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DRYING RAPESEED USING A SOLID HEAT TRANSFER MEDIUM

by

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ABSTRACT

Conventional methods of drying grain use air as the heat transfer medium but because of its low heat transfer coefficient, extended drying times are required. The feasibility of using heated granular sand to effect the rapid drying of rapeseed was investigated. A continuous flow prototype dryer was built into which hot sand and high moisture content rapeseed were introduced into a rotating cylindrical drum. A screened portion of the drum separated the sand, allowing the dried rapeseed to continue through the remaining section of the cylinder. The separated sand was recirculated by an elevator leg to a storage hopper where electric heating elements were located.

The optimum conditions for drying rapeseed were found to be a sand-to-rapeseed weight ratio of 3:1 and an initial sand temperature of 130° to 190°C. Moisture reductions at these conditions varied from 3.7 to 5.8 percent and the average drying efficiency was 64.5 percent. A greater quantity of moisture could be removed by raising the initial sand temperature for a given mixture ratio. Increasing the sand-to-rapeseed ratio reduced the drying efficiency of the process.

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CHAPTER I

INTRODUCTION

The production of grain for human and animal consumption requires the storage of grain for varying periods, depending upon the yield and market demand. It is an objective to achieve production of a grain to meet demand, and storage of surplus production is necessary to carry over supplies into years of low production. During storage, the quality of grain must be preserved to eliminate economic loss to the farmer and to maintain adequate supplies. The quality of the grain will deteriorate during storage unless optimum conditions for safe storage are met.

Grain seeds are living organisms and, like all living things, they extract oxygen from the air and produce carbon dioxide, water and heat. During this process, the food reserves of the grain are being depleted and the grain slowly loses weight (5). The food reserves of growing plants are replenished by the continuing process of photosynthesis. Seeds, separated from the plant, do not have this capacity resulting in a weight and consequently a reduction in quality. This biochemical oxidation of carbohydrates and other organic nutrients with the release of heat energy is known as respiration (2). The rate at which respiration occurs depends upon the moisture content and temperature of the grain during storage. Conditions of high moisture content and high temperature increases the rate of respiration in stored grain. Grain must therefore be stored at a moisture level below its critical moisture content in order to reduce the respiration rate and thus minimize the deterioration in quality.

Loss of quality in a cereal grain results in a lower grade and consequently a reduced price to the producer. In the case of oilseeds, however, high quality standards must be maintained or a demand for the crop would not exist. The demand for oilseeds, particularily rapeseed, has increased markedly during the past few years. The wider use of rapeseed oil as an edible oil product, and the increases use of the meal as a source of protein for livestock feed rations have greatly increased the market demand for the crop. Producers have found rapeseed to be a very profitable alternative to cereal crops, not only during the years of limited markets and low wheat prices of the late sixties but also during current market demands and higher grain prices. Production of rapeseed has steadily increased into the seventies and prices have reached an all-time high. Although the rapeseed acreage in Canada is still relatively small when compared to cereal crop acreage it has become a very important crop for the Canadian producer.

The maintenance of high quality by safe storage of rapeseed necessitates the reduction of its moisture content below the critical moisture level of 10.5 percent, wet basis. This may be achieved either through the natural drying of the seeds by the sun or by artifical drying methods. Present day farming practises utilize heated air in order to effect the drying process. Conventional methods of grain drying use air as the heat transfer medium because air can be handled easily and it does not by itself, contaminate the grain. Air, however, does not have a high heat transfer coefficient and this, coupled with a resistance to moisture diffusion within grain kernels, results in extended drying times. The process of air drying, regardless of the type of dryer used, is an inefficient process. The use of a medium having a high heat transfer coefficient would lead to a more efficient grain drying process. The overall objective of this thesis was to investigate the technical and economic feasibility of using a solid medium as the heat transfer medium to achieve rapid and efficient drying of rapeseed.

CHAPTER II

REVIEW OF GRAIN DRYING PRACTISES AND SYSTEMS

2.1 Drying Practises

The drying of grain has always been a necessary practise for safe storage. In former times, drying was accomplished by natural radiant heat energy from the sun. Crops were cut when mature, tied into bundles and dried in stooks before the final threshing operation. With increased farm mechnization, artificial methods of drying grain were developed using heat air processes. Heated air dryers were initially confined to grain elevators and processing plants. Drying on farms was undertaken only in critical years of wet harvesting conditions and primarily to reduce the moisture content to permissible levels for safe storage. The need for on-farm drying has increased recently due to marketing constraints and limited drying capacities at terminal elevators during wet harvest seasons.

There are many reasons for making a grain dryer a standard part of the harvesting operation. It has been established that grains reach maturity one to three weeks before they are dry enough to store. Most grains can be threshed at approximately 20 percent moisture content and then dried without loss of quality, grade, or germination. A farmer with his own drying facilities can save those weeks, minimizing the risk of losing all or part of his crop due to deterioration during a wet harvest season. In addition to gaining extra harvest days each year a farmer gains the advantage of working additional threshing hours in the morning and evening of each day. For a farmer who relies on custom combining, a dryer can be a great help in getting his crop threshed early. Field losses can be greatly reduced by harvesting grain at a tough or damp condition.

Over-drying of crops in the field can lead to excessive shattering and grain loss during combining. Rapeseed and fababeans are especially susceptible to shattering losses when overdried in the field. Harvesting these crops at a high moisture content followed by artificial drying can greatly reduce field losses during harvest (10).

2.2 Drying Systems Currently in Use

There are three main drying systems being used on the farm today. These are classified as bin, batch, and continuous flow drying. There are advantages and disadvantage to each system depending upon the requirements of the individual farmer.

The bin drying system consists of two bins, one equipped for the drying process, and the other for the aeration and cooling operations. These bins are generally steel bins equipped with a perforated false floor for air distribution systems, however, any bin can be adapted for the method.

Batch Dryers are available in two types: (i) the stationary batch dryer; and (ii) the recirculating batch dryer. The stationary batch dryer keeps the grain in a stationary position throughout the drying operation with the same grain in contact with the hot air for the entire drying cycle. This results in over-dried grain nearest the hot air and under-dried grain nearest the outside, however, if proper temperatures are used, a satisfactory moisture level results after mixing. The recirculating batch dryers constantly mix the grain throughout the drying operation and therefore produce uniformly dried grain. Relatively small quantities of grain can be handled by batch dryers making them suitable for smaller operators and farmers with a wide variety of crops. Batch dryers are self-contained and easy to move making them useful for drying crops in several locations.

