlet. These hoppers delivered the grain and sand into the metering head. The metering head (Figure 5.2) was a component from a conventional Mix-mill. It was used to deliver 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. The frame was also provided with casters for moving the dryer from place to place (Lapp and Manchur 1974).

The residence time of the sand and grain in the drying section could be regulated by varying the cylinder slope, the rotational speed or the feed rates. Mixing and axial movement of the sand and grain was assisted by small, gently curved spiral flights attached to the interior of the cylinder in the drying and cooling sections.

The screened separating section (Figure 5.3) consisted of steel wire cloth that separated the sand from the grain after the mixture had passed through the drying section. The sand was then recirculated to the sand hopper by a 3.05 m bucket elevator and a 15.2 cm diameter pipe insulated with fiber glass. A special high temperature belt was used in the elevator because of high sand temperatures. The sand hopper had a storage capacity of about 0.84 m^3 and contained ten 230 volt, two kW Calrod electric heating elements. These heaters were placed on three separate circuits with circuit breakers on each circuit. The sand hopper was insulated with 5.1 cm of rigid fiber glass. A fan of 17 m^3/min capacity was installed at the end of the cooling section. The fan helped to cool the grain and removed moisture which was expelled in the drying section.

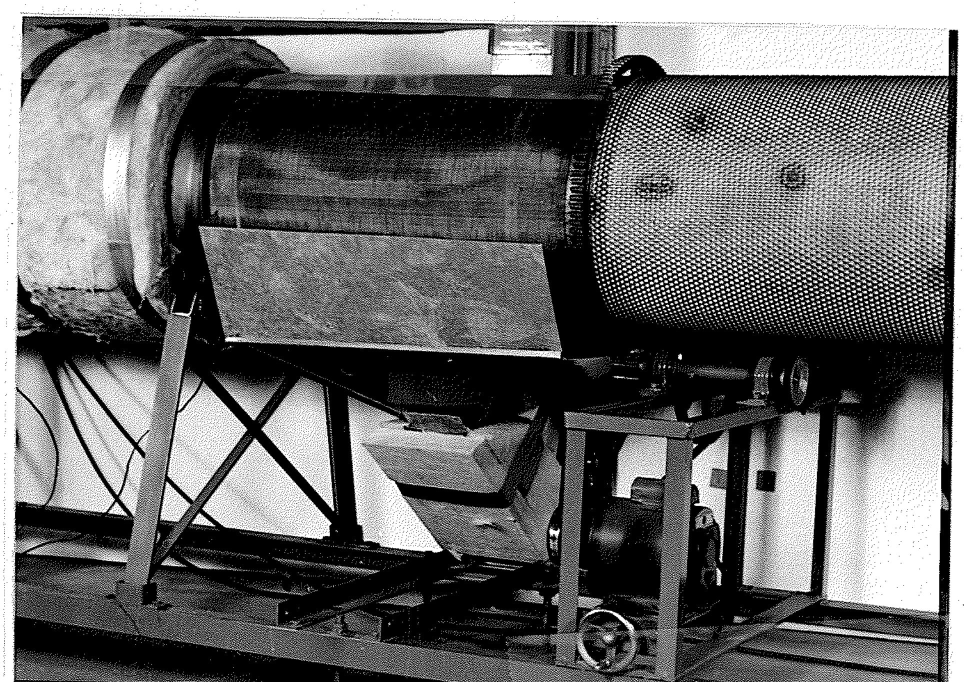


FIG. 5.3 Screened Separating Section, Driving Mechanism for Cylinder and Sand Collector for Recirculation.

5.2 Testing Procedure

The metering head had individual controls for adjusting the flow rates of sand and grain. There were four openings on the metering head. Two were used for sand and one was used for wheat. The metering head was calibrated by weighing the amount of sand and wheat delivered over a period of one minute respectively. The calibration curves were found to be linear as shown in Figures 5.4 and 5.5. The grain flow rate and the sand flow rate were determined for the desired sand to grain mass ratio. The appropriate meter settings were determined using Figures 5.4 and 5.5.

The wheat was conditioned to about 17 percent moisture content by the addition of water as discussed in section 4.2.1. Each lot was stored in sealed containers at room temperature and mixed daily for a brief interval for at least five days before use. This insured uniform distribution of moisture. The moisture content was measured as discussed in section 4.2.3.

The adjustable legs on the dryer were set for a drop of 6.8 cm in the 366 cm length of the frame. The cylinder slope was approximately 1.1 degrees. The residence time of the sand and wheat mixture in the drying section was found to be about one minute when the cylinder

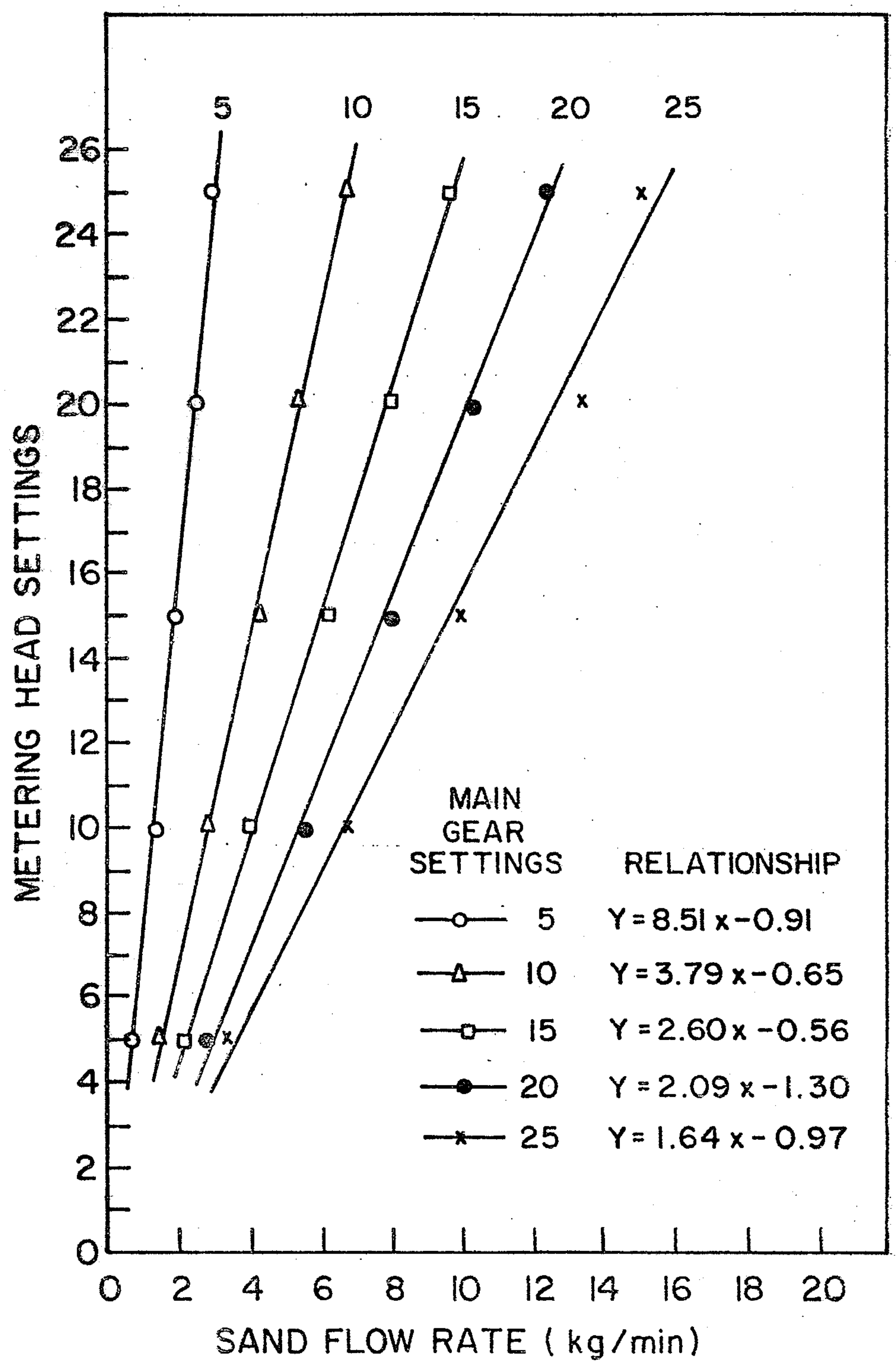


FIG. 5.4 Flow Rates of Sand for Various Control Settings of the Metering Head for Different Main Gear Settings

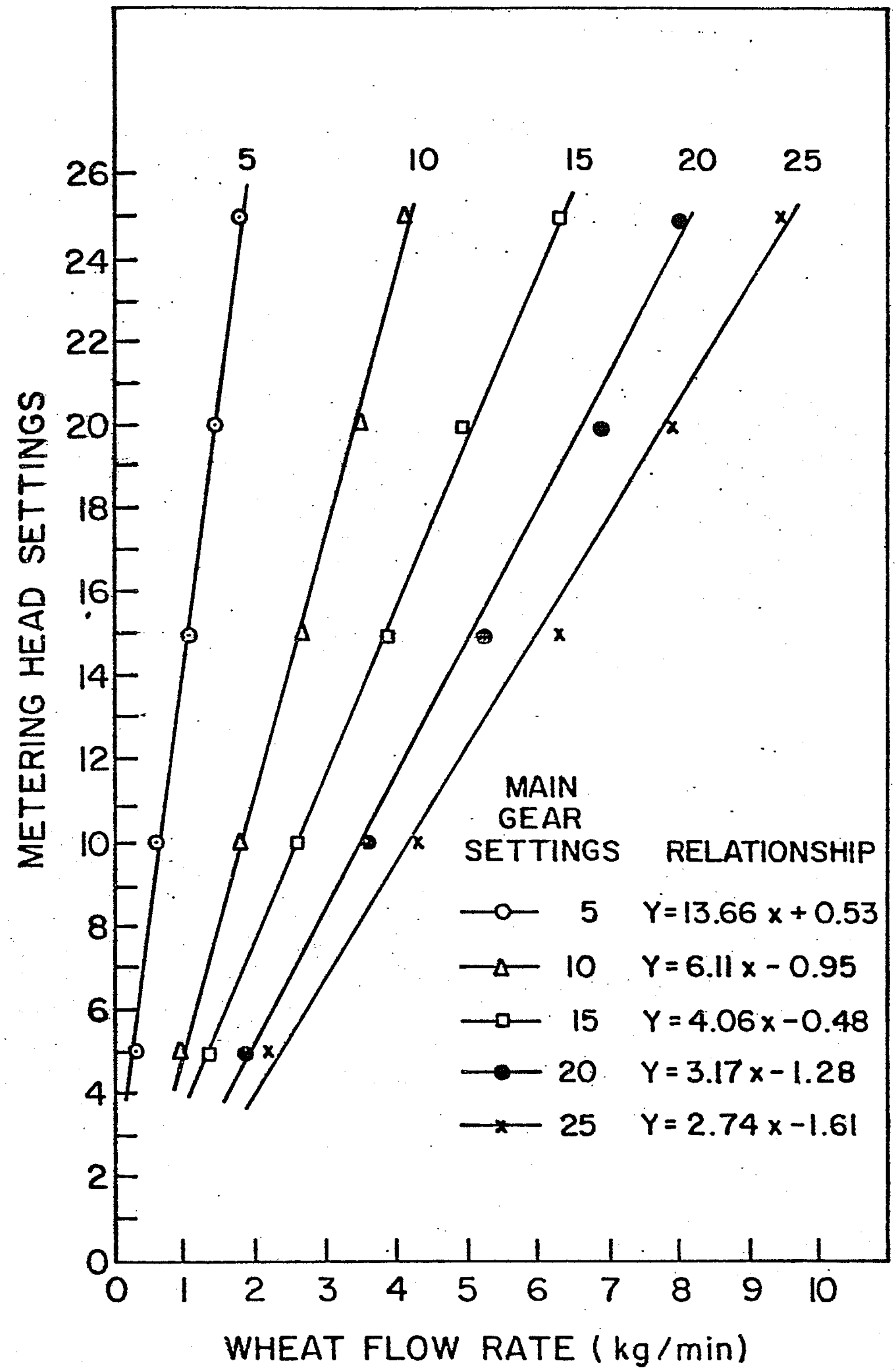


FIG. 5.5 Flow Rates of Wheat (17.2% MC) for Various Control Settings of the Metering Head for Different Main Gear Settings

rotated at 13 rev/min.

Some of the heaters were turned on for a period to preheat the sand prior to each drying trial. The desired sand flow rate was set and hot sand was allowed to flow through the dryer to preheat the dryer (Manchur, 1975). The desired wheat flow rate was then set and the observations were made.

Sand temperatures were measured at three different locations on the dryer. The initial sand temperature (T_1) was measured by a mercury-in-glass thermometer mounted at the sand discharge port on the metering head. A second thermometer was mounted in the sand collecting hopper beneath the separating section. This thermometer indicated the temperature (T_2) of sand upon completion of the drying process. The temperature (T_3) of the sand entering the sand heating hopper was measured with a third thermometer. The temperature of the discharged wheat at the outlet of the rotating cylinder was measured with a thermometer placed in the collected grain.

