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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.

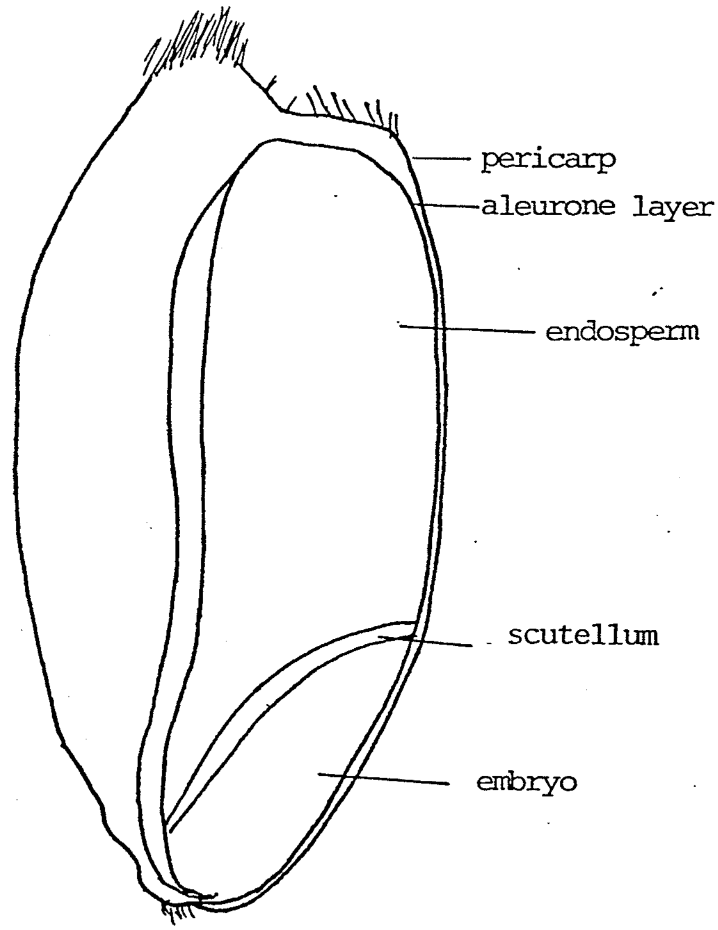

Fig. 2.1 Wheat Kernel Bisected Longitudinally Through the Crease (After Pomeranz 1971)

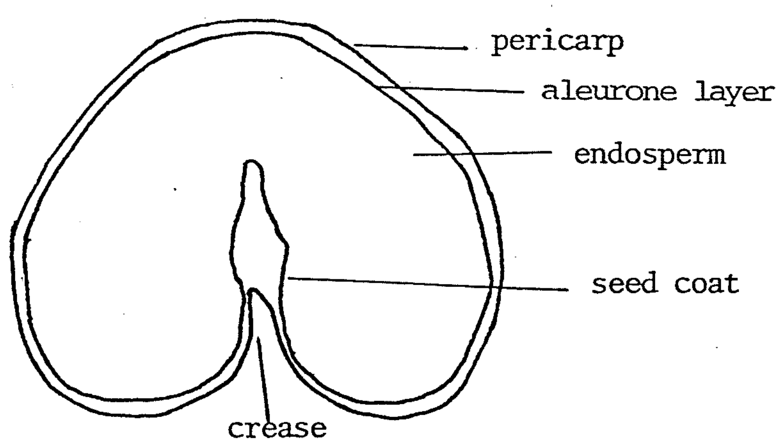

Fig. 2.2 Transection Through a Wheat Kernel above the Embryo (After Pomeranz 1971)

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 call-ed 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)	Wheat: 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 at 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°	-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, $65^{\circ}C$ 2.72×10^6 at 11% MC, $65^{\circ}C$	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^{o}C is usually recommended for drying wheat that is to be used for seed. For milling purposes temperatures above 60^{o}C should be avoided. For feed grains 88^{o}C is considered the high temperature