Continuous flow drying is a straight through one-pass system of grain drying. The dryer consists of three parts; (i) a warm air chamber; (ii) a cooling chamber; and (iii) an accurate positive means of controlling grain flow through the machine. The grain is unloaded into a hopper at the top of the dryer, flows down both sides of the hot air plenum, past the cold air plenum, and is removed by augers. The rate of grain movement is determined by the moisture content of the grain as it leaves the dryer.

The batch and continuous flow dryers may also vary in their method of air movement through the grain mass depending upon the design of the dryer. Three different types of air movement have been used; (i) crossflow; (ii) counterflow; and (iii) concurrent flow. The crossflow grain dryer has the air movement perpendicular to the grain movement. The counterflow grain dryer has the air movement parallel to and against the grain movement, while the concurrent flow grain dryer has the air movement parallel to and with the grain movement. The crossflow grain dryer is the most common method of grain drying although this method tends to overdry the grain on the input side and underdry the grain on the exhaust side of the drying column. Concurrent flow dryers have the hottest air in contact with the wettest grain, thereby allowing higher initial temperature without damage to the grain. Thompson et al. (22) found that the crossflow dryer was simplest in design, the counterflow dryer was the most efficient in the utilization of heat energy and the concurrent flow dryer the least damaging to the grain when using high temperature drying air.

2.3 Literature Review of Solid Medium Drying

Attempts to accelerate drying rates and to increase efficiencies have been undertaken by various researchers. Since air has a low heat transfer coefficient, investigations have been conducted to determine the feasibility of using a medium with a higher heat transfer coefficient accomplished by conductive heat transfer rather than convective. The use of a solid or granular material as the heat transfer medium has been considered as a possible alternative to air.

A conducted heat process for drying paddy rice in Thailand has been reported by Chancellor (7) in which he used a steel plate heat to 93°C (200°F). About 455 Kg (1000 lbs) of paddy rice was dried from 24 to 14 percent in four hours. He suggested the use of a granular medium, such as sand, to reduce excessive localized heating. Kahn (15) has reported that hot sand has been traditionally used for uniformily roasting wheat, rice, and corn in India and that is has also been used for partial drying of rice during the par-boiling process in the Phillipines. Kahn has investigations in progress at the International Rice Research Institute at Los Banos in the Phillipines using heated sand in a process for accelerated drying of paddy rice. He reported that the moisture content was reduced from 32 to 18 percent (db) in 30 seconds using sand heated to 238°C (460°F) and mixed with rice in a 20:1 sand to rice weight ratio. Raghaven and Harper (18) designed and built a dryer using heated granular salt as the heat transfer medium. During their investigations corn was dried continuously from 21 to 14 percent (wb) in 20 seconds in a salt bed at 235°C (450°F). Benson, as reported by Raghaven and Harper (18), holds a United States patent to apply an agitated bed of heat salt to rapidly heat and puff cereal pieces. Bateson and Harper, as reported in

(19), have developed an apparatus and described a continuous process for puffing pieces of food production with a granular material. A similar technique for obtaining high transfer rates in processing oil shale has been utilized in the Tosco process as reported by Raghavan *et al*. (19). Heated steel balls are used to effect drying in the cement manufacturing process.

CHAPTER III

PHYSIOLOGICAL FACTORS OF OILSEEDS

3.1 Composition of Rapeseed

Two species of rape are grown as oilseed crops in Western Canada; the species *Brassica campestris* L., commonly known as summer turnip rape or Polish type and the species *Brassica hapus* L. known as summer rape or Argentine type. Although varieties of the *Brassica hapus* species have a higher yield potential, the *Brassica campestris* varieties are preferred because of their early maturity. The climate of the district and the timing of farm operations will determine the species best suited to the individual farm (20).

The Argentine type of rapeseed has large, very dark brown to black seeds while the seeds of the Polish rape varieties are about half as large and reddish brown to black when mature. A cross-sectional view of a mature rapeseed (Fig. 3.1) illustrates the various parts of the seed. The seed coat percentage of the total seed varies with different species and varieties from about 12 to 20 percent. Yellow coloured seeds for example, have a lower percentage of seed coat than dark coloured seeds. Unlike cereal grains, the Brassica species have very little endosperm, and when the seed coat or hull is removed, the interior contains the embryo. Most of the embryo consists of the cotyledons containing about 50 percent oil and protein rich grains similar to those in the aleurone cells lying under the seed coat. The central part of the mature rapeseed is occupied by meristematic tissue (ET) from which the radicle (root), hypocotyle (stem), and epicotyl (bud) develop (3).

The major components in rapeseed are lipids (oil), protein, carbohydrates, crude fibre, and glucosinates. The oil content of the seeds of

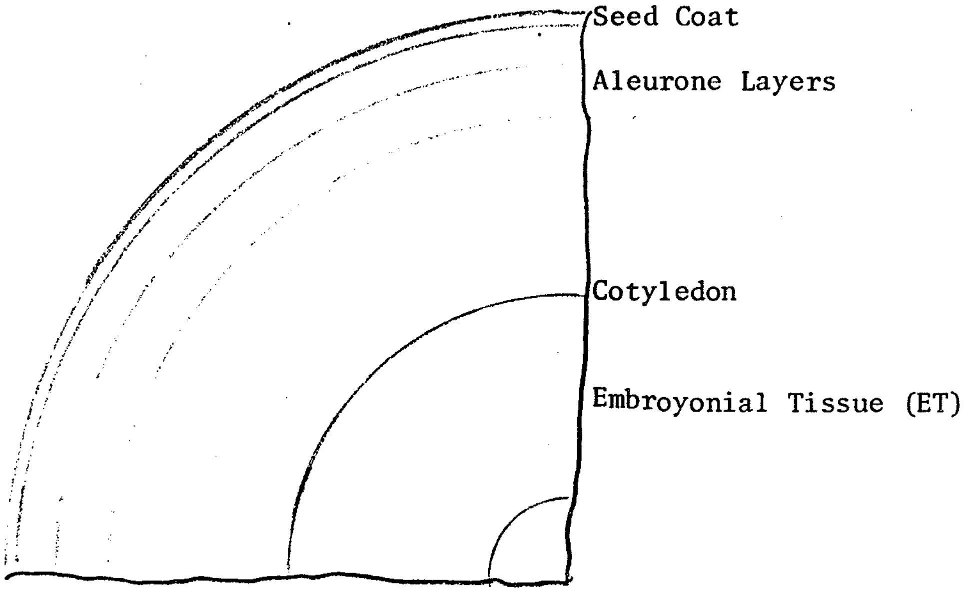

Fig. 3.1 A sectional view of a mature rapeseed displaying the relative positions of the component tissues.