Grain samples were taken at five minute intervals to determine the MC of the wheat before and after drying through-out each test. Mean moisture content was then determined from the samples taken. Electrical energy consumed was measured using a watthour meter. Wet and dry bulb thermometer measurements were taken at the inlet and outlet ends of the cylinder to determine the respective relative humidities of the air.

Experimental variables involved in the study were:

i) sand to grain mass ratios 4:1, 4.5:1 and 5:1

ii) grain flow rates 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0 and 6.0 kg/min

Other parameters including a residence time of one minute, an initial sand temperature of 105^{o}C and wheat conditioned to about 17 percent MC, were kept constant throughout the course of this investigation. A complete randomized experimental design was used.

5.3 Performance

The grain dryer are evaluated by consideration of capacity, energy consumption and grain quality. Performance of the dryer depended on environmental conditions, the crop being dried, dryer design and the method of operation. Drying capacity and efficiency are closely related in hot air dryers. In the design of an air dryer, a gain in capacity is obtained at the expense of drying efficiency. Uniformity of drying is a measure of dryer performance and effects ultimate grain quality. The influences of operating parameters on the overall performance of the prototype dryer were investigated. Some of the performance factors were energy utilization, capacity and drying efficiency.

5.3.1 Drying Capacity

The results of the drying trials on the continuous flow dryer are recorded in Table 5.1 The values in the tables are the averages of at least five observations. Figure 5.6 shows the percentage of moisture removed at different grain flow rates and for various sand to grain mass ratios. The moisture reduction during the trials varied from 1.95 to 2.45 percent. A higher percentage of moisture removal was obtained at a sand to grain mass ratio of 4.5:1 than at other ratios using similar drying and operating conditions. For grain flow rates up to 2.5 kg/min more moisture was removed using a 5:1 sand to grain mass ratio than when a 4:1 ratio was used. At higher grain flow rates the sand to grain mass ratio of 4:1 removed more moisture. The maximum amount of moisture was removed at a grain flow rate of 3.0 kg/min for all sand to grain mass ratios. At grain flow rates less than 3.0 kg/min less moisture was removed than for flow rates greater than 3.0 kg/min for all mixture ratios used. The percent moisture content reduction tended to become constant at grain flow rates greater than 5.0 kg/min.

An analysis of variance showed highly significant

Table 5.1 Performance of Continuous Flow Grain Dryer for Drying Wheat at Different Grain Flow Rates and at Various Sand to Grain Mass Ratios.

Sand to grain mass ratio	Grain flow rate kg/min	Initial sand temp. (°C)	Final sand temp. (°C)	Initial MC (%wb)	Final MC (%wb)	Moisture removed (%wb)	Drying efficiency (%)	Fuel efficiency (%)	Specific energy consumption MJ/Kg of water evaporated
4:1	1.5	106	66.0	17.30	15.35	1.95	41.9	28.3	9.07
	2.0	105	68.0	17.20	15.05	2.15	49.8	35.7	7.16
	2.5	106	73.5	17.30	15.00	2.30	60.6	37.3	6.88
	3.0	105	72.0	16.80	14.40	2.40	62.2	40.7	6.34
	3.5	105	72.0	17.10	14.75	2.35	60.8	38.8	6.62
	4.0	104	69.0	17.20	14.90	2.30	56.3	37.5	6.84
	4.5	105	65.0	17.35	15.05	2.30	54.6	36.6	7.02
	5.0	104	67.0	17.25	15.00	2.25	55.0	35.7	7.16
	6.0	105	64.0	17.30	15.05	2.25	53.5	35.6	7.20
4.5:1	2.0	106	71.0	17.30	15.05	2.25	49.0	33.2	7.74
	2.5	105	74.5	16.90	14.50	2.40	59.7	36.2	7.09
	3.0	104	74.0	17.10	14.65	2.45	62.0	39.6	6.48
	3.5	105	72.0	17.20	14.80	2.40	55.2	37.2	6.88
	4.0	106	72.0	17.30	14.90	2.40	53.5	36.3	7.06
	5.0	104	70.0	17.40	15.05	2.35	52.4	35.6	7.20
5:1	2.0	105	74.0	16.90	14.70	2.20	48.5	28.8	8.89
	2.5	106	77.0	17.20	14.85	2.35	55.2	32.5	7.88
	3.0	105	78.0	17.30	14.92	2.38	60.2	35.4	7.24
	3.5	106	76.0	17.20	14.87	2.33	53.1	33.6	7.63
	4.0	104	74.0	17.10	14.85	2.25	51.2	33.2	7.74
	4.5	104	74.0	17.20	15.00	2.20	50.0	33.1	7.74

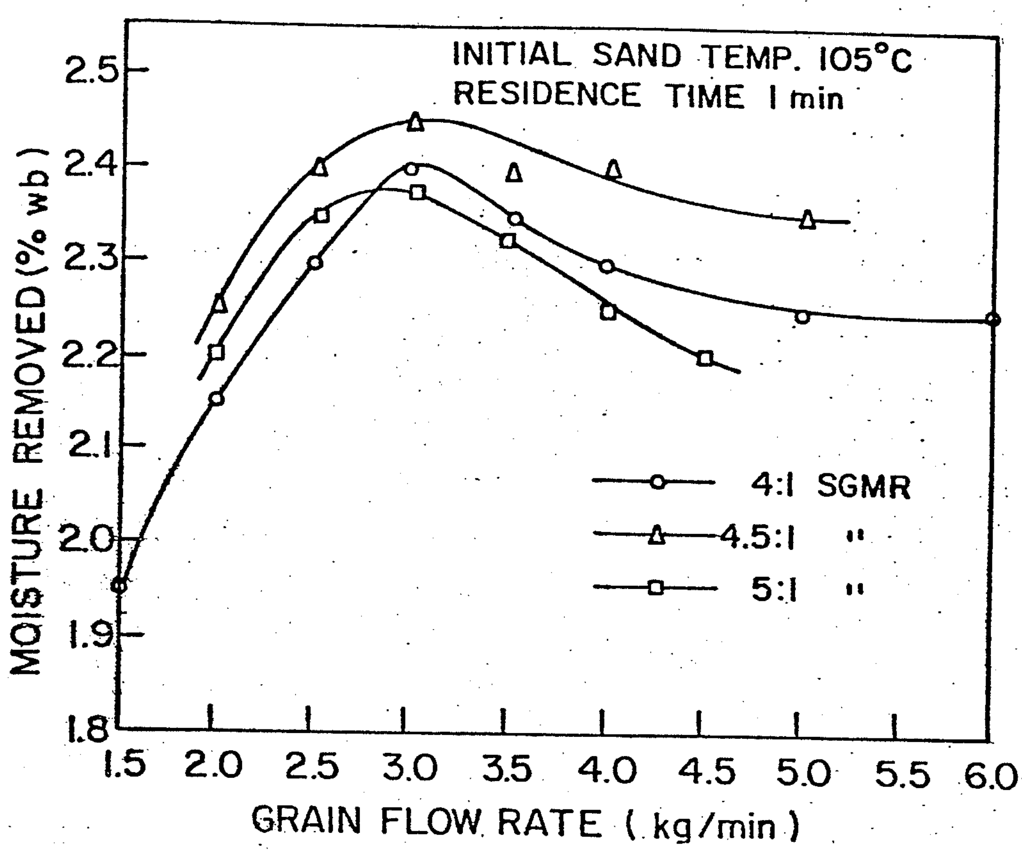


FIG. 5.6 Percentage Moisture Removed from Wheat at Different Grain Flow Rates for Various Sand to Grain Mass Ratios on Continuous Flow Dryer

differences in drying for the different grain flow rates. Significant differences in drying at the five percent level were found among different sand to grain mass ratios.

At low grain flow rates corresponding sand flow rates were also low. The sand grain mixture lost large quantities of heat to the surrounding air and to the machine components due to the large mixture surface area and the low total thermal capacity of the mixture. Thus a reduced quantity of heat was available to dry grain resulting in a smaller reduction in moisture content.

At large grain and sand flow rates mixing was less uniform. The quantity of sand and grain present in the cylinder exceeded the handling capacity of the cylinder. A large volume of sand relative to wheat in the mixture resulted in a thick layer of sand surrounding the wheat kernels. This created a physical barrier to the escape of moisture from the wheat to the surrounding air.

It was concluded that the optimum capacity of this machine for drying wheat was 3.0 kg/min. It could possibly handle up to 6.0 kg/min or more with a minor modification to the inlet section. The total amount of moisture removed might be reduced at these higher feed rates.

5.3.2 Drying efficiency

The drying efficiency is related to dryer design and operation and is expressed as given below:

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

The numerator is the product of the amount of water removed and the latent heat of vaporization. The denominator for solid medium drying will be the product of the quantity of sand, its specific heat and the maximum temperature change ($T_1 - T_2$) of the sand passing the drying section. In symbols the drying efficiency can be written as follows:

$$\eta_d = \frac{\dot{W} \cdot h_{fg}}{\dot{M}_s \cdot c \cdot \Delta T}$$

A value of 2.56×10^6 J/kg for latent heat of vaporization of water from wheat (h_{fg}) and a value of 878.6 J/(kg$\cdot$ K) for specific heat of sand (c) was used to calculate the drying efficiencies. Drying efficiencies for different grain flow rates and various sand to grain mass ratios are shown in Figure 5.7. The drying efficiency varied from 41.9 to 62.2 percent to dry wheat from approximately 17.0 to 14.5 percent MC. A sand to grain mass ratio of 4:1 provided more efficient drying than 4.5:1 ratio which was more efficient than a 5:1 ratio. Drying at the higher ratios was less efficient because of the slower

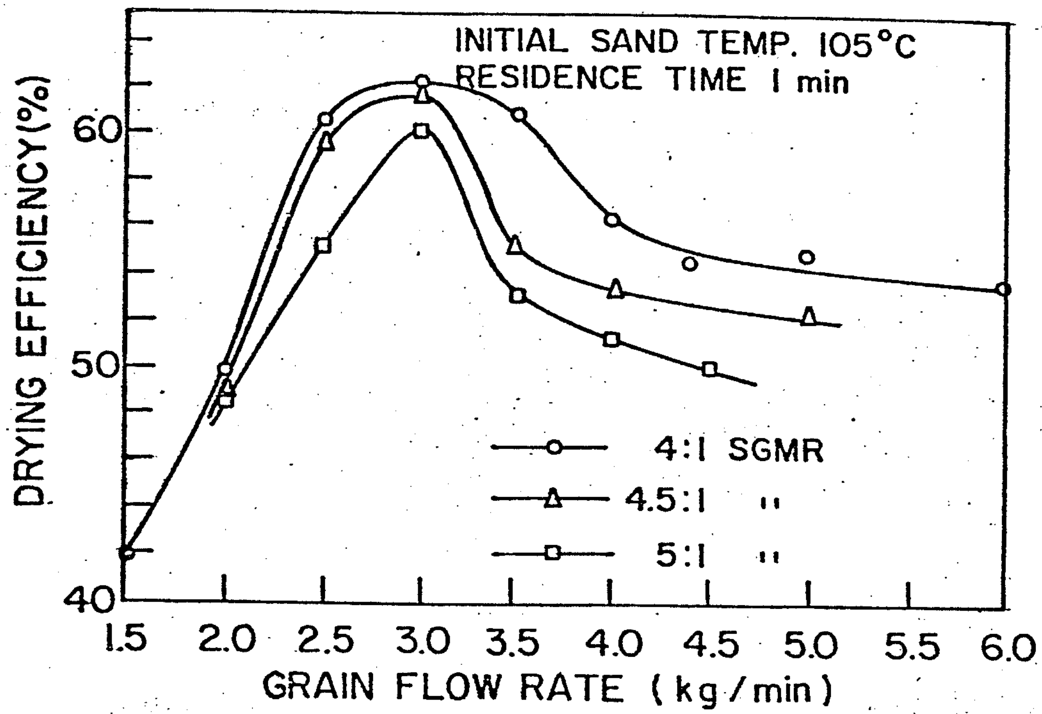


FIG. 5.7 Drying Efficiencies for Wheat at Different Grain Flow Rates for Various Sand to Grain Mass Ratios on Continuous Flow Dryer

drying rate which was thought to occur when the escape of moisture from the wheat kernels was restricted by the surrounding sand. The higher drying rates associated with the use of the lower mixture ratios permited utilization of heat for evaporation of moisture from the wheat.

The highest drying efficiency was found at a wheat flow rate of 3.0 kg/min for all the sand to grain mass ratios used. At grain flow rates lower than 3.0 kg/min drying efficiencies were lower. For a sand to grain mass ratio of 4:1 the drying efficiencies were nearly constant between 2.5 and 3.5 kg/min grain flow rates. The average drying efficiency in this range was 61.2 percent. At grain flow rates higher than 3.0 kg/min, a moderate decrease in drying efficiency was noted. The drying efficiency tended to be constant at grain flow rates above 5.0 kg/min. This constant level of drying efficiency for wheat was 53.5 percent at a sand to grain mass ratio of 4:1.