Brassica hapus and Brassica campestris as determined by extraction with hydrocarbon solvent varies over a wide range. These variations occur due to the influence of the genotype and the environment. Typical oil content for summer rape are 37 to 47 percent and for summer turnip rape 36 to 46 percent on a dry weight basis.

Seed oils are usually characterised by their fatty acid compositions which in the Brassica species, are quite complex. Fifteen fatty acids are often present in levels from 0.5 percent and higher. They range in length from 16 to 24 carbons and in number of double bonds from zero to three. If fatty acids that are normally present in levels below 0.5 percent are also included, the total number of fatty acids in Brassica oils probably amounts to about 50. Common fatty acids contained in Brassica oils are palmitic, oleic, linolenic, linoleic, eicosenoic, and erucic. Through plant breeding, cultivars of Brassica hapus and Brassica campestris with very low levels of eicosenoic and zero or small amounts of erucic acid have been developed. These varieties form the major proportion of rapeseed being produced in North America today.

The residue from hydrocarbon extraction of rapeseed oil is called rapeseed meal. The most important use of the meal is as a high protein constituent in animal feed rations while in some parts of the world such as Japan, Europe and India, the meal is used as a high nitrogen fertilizer (6). Rapeseed meal contains approximately 40 percent protein on an oil-free, dry matter basis.

The amino acid composition of rapeseed meal as reported by Tkachuk and Irvine (23) based on grams of amino acid per 100 gram sample of N. is as follows:

Tryptophan	010.4
Lysine	036.6
Histidine	016.7
Ammonia	013.1
Arginine	038.5
Aspartic acid	045.9
Threonine	027.2
Serine	027.6
Glutamic acid	113.0
Proline	038.3
Glycine	031.4
Alanine	027.1
Cysteine+cystine	017.1
Valine	033.9
Methionine	013.2
Isoleucine	027.1
Leucine	042.3
Tyrosine	016.2
Phenylalanine	024.4
N recovery, %	092.1

Protein and oil content values are much higher in the meat fraction (cotyledons and hypocotyl) than in the seed coat or hull fraction. Therefore the lowest possible hull content would be the ultimate objective of plant breeding for maximum oil and protein extraction.

The content of crude fibre, mainly cellulose and hemicellulose, amounts to about 15 percent in defatted seed meals. The large amount of crude fibre in rapeseed meal is due to the small seed size having a large proportion of hull, rich in fibre. The content of minerals, called "ash" is about 7 to 8 percent of the meal.

Carbohydrates and miscellaneous organic compounds are in proximate analysis named "nitrogen free extract". This figure represents the difference between 100 percent and the percentage of other analysed compounds such as moisture, fat, protein, fibre, and ash. The proportion of nitrogen free extract contained in the Brassica species amounts to approximately 35 percent, almost as large as the proportion of protein.

3.2 Physiological Process in Rapeseed Storage

Rapeseeds are living organisms in which a variety of physiological processes take place. The process of respiration involves the biochemical oxidation of the carbohydrates and other organic nutrients of the seeds with the release of carbon dioxide and heat. Respiration of seeds in storage results in a decrease in total sugars, starches, and other organic matter causing a reduction in weight of the seed. Deteriorative changes in the oils may be either oxidative, resulting in typical rancid flavors and odours or hydrolytic, resulting in the production of free fatty acids. Fats in rapeseed are broken down into free fatty acids and glycerol during storage expecially under conditions of high temperature and moisture content. Fat hydrolysis takes place much more rapidly than protein or carbohydrate hydrolysis in stored grain making free fatty acid content of rapeseed an index for the extent of deterioration in storage. Hydrolysis of the glycerides to produce free fatty acids may be accompanied by degradation of the nonglyceride constituents of the seeds to produce oil which is dark in colour and difficult to bleach. The stability of the oil may also suffer causing it to undergo flavour changes in storage. Extensive deterioration may also make the mechanical processing of oilseed more difficult leading to lower oil recovery although no oil is actually destroyed.

Storage conditions that are favourable to intensive respiration are equally favourable to the growth of molds and other microorganisms. The growth of micro-organisms increases at an accelerating rate during storage because they improve their growing conditions by their own growth, raising both the temperature and moisture content. These conditions, combined with the heat produced by respiration can lead to the development of hot spots. Visible sprouting of the surface layers may result, as well as invisible damage, such as decreased viability and reduced oil quality.

The principal factors affecting grain respiration are moisture, temperature, aeration, and previous history (condition) (9). Of these factors, moisture content is by far the most important. The critical moisture level for safe, short term storage (up to one year) of any grain is the percentage moisture at which the seed is in equilibrium with an atmospheric relative humidity of about 75 percent and at 20°C (68°F). For storage periods ranging from 2 to 3 years, a relative humidity equilibrium of as low as 65 percent at 20°C (68°F) must be accepted as a safe minimum. At 75 percent relative humidity, marked increases in respiration occur and the minimum level for mould growth is reached. Excessive moisture in grain creates favorable conditions for fungus growth. Bacterial growth is rarely encountered in stored grain since the relative humidity requirement for these microorganisms exceeds 90 percent.

The critical moisture content for safe, short-term commerical storage of rapeseed and other oilseeds is approximately 10.5 percent wb while for cereal grains, the value is about 14.5 percent wb. The difference between the critical moisture contents for oilseeds and for cereals suggests that, since rapeseed is approximately 40 percent oil which is not miscible in water, the moisture would be distributed in the non-oil fraction of the seed. The equilibrium moisture level in this non-oil fraction of oilseeds would approximate the equilibrium moisture level of cereals. This explanation, however, fails to hold for soybeans which contain up to 20 percent oil and yet have a critical moisture value of 14 percent.

Most biological materials keep better under refrigeration than at higher temperatures due to the fact that the speed of most chemical reactions increases with increasing temperatures. Reactions based on exzymatic action, such as those occurring in oilseeds, follow the same trend. Respiration increases rapidly with increasing temperature until it is limited by such factors as thermal inactivation of the enzymes, exhaustion of the substrate, limitation in oxygen supply, or by the accumulation of high concentrations of carbon dioxide which inhibit the respiration process (9). The effect of temperature on the respiratory rate depends upon the moisture content of the seeds and relative contributions of seeds, molds, and insects to the total respiration. As long as grain is cool and dry, biological activity proceeds at a slow rate. The optimum temperature for rapid growth of insects in stored grain is 30-35°C (85-95°F) and their activity is greatly retarded by temperatures below 18°C (65°F) (22).

Although grain may go into storage at an acceptable level of moisture content and temperature, translocation of moisture can occur due to convection currents set up within the stored grain. Formation of convection currents results from the temperature gradients established by the effects of the atmospheric temperature on the storage bin walls and of the heat produced by local pockets of insect infestation.

Respiration of grain and of the microorganisms associated with the grain involves the consumption of oxygen and the liberation of carbon dioxide. Since respiration is limited by oxygen supply, accumulation of carbon dioxide in the intergranular spaces can inhibit the rate of respiration. Although aeration of grain tends to maintain an oxygen supply for the respiration process, its main advantage lies in the cooling effect it has on stored bulk. The amount of moisture removed during aeration is usually small but evaporation of even a small amount of moisture from grain greatly increases the cooling effect.

Rate of respiration is also affected by the condition or soundness of the grain. Samples containing a high proportion of broken or damaged kernels respire at a higher rate than sound grain. Microorganisms can more readily attack the constituents when the natural protective coating of the seed is removed, increasing the probability of the grain heating in storage. Weathering of grain during a delayed harvest causes increased fungus activity in storage, and molds which began to grow during the weathering period will continue to grow in storage.

CHAPTER IV

GRAIN DRYING THEORY

4.1 Moisture Movement Within Grain Kernels

Grain is a hygroscopic material whose capilliary-porous colloidal structure permits it to take in, or release moisture to the ambient atmosphere until equilibrium is reached. The forces that hold water in the kernel structure may be either physical or chemical and are commonly called sorption forces. Sorption generally includes three processes: absorption, adsorption, and chemisovption. Water which is held in the intergranular spaces and within the pores of the material, is contained loosely in the system by capillary forces. Such water is termed absorbed water and possesses the usual properties of free water. Water held more firmly in the system by molecular attraction due to the forces of the polar or valency type is said to be adsorbed water. Under certain conditions, water held by these molecular forces is released to the ambient air resulting in desorption. The remainder of the moisture in the grain kernel is contained by the process of chemisorption in which the water is held by very strong chemical forces and is in chemical union with the kernel. Because this water is so strongly bound to the grain colloids, grain containing only bound water will respire at a much lower rate. Kretowich, Johnson and Dale (14) reported that at a moisture content of 30 percent wb, wheat contained approximately equal quantities of free and bound water, while at a moisture content of 15.6 percent, over 90% of the total water was bound water. Grain drying processes, which usually lower the moisture content to 12 to 14 percent, apparently involve teh removal of both free and bound water.

The hygroscopic nature of grain means that it exhibits a vapour pressure less than that of free water at the same temperature. Therefore, the energy required to vaporize grain moisture would be greater than free water and would increase as drying is carried out to lower moisture levels due to the removal of a larger proportion of chemically bound water. The heat of vaporization would be greatest at low moisture contents and very nearly the same as for free water at high moisture contents (9). Although lower temperatures (at which evaporation takes place) increase the heat of vaporixation, its value is more sensitive to grain moisture content than it is to temperature (4). Dale and Johnson (14) found that over the range of moisture levels encountered in actual drying systems for wheat and shelled corn, the heat required for vaporization was between 1.00 to 1.06 times that of the vaporization of free water. Based on the measurements of the heat of hydration of flour by Winkler and Geddes (1931), Hukill, as reported by Christenson (9), concluded that the heat required to dry flour must be the heat of vaporization of free water (approximately 555 cal/gm) plus 200 cal/gm, the measured value of the heat of hydration of flour. This value, however, was determined for removal of water at very low moisture contents and the heat of vaporization would be much less for drying in the range from 10 to 20 percent moisture content. In the absence of accurate data, Hukill used a value of 622 cal/gm. Calculations done by Brooker et al. (4) on the drying of cereals used a constant value of 666 cal/gm of water as the heat of vaporization. They acknowledged that this value would be high in many instances and would result in conservative estimates of drying time.

The heat of vaporization may be computed from data on vapour pressure of moisture in grain by the following close approximation of the Clausius-Clapeyron equation (2):

$$H_{fg} = V_{fg}\ T\ \frac{\delta P}{\delta T}$$

in which, H_{fg} is the heat of vaporization, V_{fg} is volume of the vapour, T is absolute temperature and P is vapour pressure.

Unfortunately, accurate measurements of vapor pressure of moisture in grain are lacking. For purposes of calculations in this thesis a value of 640 cal/gm of water was used as the heat of vaporization.

Numerous researchers (4, 8, 9, 12) agree that the drying of grain involves two fundamental processes, (i) transfer of heat to evaporate liquid water, and (ii) transfer of mass in the form of internal moisture and evaporated liquid. Mass transfer occurs as liquid and/or vapour within the grain kernel and as vapour from the grain surfaces. When grain is very wet, the drying can usually be divided into a constant rate drying period and a falling rate drying period. Constant rate drying occurs at high moisture contents when the internal resistance to moisture transport is much less than the external resistance to water removal from the surface. The magnitude of the rate of drying this period is dependent upon external conditions such as temperature, humidity, air flow, exposed area, etc. During the falling rate period, the internal resistance to moisture transport becomes greater than the external resistance to water removal and the drying rate decreases as the moisture content of the grain decreases. Most agricultural commodities dry solely during the falling rate period except for such products as potatoes and sugar beets which dry under a constant rate period when dehydrated under constant ambient conditions. Because the drying rate decreases continuously during the course of drying, it becomes more complicated to predict the drying rate during the falling rate period than during the constant rate period.

Analysis of the falling rate period must take into consideration not only the external conditions, but also transfer mechanisms within the grain. The drying rate during the falling rate period is governed mainly by internal flow of liquid or vapor. It has been assumed by numerous researchers (4, 8, 12, 13) that the mechanism of internal flow is that of diffusion and that the driving force is either the moisture concentration gradient or the vapor pressure gradient. Using these assumptions, a number of theoretical and empirical drying equations have been developed. An equation analogous to Newton's law of cooling or heating of solids which is often used in grain drying analyses assumes that the rate of moisture loss of a grain kernel surrounded by a medium at constant temperature is proportional to the difference between the kernel moisture and its equilibrium moisture content. The drying rate can be expressed as follows:

$$\frac{dM}{dt} = - k (M - M_E)$$

where M is the moisture content at any time t, M_E is the moisture content in equilibrium with the drying air, and k is a drying constant. Separating the variables and evaluating the integral leads to the expression $MR = e^{-kt}$ where MR, the moisture ratio, is the ratio of the amount of moisture remaining to be removed $(M - M_E)$ at any time t compared to the total amount of moisture removed when drying proceeds until the product is in equilibrium with the drying air $(M_o - M_E)$. M_o represents the initial moisture content of the product.