For a sand to grain mass ratio of 4.5:1 a lower drying efficiency was found than for a 4:1 ratio but the 4.5:1 ratio removed more moisture. The increase in heat capacity due to the greater sand quantity did not remove a proportionately greater amount of moisture as may have been expected.

Foster (1973) reported a drying efficiency of 51.2 percent for drying corn in a continuous flow tower type grain dryer. Air drying was stated to be an inefficient process. The drying process as represented on a psychrometric chart reveals that the drying air will reach saturation before all the sensible heat in the air can be recovered. The efficiency limitations imposed by environmental conditions become more pronounced when drying grain during cold weather. The initial moisture content of grain at which drying started affected the drying performance more than any other factor. Efficiency is affected by the rate at which a given type of grain loses its moisture in drying. Stansfield and Cook (1932) found that drying efficiency increased as the temperature of the hot air was increased. Excessively high temperatures were prohibited by the risk of loss of the baking quality of the wheat. The efficiency decreased when the flow of hot air was increased because the air passed through the dryer more rapidly and had less time for heat transfer to the grain.

It was found in this study that the drying efficiency for wheat was higher using hot sand as a heat transfer medium than that recorded for conventional hot air dryers. It is possible to improve the drying efficiency further by making modifications to the prototype. Higher drying efficiency may be achieved for drying grain at higher moisture content because it is more difficult to remove the same amount of water from low MC wheat. The drying tests for grain flow rates higher than 3.5 kg/min were conducted at the low ambient temperatures (8 to 18°C). Consequently, some improvement of drying efficiency may have been achieved had the test been undertaken at high ambient temperatures (17 to 27°C), as was the case for the low grain flow rates.

5.3.3 Fuel efficiency

The current concern for a world fuel shortage accompanied by rapid price increases particularly for oil products requires that crop drying procedures be reassessed. Current fuel availability and prices have made finding ways and means of decreasing the energy consumed by grain dryers of great importance. It is also important to achieve fuel savings through more efficient grain drying.

Fuel efficiency is defined as the ratio of the theoretical energy required to evaporate the grain moisture to the amount of energy supplied by the fuel used to heat the drying media. It is expressed as:

$$\text{Fuel efficiency} = \frac{\text{heat utilized to remove water}}{\text{heat content of dryer fuel}}$$

or

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

The total energy consumption includes the energy to heat the sand and to operate the various electrical motors. The fuel efficiencies for different grain flow rates and for various sand to grain mass ratios are recorded in Figure 5.8. The fuel efficiency for drying wheat varied from 28.3 to 40.7 percent. The maximum fuel efficiency was found at a grain flow rate of 3.0 kg/min and a sand to grain mass ratio of 4:1.

For conventional hot air dryers the fuel efficiency for corn varied from 20 to 38 percent at air temperatures of 60 to 100°C. The initial MC were 12 to 25 percent (Peart and Lien 1975). Fuel efficiency increased as air temperature increased and as air flow rates decreased. The use of high air temperatures is restricted by loss of grain quality. Low air flow rates result in non-uniform drying. Foster (1973) reported a fuel efficiency of 38 percent for drying corn in a continuous flow tower type dryer.

The fuel efficiency obtained for drying wheat using hot sand as the heat transfer medium was slightly higher than the fuel efficiency for drying corn in conventional hot air dryers. It might be possible to increase the fuel efficiency by reducing heat losses to the surrounding air by insulation of various exposed parts of the dryer. Modification of the sand circulation unit would also pre-

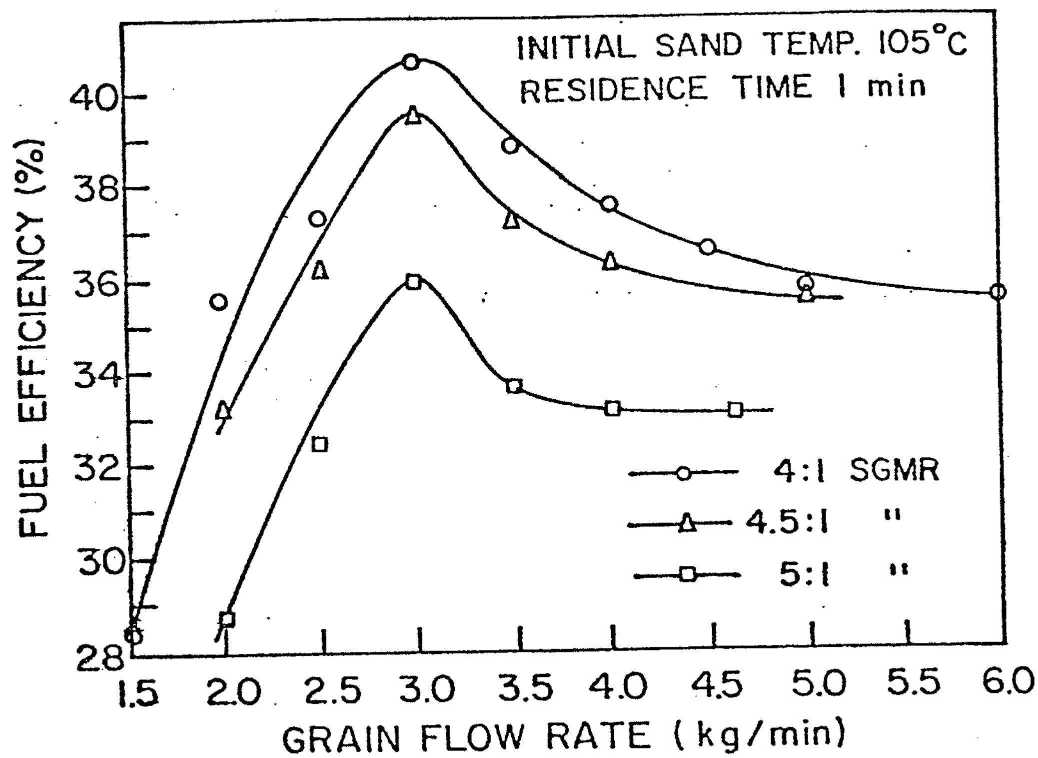


FIG. 5.8 Fuel Efficiencies for Wheat Drying at Different Grain Flow Rates for Various Sand to Grain Mass Ratios on Continuous Flow Dryer

vent heat losses.

5.3.4 Specific energy consumption

The specific energy consumptions as described by Bailey (1959) were calculated for each drying trial of this study and are shown in Figure 5.9. The specific energy consumption is the fuel or heat required to evaporate a unit quantity of water from the grain. This relationship is an indication of the thermal economy of the dryer.

The specific energy consumption varied between 6.34 to 9.07 MJ/kg of water evaporated from the wheat. A minimum energy consumption of 6.34 MJ/kg of water evaporated was found at a grain flow rate of 3.0 kg/min and a sand to grain mass ratio of 4:1. Decreasing the heat loss from the components of the prototype dryer to the surrounding air would reduce the energy consumed.

Pierce and Thompson (1975) recorded specific energy consumption for drying corn in conventional hot air dryers. An average value of 6.88 MJ/kg of water evaporated was reported with a range of 4.64 to 16.27 MJ/kg for air temperatures of 38 to 150°C and air flow rates of 0.011 to 0.111 m^3/(min-kg) of grain. The low specific energy consumption was determined at low air temperatures and low air flow rates. This is not always practical because of the resulting extended drying time. Specific energy consumption for

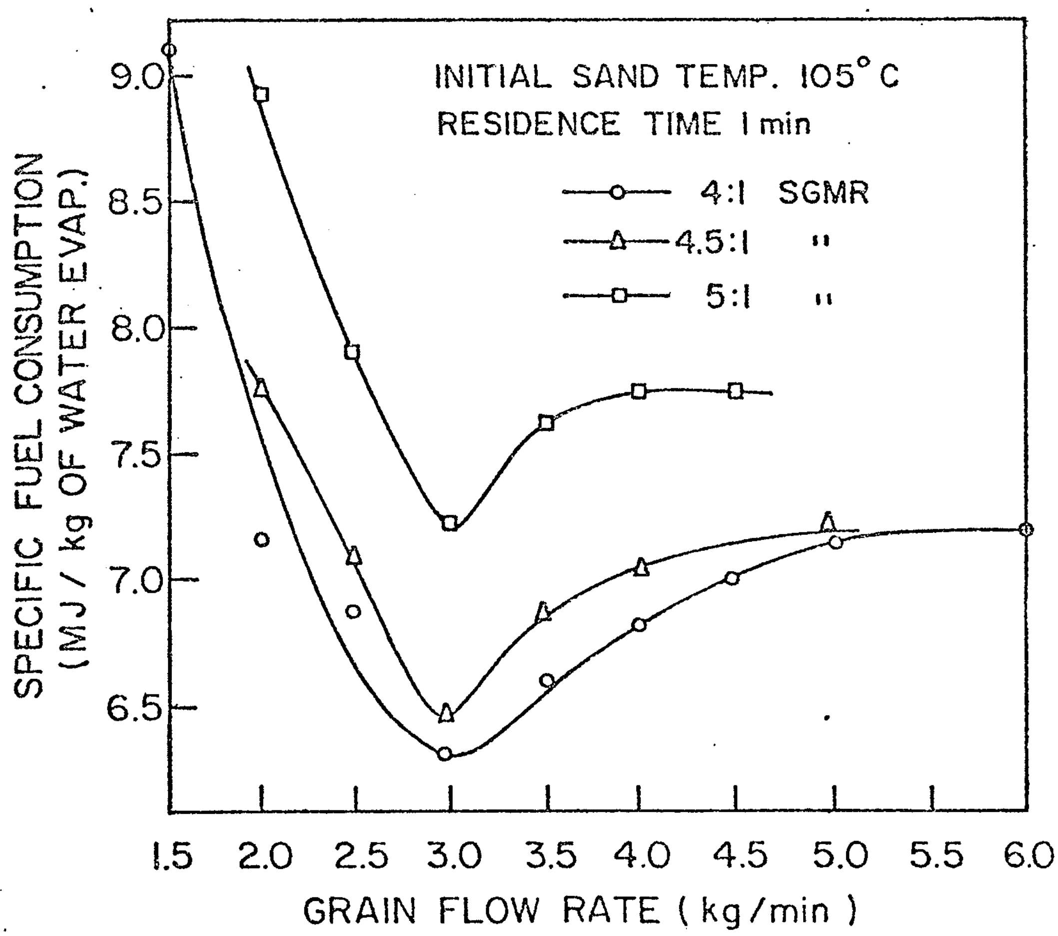


FIG. 5.9 Specific Energy Consumption for Wheat Drying at Different Grain Flow Rates for Various Sand to Grain Mass Ratios on Continuous Flow Dryer

drying wheat using hot sand as the heat transfer medium was lower than conventional hot air dryers.

5.3.5 Air flow rate

The theoretical air flow required to remove the moisture from the drying section of the prototype dryer was calculated to determine whether the capacity of the fan was a limiting factor in the drying process. The relative humidity of the ambient and exhaust air was found by measuring the respective wet and dry bulb temperatures. The amount of moisture which can be picked up by the air was calculated with the aid of a psychrometric chart. Results for various grain flow rates and sand to grain mass ratios are recorded in Table 5.2. The amount of moisture removed from the wheat in different drying trials varied from 50.4 to 158.5 g/min and the corresponding air flow rates required varied from 7.2 to 14.2 m^3/min. The 17.0 m^3/min fan installed on the prototype had sufficient capacity and therefore was not a limiting factor in the drying trials.

Table 5.2 Air Flow Rate Required to Carry Away Moisture from the Cylinder of the Continuous Flow Grain Dryer

Sand to grain mass ratio	Grain flow rate Kg/min	Ambient Air Conditions		Exhaust Air Conditions		Moisture carried by air (g/m³)	Moisture removed from grain (g/min)	Air flow rate required m³/min
		Dry bulb temp. (°C)	Wet bulb temp. (°C)	Dry bulb temp. (°C)	Wet bulb temp. (°C)			
4:1	2.0	27	24	31	28	5.10	50.4	9.9
	2.5	21	17	34	26	6.72	67.5	10.0
	3.0	19	17	26	24	8.40	84.3	10.0
	4.0	19	16	31	26	10.69	108.0	10.1
	4.5	18	14	27	24	9.78	121.5	12.4
	5.0	19	16	29	26	9.82	132.0	13.4
	6.0	16	12	28	24	11.17	158.5	14.2
4.5:1	2.5	19	18	30	25	6.07	70.2	11.6
	3.0	21	19	36	28	8.56	86.1	10.1
	3.5	14	9	24	19	8.61	97.5	11.3
	4.0	14	9	25	21	9.69	112.4	11.6
	5.0	12	11	24	18	11.48	137.5	12.0
5:1	2.5	17	16	25	25	9.36	67.7	7.2
	3.0	21	17	37	28	7.42	83.7	11.3
	3.5	8	7	19	17	7.04	95.5	13.6
	4.0	11	7	23	18	8.05	105.6	13.1
	4.5	11	7	24	19	8.90	116.0	13.0

CHAPTER VI

DRYING WITH DIFFERENT SAND TEXTURES

Investigations discussed in previous chapters used 12-30 sand texture (0.589 to 1.651 mm particle size) in all the drying trials. It was thought that the use of a finer textured sand might result in more efficient drying. The smaller particles of sand would result in a greater number of point contacts between sand and kernels and would also have a greater aggregate surface area. Both factors have the potential to increase heat transfer to provide more efficient drying.

Drying studies were undertaken on the batch dryer to investigate the effect of sand texture. Five sand textures (12-30, 20-40, 30-50, 40-60 and 60-100) were selected. Mechanical sieve analysis of these sand textures were conducted according to ASAE standard S319 (ASAE Yearbook 1976) and the results are recorded in Figure 6.1. A set of seven sieves (30 to 100 mesh) were used and shaken for five minutes in a sieve shaker. Two replications were completed for each sand texture. The modulus of fineness, effective size and uniformity coefficient were calculated from the sieve analysis data and are recorded in Table 6.1.

Drying tests were conducted using SGMR of 4:1 and

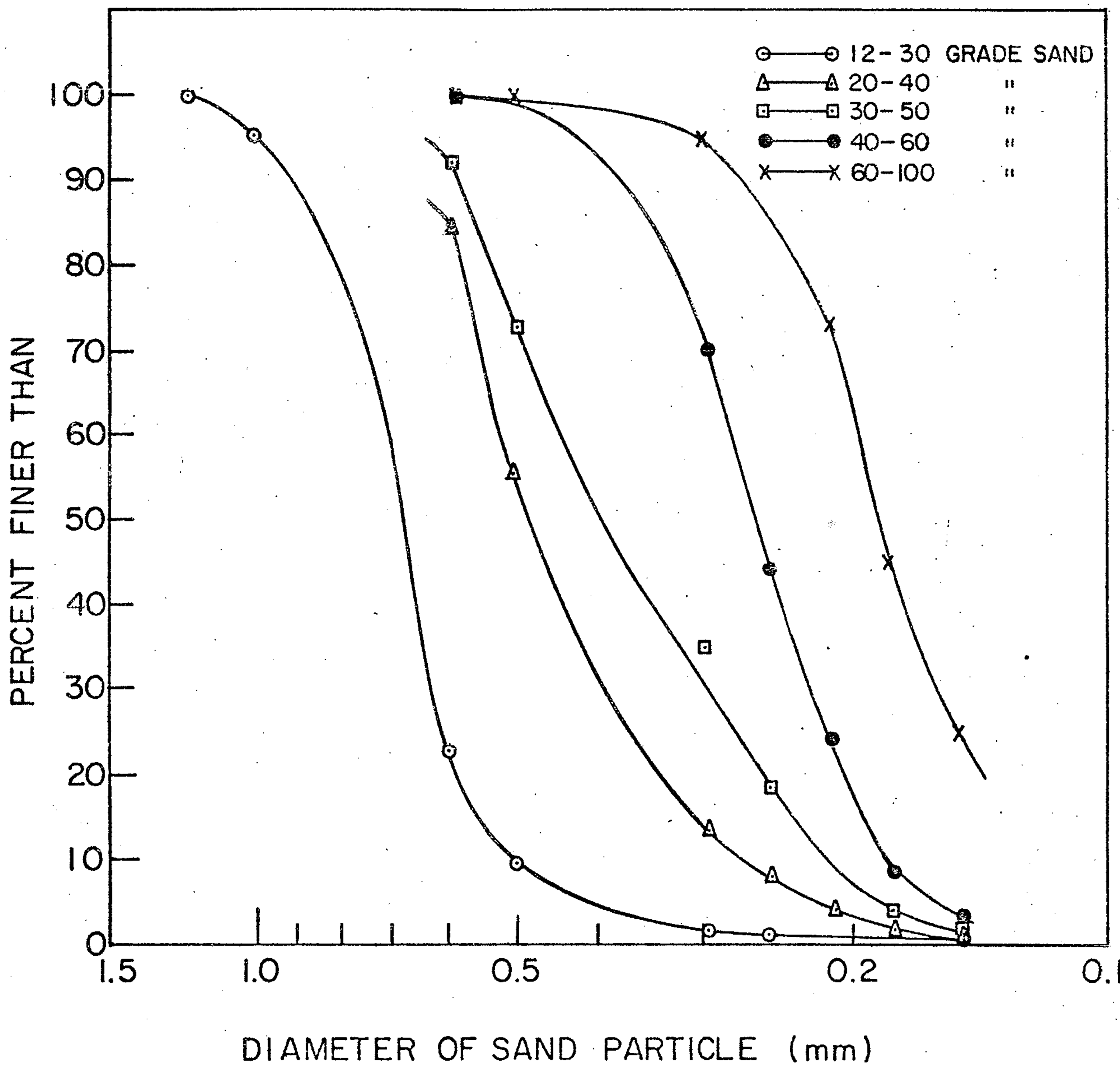


FIG. 6.1 Sieve Analysis of Different Texture of Sand

Table 6.1 Mechanical Sieve Analysis of Different Sand Textures

Sand texture	Percentage of sand retained — Sieve mesh number (μm) 16 (1190)	18 (1000)	30 (595)	35 (500)	50 (297)	60 (250)	70 (212)	80 (180)	100 (150)	Pan	Modulus of fineness	Effective size (D_{10}) (mm)	Uniformity Coefficient (D_{60}/D_{10})
60-100	--	--	0.20	0.07	5.34	8.22	13.70	27.68	20.31	24.48	0.81	--	--
40-60	--	--	0.05	0.43	29.80	25.77	20.02	15.40	5.43	3.10	1.27	0.185	1.503
30-50	--	--	8.02	19.20	42.36	12.42	8.17	6.07	2.30	1.46	1.76	0.212	1.986
20-40	--	--	15.83	26.83	44.23	5.72	3.61	2.53	0.90	0.35	2.02	0.274	1.891
12-30	0.22	4.16	72.93	13.60	7.82	0.41	--	0.47	0.16	0.23	2.76	0.510	1.373

5:1. Initial sand temperature was 100°C and the residence time was two minutes for these tests. Results of these tests are recorded in Table 6.2 and are shown in Figures 6.2 and 6.3. The percentage moisture removed increased as the sand texture changed from 12-30 to 20-40. A reduction in moisture removal was found when the sand texture was reduced from 20-40 to 60-100 for both 4:1 and 5:1 SGMR. The highest moisture was removed at a fineness modulus of 2.0 as noted in Figure 6.3. A decrease in moisture removal was found when the fineness modulus was greater than 2.0.

The quality test conducted by the Grain Research Laboratory of the Canadian Grain Commission showed that the baking quality was unaffected using different texture of sand. It was concluded from these results that the 20-40 sand texture was most efficient for drying wheat.

Increasing the fineness of sand texture did not lead to increased drying over the entire range of textures tested. Very finely textured sand probably created a physical barrier against the escape of moisture from the grain kernels to the air in the sand voids and to the surrounding air. Finely textured sand has less permeability than coarse sand thus less air is available for moisture removal. These physical characteristics explain the occurrence of

Table 6.2 Results of the Wheat Drying Using Different Sand Textures

Sand to grain mass ratio and residence time (min)	Sand texture	Moisture removed (%wb)	Initial sand temp. (°C)	Final sand temp. (°C)	Initial grain temp. (°C)	Final grain temp. (°C)	Drying efficiency (%)
4:1, 2	60-100	2.20	102.0	63.2	30.0	58.0	48.7
	40-60	2.25	101.0	62.0	30.0	58.0	49.5
	30-50	2.50	100.0	62.5	28.0	59.0	56.7
	20-40	2.65	100.0	62.0	28.0	59.5	59.4
	12-30	2.43	100.3	59.6	21.4	54.3	50.9
5:1, 2	60-100	2.25	101.0	64.0	26.0	60.0	41.5
	40-60	2.35	100.0	64.5	28.5	60.5	45.3
	30-50	2.55	101.0	65.0	28.0	59.0	48.4
	20-40	2.80	100.0	65.2	29.0	60.0	54.9
	12-30	2.50	101.5	68.5	22.0	61.8	51.7

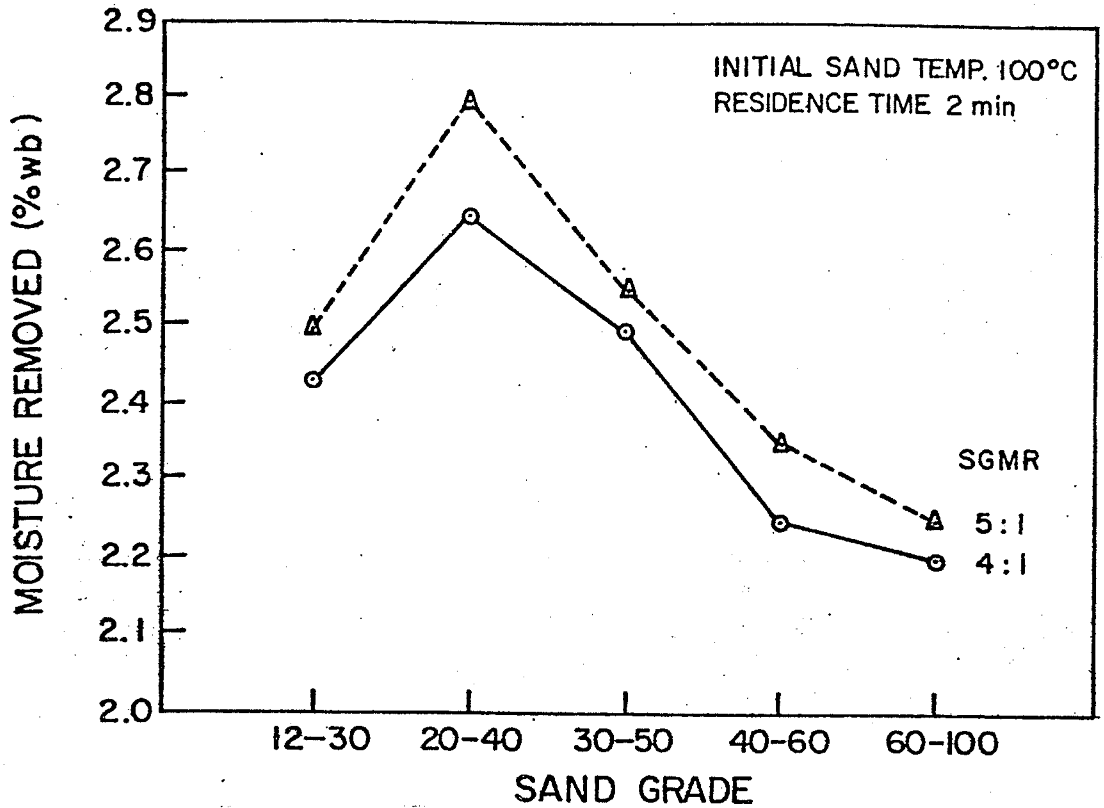


FIG. 6.2 Effect of Sand Texture on Wheat Drying

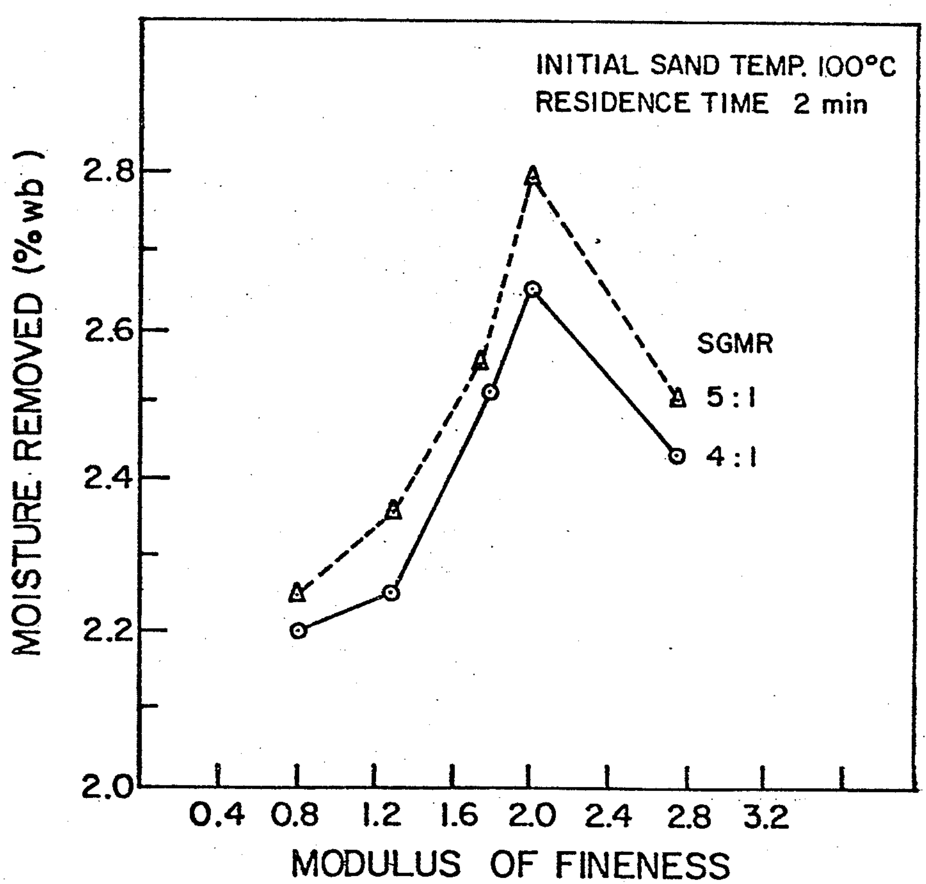


FIG. 6.3 Effect of Modulus of Fineness of Sand on Wheat Drying

an optimum texture of 20-40 for wheat.