The diffusion equation is a similar relationship derived by Crank

(4, 13) for a homogeneous, isotropic, symmetrical sphere with radius R and constant diffusion coefficient D. The equation is as follows:

$$MR = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} e^{-n^2 kt}$$

where

$$K = D \frac{\pi^2}{R^2}$$

The drying equations developed by these and other authors all contain a drying constant or a diffusion coefficient. Each set of coefficients and constants apply to a specific drying equation and should not be used in other expressions. In addition, their values are applicable only to specified temperature and moisture content ranges. Along with the constraints imposed upon their use there is a limited amount of published data on the value of the constants and coefficients for various grains, especially oilseeds thereby restricting their use in grain drying calculations.

The use of a solid heat transfer medium in grain drying involves heat transfer between granular particles having different temperatures. The particle properties have a definite effect on the rate of heat transfer but the mechanism of heat transfer in particle-particle heat exchange requires much more research. Raghaven _et al_. (19) found in experiments using salt as the heat transfer medium, increased heat transfer coefficients were obtained by reducing particle size and increasing velocity of the particles. Analytical models for heat exchange between a sphere and moving particulate beds were developed and were found to fit the experimental data well but the thermal properties of the particulate material were not included in the model. Experimental determinations of the surface heat transfer coefficient for moving granular salt past a sphere yielded values of 171.2 – 366.8 KCAL/hr-m^2-°C (35-75 BTU/hr.-ft^2-°F). This compares with a value of 4.9-24.5 KCAL/hr-m^2-°C (1-5 BTU/hr-ft^2-°F) for the convective heat transfer coefficient of air (16). The use of a granular solid material with its high rate of heat transfer appears to have a large potential for rapid continuous drying.

4.2 Efficiency

Drying grain using heated air methods is an inefficient process. Looking at the drying process as represented by the psychometric chart, it can be seen that the drying air will reach saturation before all of the sensible heat in the air can be recovered. The utilization of heat energy in the drying process can be described by two different expressions of efficiency as used by Foster in (22). The first expression, termed fuel efficiency, indicates the efficiency of fuel utilization and is a ration expressed as:

$$\text{fuel efficiency} = \frac{\text{HEAT UTILIZED TO REMOVE WATER}}{\text{HEAT CONTENT OF FUEL SUPPLIED}}$$

The second expression, drying efficiency, relates to the efficiency of the drying process in removing moisture and is a ratio expressed as:

$$\text{drying efficiency} = \frac{\text{HEAT UTILIZED TO REMOVE WATER}}{\text{HEAT AVAILABLE FOR DRYING}}$$

In both expressions, the numerator represents the amount of heat energy required to vaporize the moisture from the grain and is the product of the amount of water removed W, and the latent heat of vaporization, H_{fg}.

The denominator in the fuel efficiency ratio indicates the heat content of the fuel furnished to the drying medium for the removal of grain moisture. Fuels used in heated air dryers are coal, fuel oil, gasoline, kerosene, natural and manufactured gas, and wood. The most commonly used fuel is propane, having a heating value ranging from 11,000 to 12,000 cal/gm.

Hall (12) used the term thermal efficiency to express the fuel efficiency ratio. He reported that the approximate thermal efficiency of heated air systems ranged from 60 percent in the summer to 36 percent in the winter. Foster in Sinah and Muir (22) found that in drying field shelled corn from an average initial moisture content of 25.1 percent to an average final moisture content of 14.6, a fuel efficiency of about 40 percent was achieved by the heated air systems. He also stated that fuel and drying efficiencies were about 17 to 19 percent higher for corn at an initial moisture content above 27 percent than for corn at below 23 percent moisture level.

The denominator of the drying efficiency ratio represents the heat available for drying. For heated air systems, this would be the product of the quantity of drying air, Q its specific heat Cp, and temperature reduction ΔT that occurs in the drying air. Considering a solid medium drying process, the denominator of the drying efficiency ratio would be the product of quantity of solid medium M, its specific heat, Cp and the temperature reduction in the solid medium ΔT.

Foster in Sinah and Muir (22) reported that the drying efficiency of heated air methods in drying field shelled corn from 25.1 percent to 14.6 percent moisture content ranged from 51.2 percent for continuous flow systems to 57.5 percent for batch type driers. He also found that the drying air temperature did not significantly affect the drying or the fuel efficiency in the range from 60° to 143°C.

Efficiences are affected by the resistance to moisture removal offered by particular grains. In general, smaller seeds lose their moisture easier than larger seeds. It has been observed that corn requires 1.67 as much time to dry as does wheat while rice dries slightly faster.

4.3 Drying Temperatures

The temperature at which the drying process occurs has a significant effect on grain quality. Brooker et al. (4) state that the maximum allowable grain temperature depends upon the purpose for which the grain is to be used, the moisture content of the grain, and the type of grain. Grain can be used for seed, for commercial use, and for feed. Seed grain or malting barley cannot be dried at high temperatures without destroying the ability of the seed to germinate. The temperature above which germination declines also depends upon the initial grain moisture, (4, 9, 12). The higher the initial moisture content of the grain, the lower the temperature limit must be.

McKnight and Moysey (17) suggested a decrease in the drying air temperature of 5.5°C (10°F) for each 2 percent increase in moisture content above 11 percent. Where removal of a large percentage of moisture is required, lower temperatures should be used or drying should be done in two stages with cooling between stages. To ensure the viability of the seed, regulations of the Canada Grains Commission state that any grain which is to be used for (seed purposed) must not be dried at a temperature exceeding 43°C (110°F).

Grain to be used for commercial purposes can withstand somewhat higher temperatures than seed grain. Drying wheat at temperatures up to

65°C (150°F) does not seriously affect its baking or milling qualities (4, 10). At higher drying temperatures however, wheat becomes case hardened, making it more difficult to mill and resulting in a deterioration of its baking qualities. Brooker et al. (4) state that excessively high kernel temperatures in corn cause increased breakage, stress cracking and kernel discoloration and lead to a decrease in starch separation (millability), oil recovery and protein quality. A maximum drying temperature of 55°C (130°F) is recommended for corn which is to be used for milling. Rice is also limited to a drying temperature of 55°C (130°F) since higher temperatures result in stress cracks in the kernels, reducing its milling quality (9). Although cereal grains for commerical use are limited to maximum drying temperatures of between 55°C (130°F) to 65°C (150°F), it appears that higher drying temperatures are possible for oilseed grains. McKnight and Moysey (17) concluded that air temperatures up to at least 93°C (200°F) can be used for drying rapeseed without affecting the quality of the oil. Schuler and Zimmermen (21) found that the oil content and fatty acid composition of sunflower seeds were unaffected by drying temperatures of up to 104°C (220°F). Sorenson and Davenport in (22) reported no change in oil content, iodine number, or acid number of flaxseed dried at temperatures of 70°C (175°F) A maximum allowable air temperature of 82°C (180°F) was recommended by Friesen (10) for drying flaxseed for commerical use.