An analysis of variance indicated highly significant differences among different textured sand treatments as recorded in Table B.4. A comparison between the different treatments also showed highly significant differences except between 60-100 versus 40-60 and 30-50 versus 12-30 sand textures. Hence the 20-40 sand texture gave the most efficient drying among all the five textures. There was no significant difference between 60-100 versus 40-60 and 30-50 versus 12-30 sand textures.

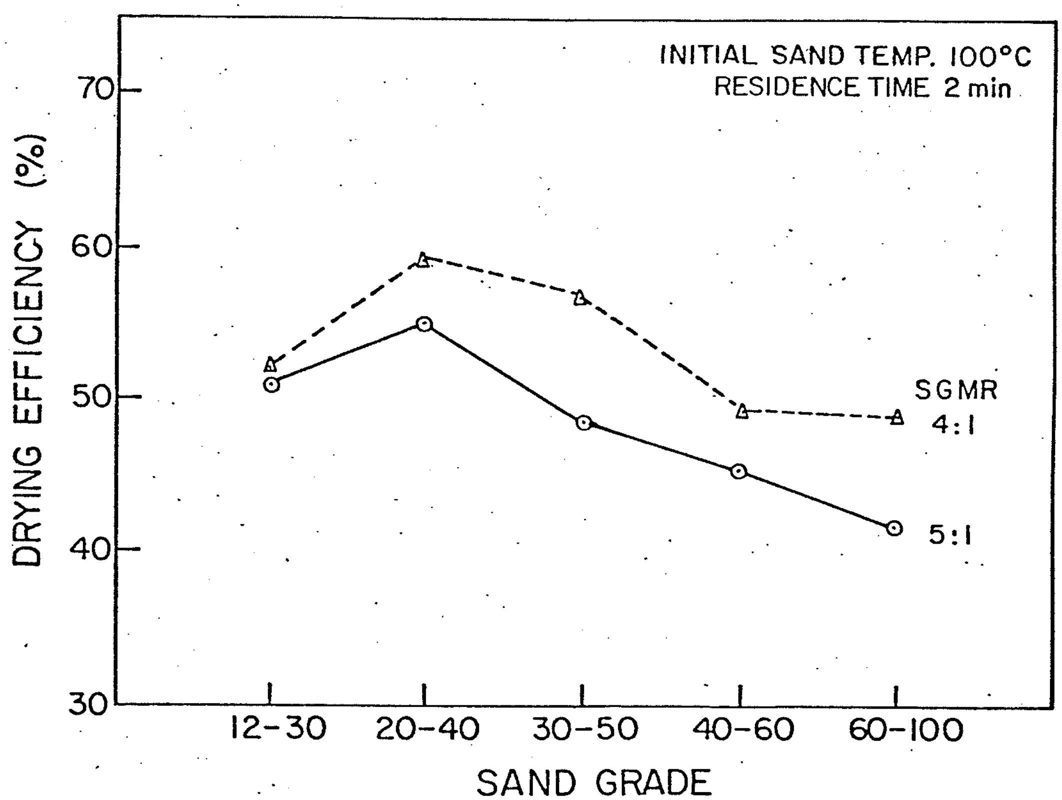


FIG. 6.4 Effect of Sand Texture on Wheat Drying Efficiency

The drying efficiency as defined in section 5.3.2 was calculted for various treatments of sand textures. These drying efficiencies are recorded in Table 6.2 and shown in Figure 6.4. The drying efficiency was found to be highest for the 20-40 sand texture.

CHAPTER VII

THERMAL DISINFESTATION

7.1 Review of Literature

Hot and cold termperatures are not extensively used for disinfecting cereals and cereal products. Cold arrests the activity of insects but does not kill them unless the temperature is very low or the time of exposure is very long. It is possible to kill any insect quickly by heating. This principle is used effectively in hot climates on a small scale by spreading a thin layer of grain to dry in the sun. Some species of insects are more heat tolerant than others. The humidity also influences the lethal effects of a particular temperature. Exposure to 60°C for 10 minutes or 49°C for 20 minutes in practice can be relied on to provide 100 percent control (Kent and Amos 1967). Russian investigators (Gerzhoi et al. 1961) indicated the minimum temperature at which several insects and their larvae perished. For grain pests they found these temperatures were in the range of 45 to 60°C.

Trisvyatskii (1966) found in trials of gas dryers that the grain temperature changed at a rate of 30 to 40°C/s and lethal conditions for cereal pests were reached in 1.0 to 1.5 seconds after the grain was placed in the dryer.

Observations have shown that the eggs of both the granary and rice weevils were killed within 1 to 2 minutes at these conditions. Mortality of mites or of weevils depended mainly on the temperature at which the grain was exposed and on the length of exposure time at this temperature. According to Gerzhoi et al. (1961) complete disinfestation of mites (flour, elongated hairy) in all stages of development except the hypopus stage can be achieved by heating wheat to 45°C for 55 minutes.

Disinfestation of cereal grains by heating is limited in application not only by economic and mechanical difficulties but also because of the small difference between the heating necessary to achieve control and that which will damage the commodity. For example it has been demonstrated by Trisvyatskii (1966) that heating above 60°C for any length of time may damage the baking quality of wheat. Experiments have also shown that the disinfestation of dry seed grain from cereal crops (at 12 to 13 percent MC) did not cause loss of seed viability.

The results of the thermal disinfestation will depend on the uniformity of the grain heating and the residence time of grain in the drying chamber. Numerous investigations (Trisvyatskii 1966) have shown that thermal drying of batches of grain in thermal dryers under regimes in use at the present time did not result in a large reduction of insects and micro-organisms.

7.2 Studies on the Batch Dryer

The batch dryer described in section 4.1 was used to investigate the effect of solid medium (12-30 texture sand) drying on insect survival. Grain infested with adults and larvae of *Cryptolestes ferrugineus* (Stephens) was supplied by the Winnipeg Research Station, Agriculture Canada. Each 500 g sample, composed of 50 g of infested grain mixed with 450 g of moist grain, was treated with hot sand. Five treatments were used (Table 7.1) and each treatment was replicated three times. Initial moisture content of the wheat was kept at about 17 percent.

The survival of the insects was assessed at the Winnipeg Research Station, Agriculture Canada. Adult survival was determined 24 h after the treatment and survival of immatures was determined from the number of adults found at weekly examinations of each sample. The results of the analysis are recorded in Table 7.2. No adult survived in the treatments, whereas the average survival of adults in the untreated samples was 27.3. No survival of immature insects was found in treatments 2, 4 and 5. However, one immature survived in one of the samples in treatment 1, probably an egg. The other two samples had no survivors.

Table 7.1 Different Treatments for Thermal Disinfestation Studies in Batch Dryer

Treatment number	Sand to grain mass ratio	Initial sand temp. (°C)	Residence time (min)	Stages of drying	Initial grain temp. (° C)	Initial grain MC (%wb)
1	4:1	99.7	2	one	24.0	17.5
2	4.5:1	106.0	1	one	28.0	17.3
3	4:1	91.0	2	two	29.3	17.4
4	4:1	99.3	2	four	30.0	17.2
5	4:1	99.3	2	two	28.3	17.4

Table 7.2: Survival of Adults and Immatures of *Cryptolestes ferrugineus* after Thermal Disinfestation in Batch Dryer (3 replicates per treatment)

Treatment number	Adult survival/replicate: Treated	Adult survival/replicate: Untreated	Survival of immatures/replicate, Treated, Weeks after treatment: 1 (Pupae)	2 (large larvae)	3 (medium larvae)	4 (small larvae)	5 (eggs)	Untreated: Average of all stages
1	0	14.0	0	0	0	0	0.3	30.8
2	0	18.7	0	0	0	0	0	33.1
3	0	23.7	0	0	0	0.3	1.0	33.1
4	0	36.0	0	0	0	0	0	33.1
5	0	44.0	0	0	0	0	0	28.8

Treatment 3 was not as effective as the other treatments because a total of four immatures survived (probably one small larva and three eggs).

Results showed the possibility of thermal disinfestation by heating infested wheat with sand at 105^{o}C for one minute using a sand to grain mass ratio of 4.5:1. No significant improvement was obtained by heating wheat in four stages since two stages using sand at 100^{o}C for two minutes and a sand to grain mass ratio of 4:1 was equally effective.

4.3 Studies on the Continuous Flow Dryer

Thermal disinfestation studies were also conducted using the continuous flow dryer described in section 5.1. The wheat samples (50 g) infested with adults and larvae of C.ferrugineus were placed in cloth bags which were then sealed. These bags were placed at the inlet of the drying section while the dryer was in operation. Moist grain mixed with hot sand was also introduced at the same time into the drying section through a metering device. The treatment applied to each of six samples is shown in Table 7.3. Treatments 1, 5 and 6 were subjected to two stages of drying; treatments 2, 3 and 4 were dried in one stage.

Treated samples were analysed at the Winnipeg Re-

Table 7.3 Different Treatments for Thermal Disinfestation Studies in Continuous Flow Dryer

Treatment number	Sand to grain mass ratio	Initial sand temp. (°C)	Residence time (min)	Stages of drying
1	4.5:1	105	1	two
2	4.5:1	105	1	one
3	4:1	115	1	one
4	4:1	105	1	one
5	4:1	105	1	two
6	4:1	105	1	two

search Station of Agriculture Canada and the results are recorded in Table 7.4. No adult survived in any treatment, while in the untreated samples the average number of live adults per sample was 22.2. The average number of dead adults in each treatment was 17.8, whereas in the untreated samples the average number of dead adults was 1.8. These results confirmed the feasibility of destroying adult insects by heating with hot sand. The temperature of the sand used for drying was sufficient to kill them in one to two minutes.

Observations were also recorded on the survival of

Table 7.4: Survival of Different Stages of *Cryptolestes ferrugineus* after Thermal Disinfestation in Continuous Flow Dryer

Weeks after treatment	Survival in different treatments													
	1		2		3		4		5		6		Average of six untreated samples	
	L*	D*	L	D	L	D	L	D	L	D	L	D	L	D
0 (adults)	0	16	0	15	0	18	0	34	0	14	0	10	22.2	1.8
1 (pupae)	1	0	7	2	11	1	11	1	3	1	13	1	19.0	1.0
2 (large larvae)	3	0	32	1	5	1	51	0	7	2	8	1	68.2	0.3
3 (medium larvae)	1	0	160	0	6	1	194	0	4	1	0	0	182.5	0.5
4 (small larvae)	3	0	141	0	3	0	152	0	5	0	1	0	173.3	1.0
5 (eggs)	6	0	52	0	4	0	81	0	4	0	3	0	103.7	0.0
Total	14	16	392	18	29	21	489	35	23	18	25	12	552.2	4.2
Mean	2.3	2.7	65.3	3.0	4.8	3.5	81.5	5.8	3.8	3.0	4.2	2.0	92.0	0.7

*L - Live, D - Dead.

the immature stages in grain. Results indicate that treatments 2 and 4 were not effective in killing insects that were inside the kernels of wheat. A total of 392 and 489 live insects respectively were recorded while in the untreated samples the average population of insects was 552. The treatments in which either two stage drying (1, 5 and 6) or higher sand temperature (3) was used, were more effective. In treatments 1, 5 and 6 the total number of live insects was 14, 23 and 25 respectively as compared to the average in the control samples of 552. In treatment three, 29 live immature insects were recorded.

These results show the effectiveness of solid medium drying in controlling insect populations. Because the infested grain was contained in bags, it was not mixed thoroughly with the hot sand as was the case in the batch dryer. Since a large amount of infested grain would require considerable time and labor to examine only small samples of infested grain were used. Thus each sample was enclosed in a bag. It was observed that the grain in the bags was not as hot as the free flowing grain. The layer of sand in the rotating cylinder was shallow, and therefore the sample bags were not covered completely by the sand. This resulted in less effective heating. Free flowing grain reached a higher temperature and would probably result in a lower survival of insects.

It was concluded that one stage heating of wheat was effective for killing adults but was not effective in killing the immature stages. At least two stage heating was required for a significant reduction of the immature stages. A more efficient method would be to increase the residence time in the drying section. One stage heating with sand at 115°C was as effective as two stage heating at 105°C. Possibly two stage heating at 115°C would give complete disinfestation of adult and immature *C. ferrugineus*.

CHAPTER VIII

ALTERNATIVE HEAT TRANSFER MEDIA

Sand was used as the heat transfer medium for all studies discussed in previous chapters. Many investigators have used alternate heat transfer media such as steel plates (Chancellor 1968; Finney et al. 1963 and Hall and Hall 1961), granulated salt (Benson 1966 and Raghavan and Harper 1974) and steel balls (Lapp 1973). No work has been reported on comparative studies of different heat transfer media.

The batch dryer was used in this study to compare sand, granulated salt and steel balls for their drying performance. Values of experiemental variables included initial temperature of the media (100, 120 and 140^{o}C) and medium to grain mass ratio (MGMR) (4:1, 6:1 and 8:1). Wheat at an initial MC of about 17 percent with a residence time of two minutes was used in the drying trials. The three media used were a 12-30 texture sand, 1.12 mm diameter steel balls and granulated salt. The granulated salt passed through a 10 mesh sieve. The salt had a fineness modules of 3.05 and an average particle diameter of 1.83 mm. The results of the mechanical sieve analysis of the salt is shown in Figure 8.1. Thermophysical properties of these media are recorded in Table 8.1.

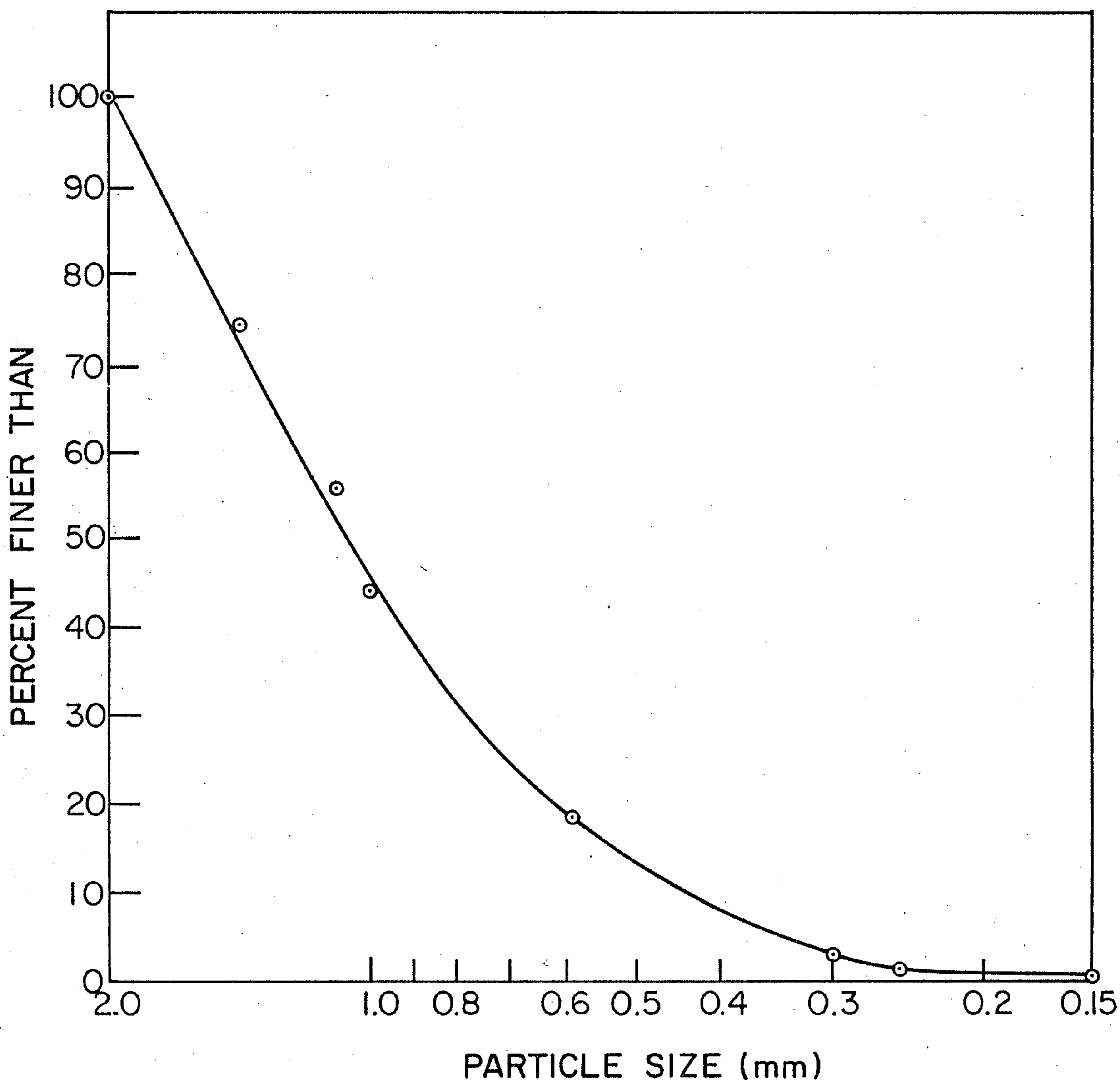


FIG. 8.1 Sieve Analysis of Salt

Table 8.1 Physiothermal Properties of Different Solid Media, Air and Wheat (Parry et al. 1969)

	Property	Wheat	Sand	Granulated Salt	Steel (1%C)	Air ($0^\circ C$, 1 Atm.)
1.	Specific gravity ($20^\circ C$)	1.3 (10%MC)	1.52	0.77	7.80	0.0013
2.	Specific heat J/(kg.K)	1673.6 (15%MC)	878.6 ($20^\circ C$)	799.1	502.1 (20° to $100^\circ C$)	995.8
3.	Thermal Conductivity W/(m.K)	0.15 (12%MC)	0.33 ($20^\circ C$)	--	44.8 (20° to $100^\circ C$)	0.0242

The large difference in density between the steel balls and wheat (6 times) created difficulties in mixing at low MGMR. The higher density steel balls had a tendency to settle towards the bottom of the mixture while the wheat remained near the top. Sand density is slightly higher than wheat while salt density is one half that of wheat. The difference in densities between salt, sand and wheat was not great and no difficulty was experienced in mixing. Sand and salt have the advantage of being commercially available in various texture ratings.

There were some problems in separating steel balls and salt from wheat. The flow characteristics of the steel balls required considerable time to accomplish separation from wheat. A magnetic separating device of some form would probably be necessary to assure complete removal of the steel balls. The hygroscropic nature of salt affected its flow characteristics which resulted in a separation problem. Salt at high MC had a tendency to adhere to the wheat kernels, which further amplified the separation problem. Thus salt is suitable only at higher temperatures and can be used for the drying of grains which can sustain higher temperatures. Therefore, salt would not be suitable for drying wheat.

The relationship between the initial temperature of a solid medium and the percentage of moisture removed as recorded in Figure 8.2 shows that at 100°C sand removed more moisture than the other solid media and that steel balls removed less than the salt. At 120°C there was no significant difference in drying between steel balls and salt, but at 140°C salt removed more moisture than steel balls.

Because of the hygroscopic nature of the salt it gave better drying results at higher temperatures. The high thermal conductivity of steel balls was responsible for rapid and significant heat losses to the machine components and to the air. This resulted in less moisture removal from the wheat.

The maximum amount of moisture was removed at a 6:1 MGMR using salt and a 5:1 MGMR using sand. These ratios appear to be maximum for drying wheat as shown in Figure 8.3. Large MGMR create a physical barrier to the escape of moisture and there is less opportunity of heat transfer to grain. For steel balls the maximum moisture was removed at an 8:1 MGMR. More moisture could possibly be removed at higher MGMR. Steel balls have a low thermal capacity as their specific heat is about 60 percent that of sand. Therefore more mass of steel balls is required to remove an equal amount of moisture for the same temperature

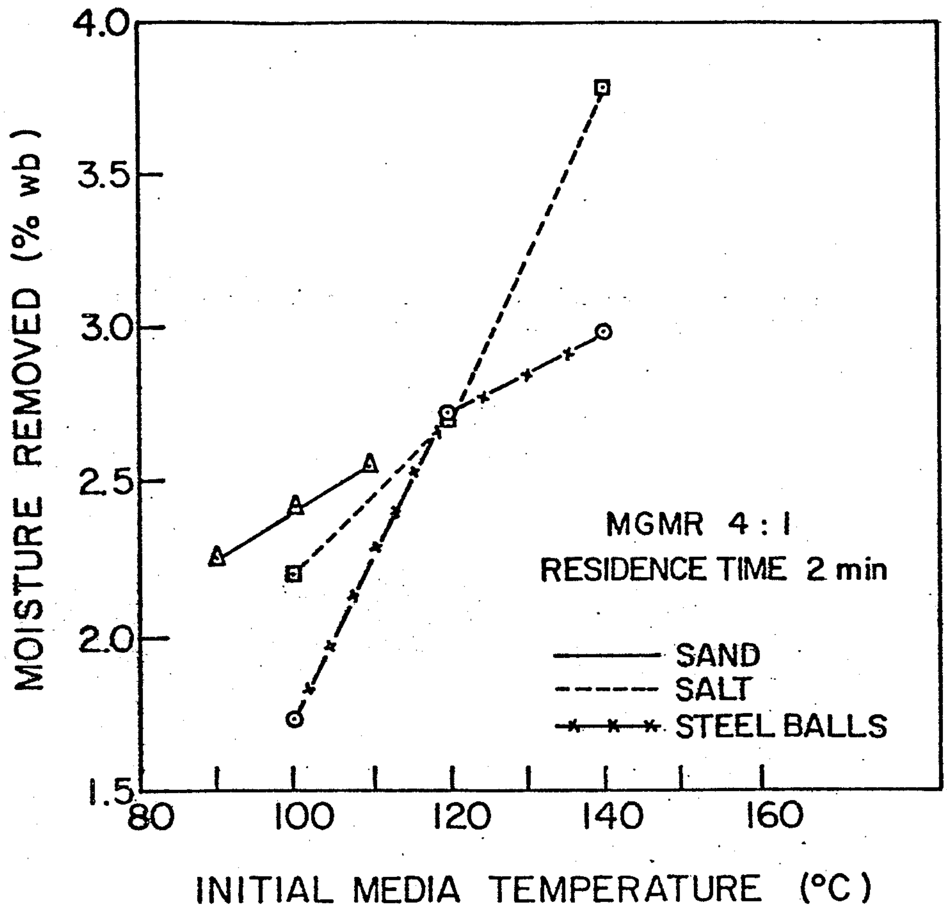


FIG. 8.2 Relationship between Initial Temperature of Solid Media and Percentage of Moisture Removed from Wheat

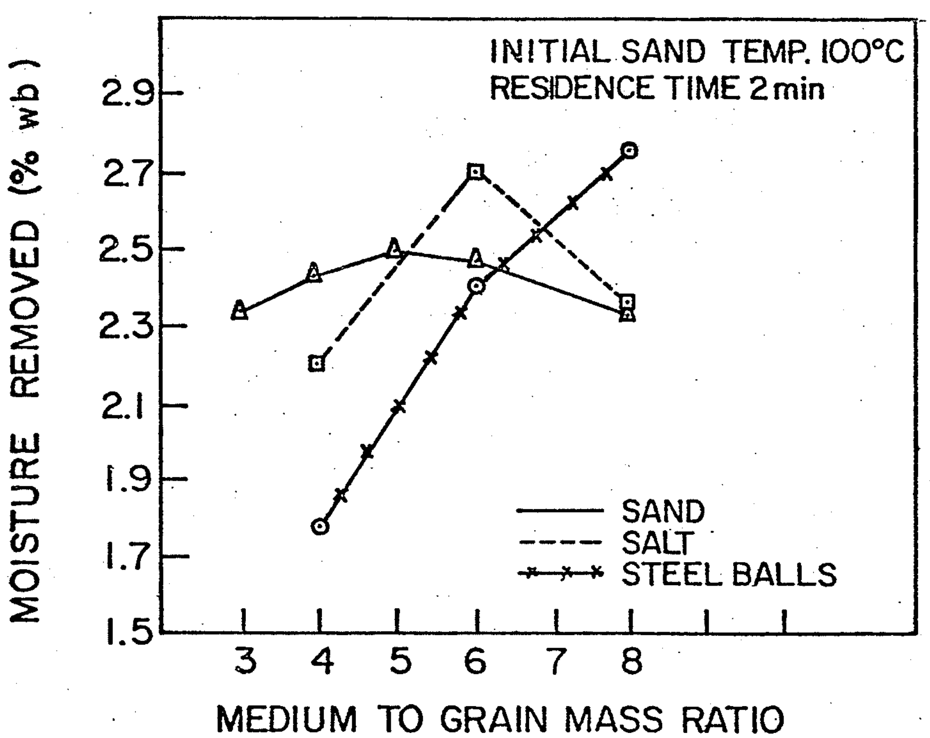


FIG. 8.3 Percent Moisture Removed from Wheat for Different Medium to Grain Mass Ratios for Various Media

differentials.