The effect of high drying temperatures on the feeding value of grains is difficult to determine since the various nutritional components such as carbohydrates, proteins, and vitamins react differently to temperature treatment. Also, various animals such as pigs, poultry, and ruminants are not equally affected by the quality of these components.

Protein is the principle nutrient obtained from grain meals and it is this nutrient component which exhibits sensitivity of heat treatment.

Application of heat has both beneficial and adverse effects on the feeding value of grains. Cooking of grain is considered desirable for livestock feeds since the denatured protein is more readily assimilated. Raw soybeans, rapeseed and cottonseed all contain elements that tend to depress growth. For this reason, soybean flakes are cooked at 90-100°C (190-210°F) for 20 to 30 minutes. The degree of improvement in the nutritional value will depend upon the temperature, duration of heating, and moisture conditions. Moisture contents from 18 to 20 percent are used since the trypsin inhibitor is destroyed in less time and with less heat under moist conditions. The trypsin inhibitor is thought to be the major cause of poor utilization of the protein in raw soybeans (1). A similar procedure of heat treating at high mositure contents is used with cotten seed. Rapeseed, however, must be cooked without the addition of moisture to inactivate the enzyme, myrosinase. This enzyme is responsible for the breakdown of the thioglucosides resulting in the release of sulphur compounds into the oil and meal. This, along with the product of other enzymatic reactions, determines the refining and hydrogenating properties of the oil and the toxicity of the meal. The inactivation of the enzyme is therefore a very important objective. In rapeseed the inactivation of myrosinase will occur at seed temperatures of between 80 and 95°C (176-203°F). Heating should be done quite rapidly as slow drying at elevated temperatures may create ideal conditions for mold growth and enzyme activity.

Severe heat treatment may lead to changes in or destruction of a number of amino acids, particularily lysine, arginine, tryptophan, methionine, and cystine. In soybean protein, the amino acids involved are lysine and methionine, both of which are required for maximum nutritive value. The damaging effects of excessive heat can be partially precented by addition of large amounts of water. Rapeseed meal, heated for 5 hours at 150°C (302°F) produced a non-toxic meal which had rather poor growth-promoting quality, probably die to heat injury to the protein (1). The nutritive value of cereal proteins is also affected by excessive heat. Liener in (1) reported that Morgan and others had found that the toasting of wheat, rice or corn at 150°C to 200°C (302 to 392°F) for 30 to 45 minutes reduced the growth promoting quality of the protein. Liener also stated that Kon and Markuze discovered that the crust of the bread which receives more severe heat treatment than the center of the loaf, has a lower nutritive value than the crumb. The difference in nutritive value was attributed to decreased digestibility of the crust and to the destruction of lysine, during baking to the extent of about 15 percent. Liener also reported that similar destruction of lysine has been found in oat protein damaged by a toasting process, sunflower seed meal processed at a temperature of 130°C , and by corn dried at temperatures in excess of 60°C. Raghavan and Harper (18) found that corn dried from 21 to 15 percent wb in a heated particulate salt bed at 232°C (450°F) during a residence time of 13 to 20 seconds did not affect the nutritive value of the corn when fed to young children. However, they did acknowledge that ruminants may react differently to the heat treated corn than the monogastric chicken. In most instances, vegetable proteins are not consumed in their native state but in a form which has been subjected to some degree of heat treatment.

CHAPTER V

DRYING USING A SOLID MEDIUM

5.1 Design Considerations

The objective in the design of a solid medium drying system, was to develop a continuous flow process in which the rapeseed and the heated solid medium could be mixed to effect drying, followed by separation of the two components, after which the solid medium would be recycled and the rapeseed allowed to cool. The various parameters involved in the process would require some method by which they could be accurately controlled, measured and varied throughout a range of values. These parameters would include the initial temperature of the solid medium, the mixing ratio of solid medium to rapeseed, and the length of mixing time of the two components.

Selection of the particular solid medium to be used would affect the design of the system. A number of different granular solid mediums were considered, namely sand, steel shot, and salt. To test the suitability of the granualr solid media and the feasibility of the drying process, initial laboratory trials were run in a small bench model dryer consisting of a rotating 45.72 cm (18 in) length of 30.5 cm (12 in) diameter indent cylinder. The cylinder was insulated with fiberglass and contained access ports for introducing and removing rapeseed and the solid medium. The solid medium was heated in an electric oven, placed with the rapeseed in the cylinder, then removed and separated by hand screening.

The use of steel shot as the solid medium indicated a possible problem with separation, size and colour of the steel shot was similar to that of rapeseed making it difficult to determine if separation was complete after screening the mixture using hand sieves. A magnetic separating device of some form would probably be necessary to assure complete removal of the steel shot. Also, the large difference in density between the steel shot and rapeseed created difficulties in the mixing of the two components. The higher density steel shot had a tendency to settle towards the bottom of the mixture while the rapeseed remained near the top. Although the sand density was also greater than that of rapeseed, the difference in densities was not as large, and more complete mixing action occurred. Sand had the added advantage of being available in various texture ratings, making it possible to chose the texture of sand such that separation of the sand and rapeseed would be 100 percent. Although salt was considered as a possible solid medium, no trials using salt were attempted.

Trials on the bench model dryer with sand at 232°C (450°F) and a sand-to-rapeseed weight ratio of 2.5:1 reduced the moisture content of rapeseed from 17.6 percent to 13.3 percent in two minutes. Similar drying results were obtained using steel shot. Due to mixing and separation problems which incurred in the trials with the steel shot, sand was chosen as the solid medium to be used for further testing. Since the drying process seemed to be quite feasible, a larger prototype dryer was designed for further testing of the solid medium drying principle.