Drying efficiencies were also calculated and shown in Figure 8.4. Steel balls gave higher efficiencies at all the MGMR, reaching a maximum of 62 percent using a 4:1 MGMR. The maximum drying efficiency using salt was found at a 6:1 MGMR which is comparable to sand. The drying efficiencies for salt at high MGMR decreased. This same result was obtained with sand at the higher SGMR.

These results show advantages and disadvantages of different heat transfer media. Sand gave superior drying characteristics when compared with salt at low temperatures while salt was superior at high temperatures. Steel balls displayed drying characteristics superior to sand in drying efficiency. Due to the low specific heat of steel balls, less heat is required to raise their temperature, but their higher thermal conductivity (135 times that of sand) resulted in a rapid heat transfer to the surrounding air. The heat required for further heating of the steel balls will result in a lower drying efficiency. There will also be a substantial heat loss by conduction to the machine components and by convection to the surrounding air. Sand does not release heat rapidly thus less heat needed to be added for reheating.

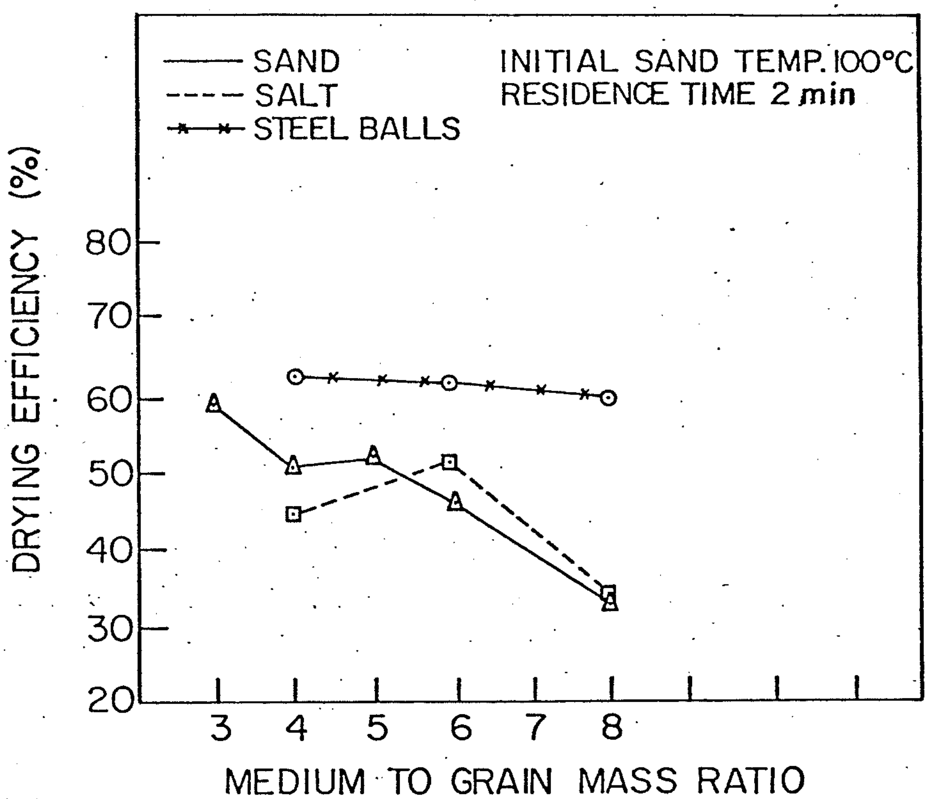


FIG. 8.4 Drying Efficiencies for Different Medium to Grain Mass Ratios for Various Media

CHAPTER IX

ROASTING AND PUFFING

9.1 Introduction

Parching or roasting is an ancient method of treating wheat grains. Parched grains are not difficult to masticate and are reasonably palatable. The roasting process also dries the grain and therefore it stores well and can be eaten without further cooking. The parched grains may be ground into dry powder which is eaten as such or incorporated into a gruel. The above practice is still followed in rural Peru. In Tibet, wheat is usually parched before being ground (Aykroyd and Joyce 1970).

Two methods have been commonly used for roasting food grains. The first method involves placing the dry grain in a hot pan or hot sand. The roasted grain is used mostly in the form of powder or flour, for direct consumption or in processed foods. The second method involves puffing, in which moisture is used to give a light and porous texture to the food grain. A sand bath can be used for both methods, but roasting should be done very quickly. Roasting of food grain is normally accomplished at 120-130^{o}C and puffing requires a temperature of 250^{o}C using a sand bath.[1]

Puffing quality depends on the variety of grain. Varietal differences that influence puffing quality, have been ascribed variously to kernel structure, amount and distribution of protein, starch composition, tightness of glumes enveloping the kernels and other factors. Optimum maturity of grain at an average moisture content of 20 to 24 percent was essential for maximum puffing. (Srinivas and Desikachar 1973).

9.2 Studies on Roasting of Wheat

Studies were undertaken on the roasting of wheat using both the batch and the continuous flow dryer. Experimental variables considered were sand to grain mass ratios of 4:1 and 5:1, initial sand temperatures ranging from 200 to 250 °C, residence time of two and three minutes and an initial moisture content ranging from 17.0 to 26.0 percent. Results of the limited study are recorded in Table 9.1. The protein content of the roasted grain was determined by the Plant Science Department, University of Manitoba. The Kjeldahl method was used.

The amount of moisture removed from the wheat rang-

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[1]Personal correspondence with Director, Central Food Technological Institute, Mysore, India.

Table 9.1: Results of Wheat Roasting Using Hot Sand

Sand to grain mass ratio	Residence time (min)	Initial sand temp. (°C)	Final sand temp. (°C)	Initial grain MC (%wb)	Final grain MC (%wb)	ΔMC (%wb)	Protein content (Nx5.7) (%db)	Drying efficiency (%)	Remarks
				BATCH DRYER					
4:1	2	202	126	17.50	11.00	6.50	--	70.0	One stage
	3	201	117	17.50	10.90	6.60	--	64.3	One stage
	2	200	112	20.50	12.80	7.70	--	73.1	One stage
	3	200	109	20.50	12.80	7.70	15.8	70.7	One stage
	2	200	103	24.00	15.45	8.85	--	76.0	One stage
	3	200	102	24.00	15.40	8.60	--	75.6	One stage
	3	250	133	18.50	9.75	8.75	15.9	60.4	One stage
	3	225 225	127 142	21.80 --	-- 7.35	-- 14.50	-- --	-- 62.8	Two stage
	3	240 240	119 142	26.00 --	-- 7.50	-- 18.50	-- --	-- 66.5	Two stage
	3	250 250	139 159	26.00 --	-- 5.30	-- 20.70	-- 16.2	-- 78.8	Two stage
5:1	2	201	125	17.50	11.15	6.35	--	54.8	One stage
	4	200	116	17.50	10.85	6.65	--	51.8	One stage
	2	200	121	20.50	11.80	8.70	15.9	72.9	One stage
	3	200	118	20.50	11.70	8.80	--	70.8	One stage
	2	200	107	24.00	15.00	9.00	15.8	66.4	One stage
	3	200	104	24.00	14.95	9.05	--	64.6	One stage
	3	250	135	18.50	9.45	9.05	--	50.7	One stage
	3	225 225	129 143	21.80 --	-- 7.60	-- 14.20	-- 16.0	-- 50.3	Two stage
	3	240 240	128 144	26.00 --	-- 7.40	-- 18.60	-- 16.2	-- 56.3	Two stage
	3	250 250	141 162	26.00 --	-- 5.25	-- 20.75	-- 15.8	-- 64.8	Two stage
				CONTINUOUS FLOW DRYER					
4.5:1	1	170	110	17.20	11.50	5.70	16.2	77.3	(2.5 kg/min grain flow rate)

Protein content in untreated sample (Average of four samples) 13.3%

ed from 5.7 to 20.7 percent. These tests indicated the feasibility of roasting grains using a solid heat transfer medium. Extensive studies on the quality of roasted grain was not undertaken.

An interesting observation noted, after biochemical analysis of the roasted wheat, was an increase in the protein content ranging from 2.5 to 2.9 percent (db). The increase in protein content was found to be proportional to the initial sand temperature. It was also noted that a larger increase in protein content was found when roasting was performed in the continuous flow dryer than when it was done in the batch dryer under similar drying conditions. No explanation can be offered for this observation at this stage. It was expected that a decrease in protein content would occur. A probable cause is the entry of nitrogen into the kernels from surrounding air. This phenomenon requires further investigation.

CHAPTER X

CONCLUSIONS

1. It was found to be technically feasible to dry wheat using heated sand as a heat transfer medium. Wheat was dried in a small batch dryer from 17.0 to 14.5 percent moisture content using sand heated to 100°C with a sand to grain mass ratio of 4:1 in two minutes. Sand heated to 105°C and a sand to grain mass ratio of 4.5:1 reduced the moisture content from 17.0 to 14.5 percent in one minute. The baking quality of the flour was unaffected.

2. An increase in sand to grain mass ratios above 5:1 resulted in no significant increase in the quantity of moisture removed and with some ratios a decrease was noted.

3. The quantity of moisture removed from the wheat was proportional to the initial sand temperature.

4. A residence time of two minutes was found to be the optimum time and no increase in moisture removal was observed for longer residence times.

5. Wheat dried at temperatures not greater than 105°C

with sand to grain mass ratios not more than 4.5:1 and with a residence time not exceeding two minutes did not show a serious reduction in germination. Germination counts exceeded 90 percent after three days, and 95 percent after six days, of the germination count of untreated wheat.

6. Sand texture of 20-40 removed a greater amount of moisture from wheat than sand textures of 12-30, 30-50, 40-60 and 60-100. A 20-40 texture of sand also gave the highest drying efficiency of the different sand textures used.

7. Salt was found suitable for drying only at high temperatures because of its hygroscopic nature and thus can only be used for drying grains which can remain undamaged at high temperatures. Salt was more effective than sand and steel balls at temperatures greater than 120°C. It was difficult to remove salt from grain at lower temperatures.

8. Greater heat losses to the machine components and to the surrounding air were found to occur when steel balls were used in the drying process. These losses were attributed to the high thermal conductivity of steel (135 times greater than sand). A large differ-

ence in density between the steel balls and the wheat (6 times) resulted in poor mixing of the two components at low mixture ratios in the dryer.

9. A 20-40 texture sand was found to have more desirable characteristics as a solid heat transfer medium for drying wheat than either granular salt or steel balls.

10. Studies using the batch dryer showed that complete thermal disinfestation of C. ferrugineus was accomplished during the solid heat transfer medium drying process. Samples of infested wheat in cloth bags passed through the continuous flow dryer also demonstrated the feasibility of thermal disinfestation.

11. A sand to grain mass ratio of 4.5:1 used in the continuous flow dryer removed more moisture than a 4:1 or a 5:1 ratio, when 12-30 texture sand at an initial temperature of 105°C was used. The maximum amount of moisture was removed at a grain flow rate of 3.0 kg/min under these conditions.

12. An average drying efficiency of 61.2 percent was obtained for grain flow rates ranging from 2.5 to 3.5 kg/min using a sand to grain mass ratio of 4:1. Lower drying efficiencies were observed for higher sand to

grain mass ratios. Drying efficiency decreased moderately at higher grain flow rates and tended to become constant at 53.5 percent above grain flow rates of 5.0 kg/min.

13. The maximum fuel efficiency of 40.7 percent was found at a grain flow rate of 3.0 kg/min using a sand to grain mass ratio of 4:1.

14. The specific energy consumption varied from 6.34 to 9.07 MJ/kg of water evaporated.

15. The performance of the hot sand heat transfer medium drying process was found superior to conventional hot air drying in drying and fuel efficiencies and in specific energy consumption.

16. The potential of using hot sand to accomplish the roasting of wheat was indicated by limited tests.

CHAPTER XI

RECOMMENDATIONS

1. More work should be done on the drying of different crops under various drying conditions to more clearly define the parameters associated with solid medium drying.

2. Drying investigations should be done on wheat having moisture content above 17 percent.

3. A higher capacity continuous flow dryer should be developed to exploit this process commercially. Some modifications suggested are:

   a) installation of automatic sand temperature controls,

   b) modification in sand conveying system to reduce heat losses,

   c) insulation of various parts to reduce heat losses,

   d) extension of the residence time in the drying section to increase drying time and in the cooling section for adequate cooling, and

   e) modification of the sand heating hopper to provide sufficient height to insure that the heaters will remain covered with sand at all times.

4. Sand texture versus kernel size investigations should be undertaken to select the optimum sand texture for solid medium drying of different grain. It is possible

that some relationship exists between sand particle size and grain dimensions.

5. Investigations should be conducted on thermal destruction of grain insects and micro-organisms by solid medium drying.

6. Grain drying investigations using sand and alternate heat transfer media should be continued.

7. Further investigations should be undertaken on grain roasting using solid heat transfer media. In particular, detailed investigations of the phenomenon of apparent protein content increase as observed in the limited roasting tests should be carried out.

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APPENDIX A

STANDARD CURVES FOR DIFFERENT CATEGORIES OF WHEAT QUALITY

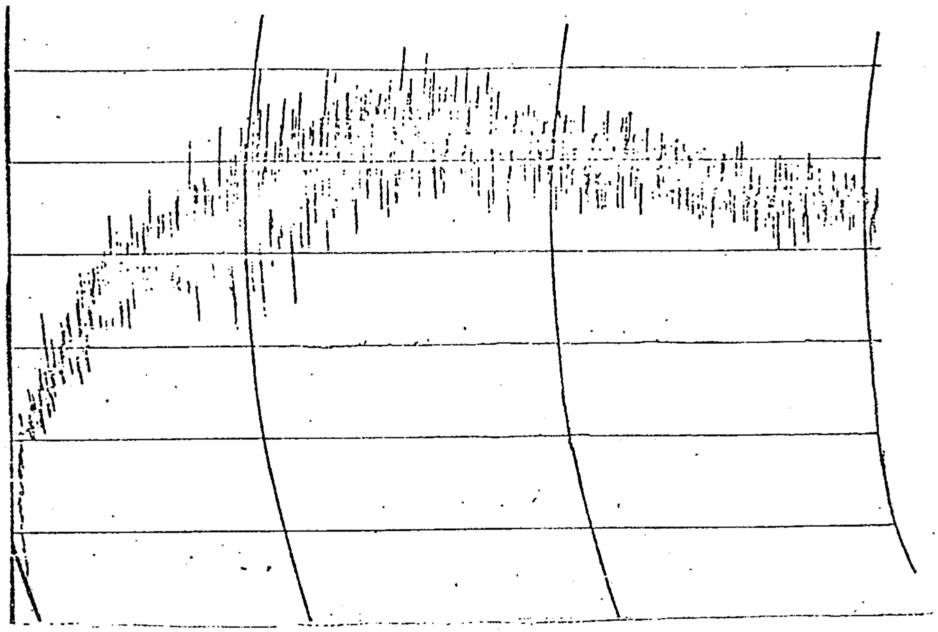

FIG. A.1 Standard Curve for Control Category 0 (Unchanged Quality)

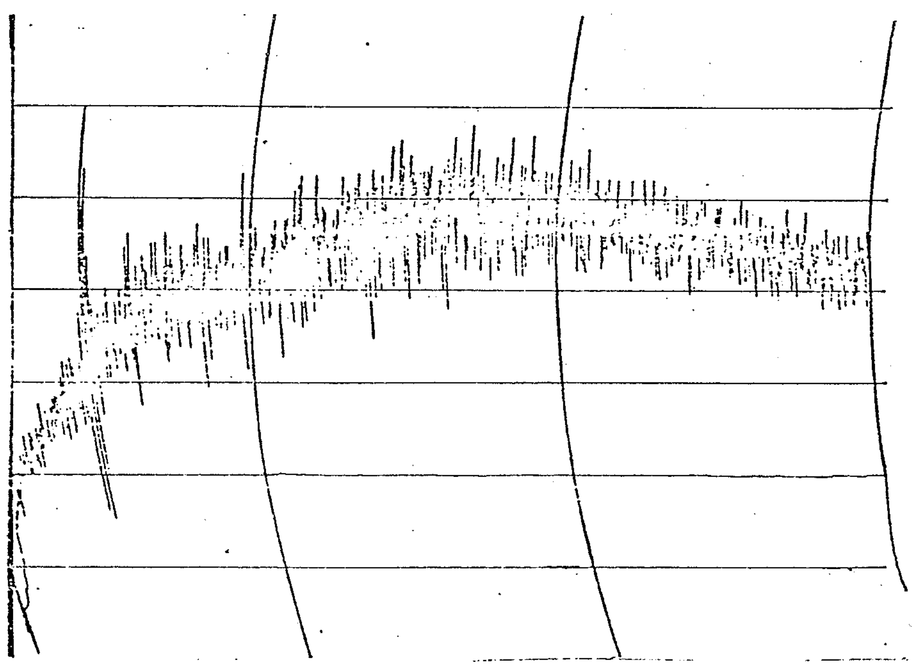

FIG. A.2 Standard Curve for Category 1 (Reduced Quality)

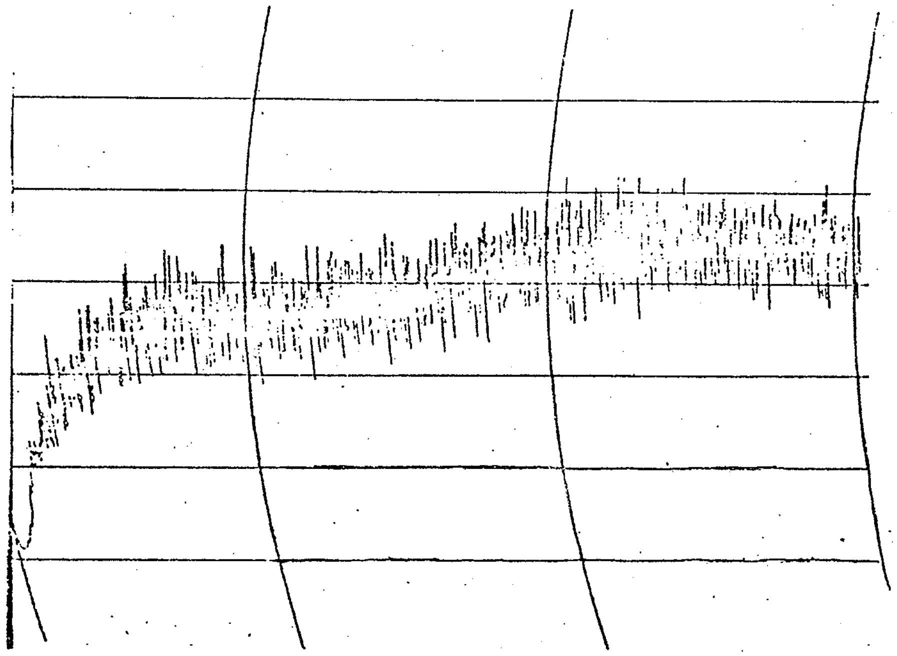

FIG. A.3 Standard Curve for Category 2 (Severely Reduced Quality)

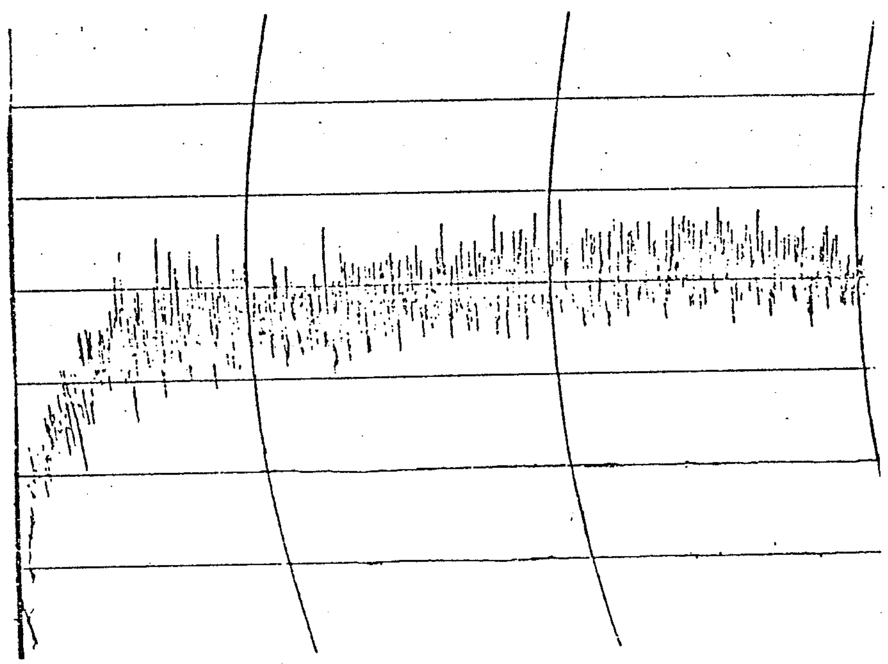

FIG. A.4 Standard Curve for Category 3 (Damaged Quality)

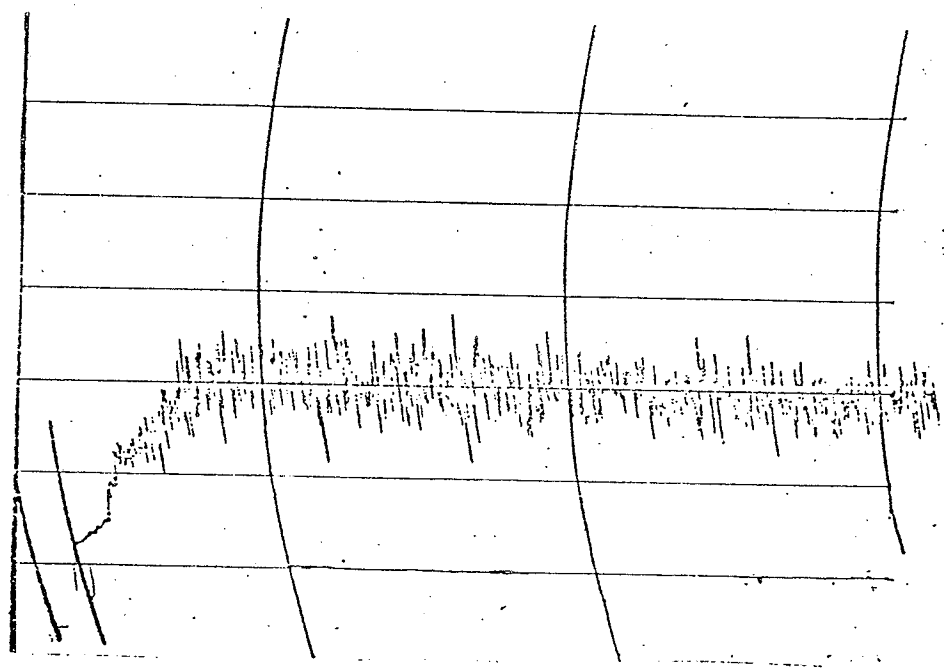

FIG. A.5 Standard Curve for Category 4 (Severely Damaged Quality)

APPENDIX B

ANALYSIS OF VARIANCE FOR DRYING DATA

Table B.1 Analysis of Variance for Effect of Sand to Grain Mass Ratio on Drying[1]

Initial sand temperature (°C) and residence time (min)	Analysis of Variance										
	Among all the treatments	Comparison between different treatments									
		3:1 and 4:1	3:1 and 5:1	3:1 and 6:1	3:1 and 8:1	4:1 and 5:1	4:1 and 6:1	4:1 and 8:1	5:1 and 6:1	5:1 and 8:1	6:1 and 8:1
100,1	*	*	**	**						*	*
100,2	*		*	*						*	*
100,3		*	*	*	-			-		-	-
110,1	*			*	-		*	-	*	-	-
110,2											
110,3	*		*		-		*	-	*	-	-

[1] * Significant at five percent level
** Significant at one percent level
Blank No significant difference
\- No test

Table B.2 Analysis of Variance for Effect of Initial Sand Temperature on Drying[1]

Sand to grain mass ratio and residence time (min)	Analysis of Variance			
		Comparison between different treatments		
	Among all the treatments	90 and 100°C	90 and 110°C	100 and 110°C
4:1,1				
4:1,2	*		*	*
4:1,3	**	**	**	*
5:1,1				
5:1,2		*		
6:1,1	**	**	**	
6:1,2	**	**	**	
6:1,3	**	**	**	
8:1,2	*		*	*

[1] * Significant at five percent level
** Significant at one percent level
Blank No significant difference

Table B.3 Analysis of Variance for Effect of Residence Time on Drying[1]

Sand to grain mass ratio and initial sand temperature (°C)	Analysis of Variance			
	Among all the treatments	Comparison between different treatments		
		1 and 2 min	1 and 3 min	2 and 3 min
4:1,100				
5:1,100		*		
6:1,100				
6:1,110				
8:1,100	**	**	**	**

1
* Significant at five percent level
** Significant at one percent level
Blank No significant difference

Table B.4 Analysis of Variance for Effect of Sand Texture on Drying[1]

Sand to grain mass ratio, residence time (min) and sand temp. (°C)	Analysis of variance										
		Comparison between different treatments									
	Among all the treatments	60-100 and 40-60	60-100 and 30-50	60-100 and 20-40	60-100 and 12-30	40-60 and 30-50	40-60 and 20-40	40-60 and 12-30	30-50 and 20-40	30-50 and 12-30	20-40 and 12-30
4:1,2,100	**		**	**	**	**	**	**	**		**
5:1,2,100	**		**	**	**	**	**	**	**		**

1 ** Highly significant
Blank No significant difference