5.2 Description of Prototype

The prototype (Fig. 5.1) consists of a rotating cylindrical drum, 3.5 m (10 ft) long and 45.72 cm (18 in) in diameter, which is divided into a 1.22 m (4 ft) length of insulated drying section, a 0.61 m (2 ft) screened separating section, and a 1.22 m (4 ft) cooling and dry seed delivery section. Two hoppers, one for high moisture content rapeseed

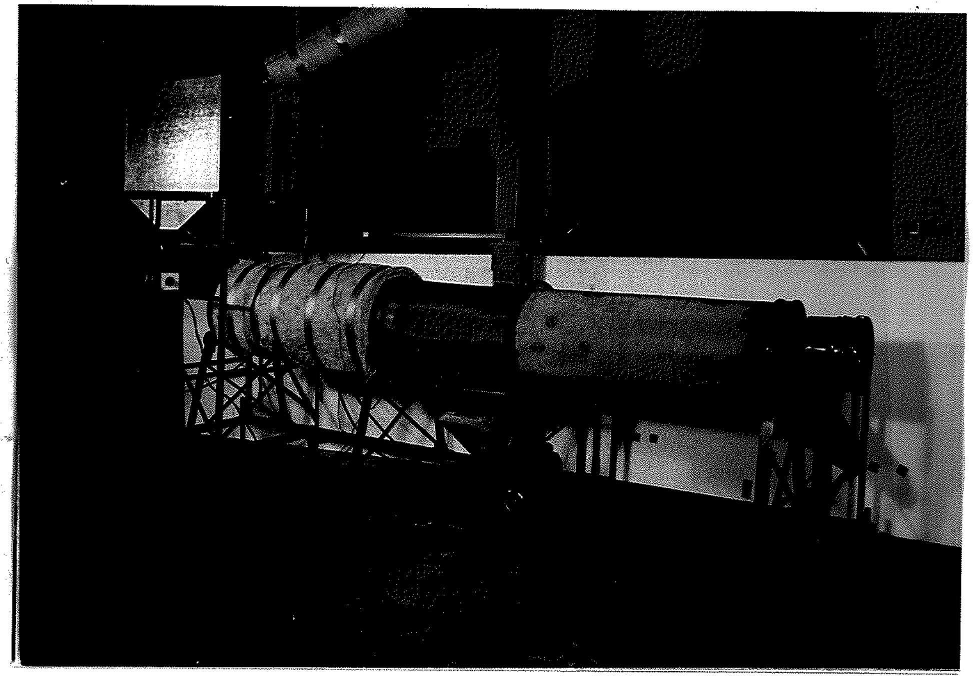

Fig. 5.1 Continuous flow prototype dryer

and one for hot sand, were mounted above the drying section opening, and introduce the rapeseed and the sand into the metering head device. The metering heat (Fig. 5.2) delivers the desired flow rates of sand and rapeseed into the drying section so that various sand to rapeseed weight ratios can be selected.

The residence time of the sand and rapeseed in the dryer can be regulated by varying the slope of the cylinder and the rotational speed of the cylinder. Mixing and propulsion of the sand and rapeseed is assisted by small and gently curved spiral flights attached to the interior of the cylinder in the drying and cooling sections.

The adjustable legs, which control the angle of inclination of the dryer, could also be raised off the floor and the whole unit moved on the mounted castors.

The cylinder is driven by a pinion gear from the drive mechanism which meshes with the large 46.8 cm (18½ in) I.D. external ring gear attached to the rotating drum (Fig. 5.3). Using a pulley reduction system and a variable pitch sheave on a .373 KW (½ hp) electric motor, the speed of rotation of the drum can be varied from 15 to 30 rpm. The rollers on which the drum rotates consists of 7.62 m (3 in) diameter colsonite rubber casters. The three roller guides were rolled from 0.64 cm by 8.62 cm (¼ in by 3 in) wide flat iron into 44.45 cm (17.5 in) I.D. rings and attached to the cylinder. Adjustment bolts on the roller guides were necessary for the alignment of the three roller guides and ring gear into the same cylindrical plane, in order that the ring gear would run true and mesh with the pinion gear on the drive mechanism when the roller guides were in contact with the rollers. The pinion gear was rubber mounted to allow for deflection which would occur if any eccentricies remained in the system.

The screened separating section (Fig. 5.3) consisted of 18 mesh steel wire cloth having a wire diameter of .584 mm (0.23 in). The mesh size was selected such that the variety of rapeseed having the smaller diameter, Polish rapeseed, would not pass through the screen. Silica sand having a 40-60 texture rating was chosen because all the sand of this texture passed through the steel wire cloth.

The sand, after passing through the screened separating section was recirculated by a 3.05 m (10 ft) bucket elevator leg and a 15.24 cm (6 in) diameter fibreglass insulated pipe to the sand hopper. A special high temperature belt was used in the elevator leg because of the possible

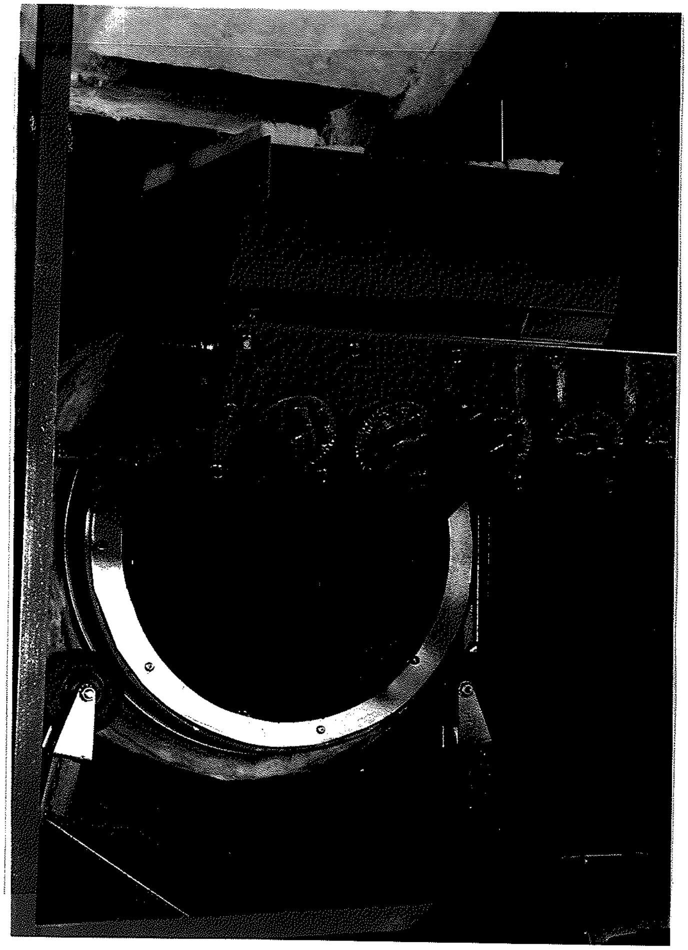

Fig. 5.2 Metering head device for setting sand-to-rapeseed ratios

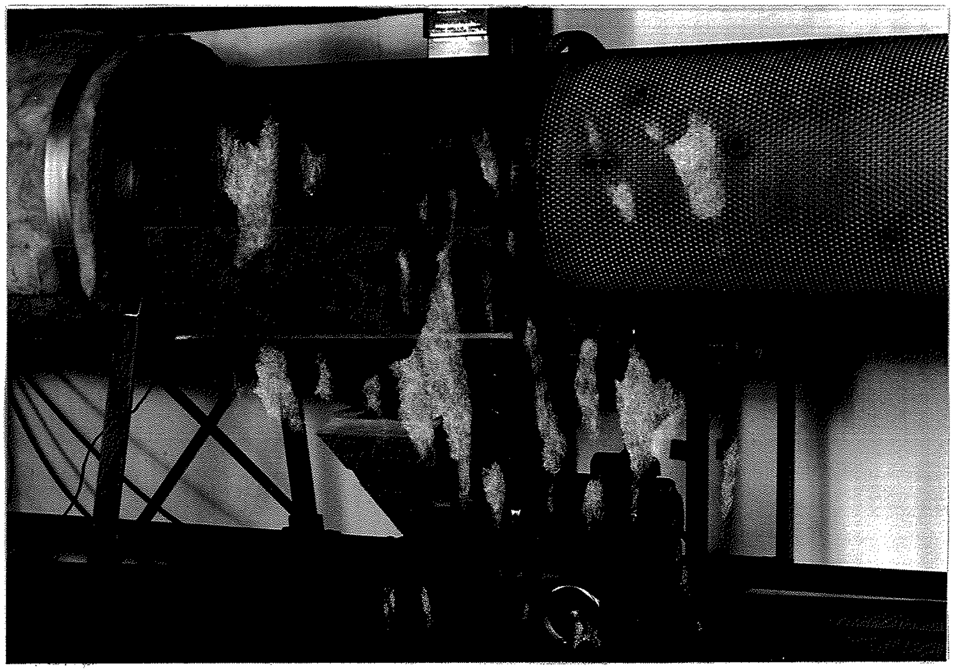

Fig. 5.3 Drive mechanism, screened separating section, and collection hopper for elevator leg.

high sand temperatures involved. The sand hopper has a storage capacity of about 0.84 m^3 (3 ft^3) and contains 10-230 volt 2 KW V-bend electric heating elements. The elements were placed on three separate circuits with breakers on each circuit (Fig. 5.4). The sand hopper was insulated with 5.08 cm (2 in) rigid fibreglass insulation.

A 17.00 m^3/min (600 cfm) fan was installed at the end of the cooling of the grain and to remove the moisture which was driven off in the drying section.

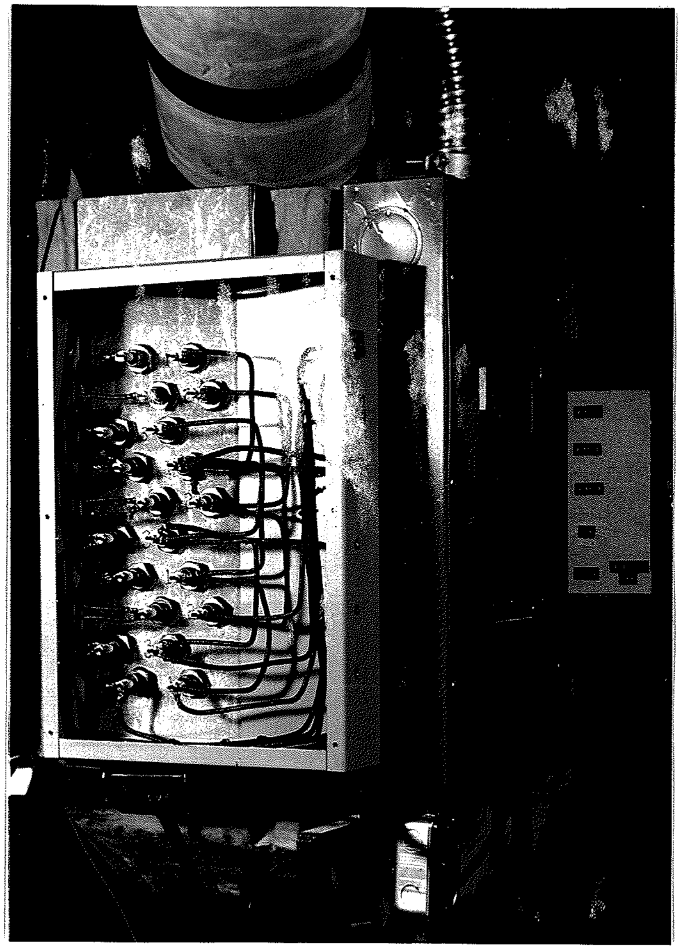

Fig. 5.4 Circuit control panel for electric heating elements and motors.

5.3 Test Procedure

The rapeseed used for all drying trials was the Midas variety (Polish type) graded No. 1 Canadian certified seed. The initial moisture content of the rapeseed was 6.8 percent wb but was conditioned to moisture contents ranging from 13.5 to 15.0 percent wb by the addition of water. Each lot was stored in sealed containers at about 18°C (65°F) and mixed every day for at least 5 days before drying to insure that the rapeseed had reached an equilibrium.

Moisture content of all samples, before and after drying were taken with the model 919 Halross moisture meter. Previous to the drying trials, the calibration of the moisture meter was checked at the Canada Grains Commission as was found to be within the limits of accuracy specified by the manufacturer. Moisture content measurements were accurate to within 0.1 percent moisture content.

The metering head device mounted at the front of the drying section had individual controls for adjusting the flow rates of sand and rapeseed. The control settings were calibrated by weighing separately the amount of sand and rapeseed delivered by the metering device over a period of one minute. The relationship between the flow rates and control settings was found to a straight line as shown by Figure 5.5.

To obtain the various desired ratios of sand to rapeseed for the drying trials, a sand flow rate was selected with the corresponding control setting being determined from the graph. Upon calculating the rapeseed flow rate required for the desired ratio, the correct control setting for the rapeseed could then be found from the graph. A number of the ratio settings were checked by removing a portion of the sand-rapeseed mixture from the discharge port of the metering head device during

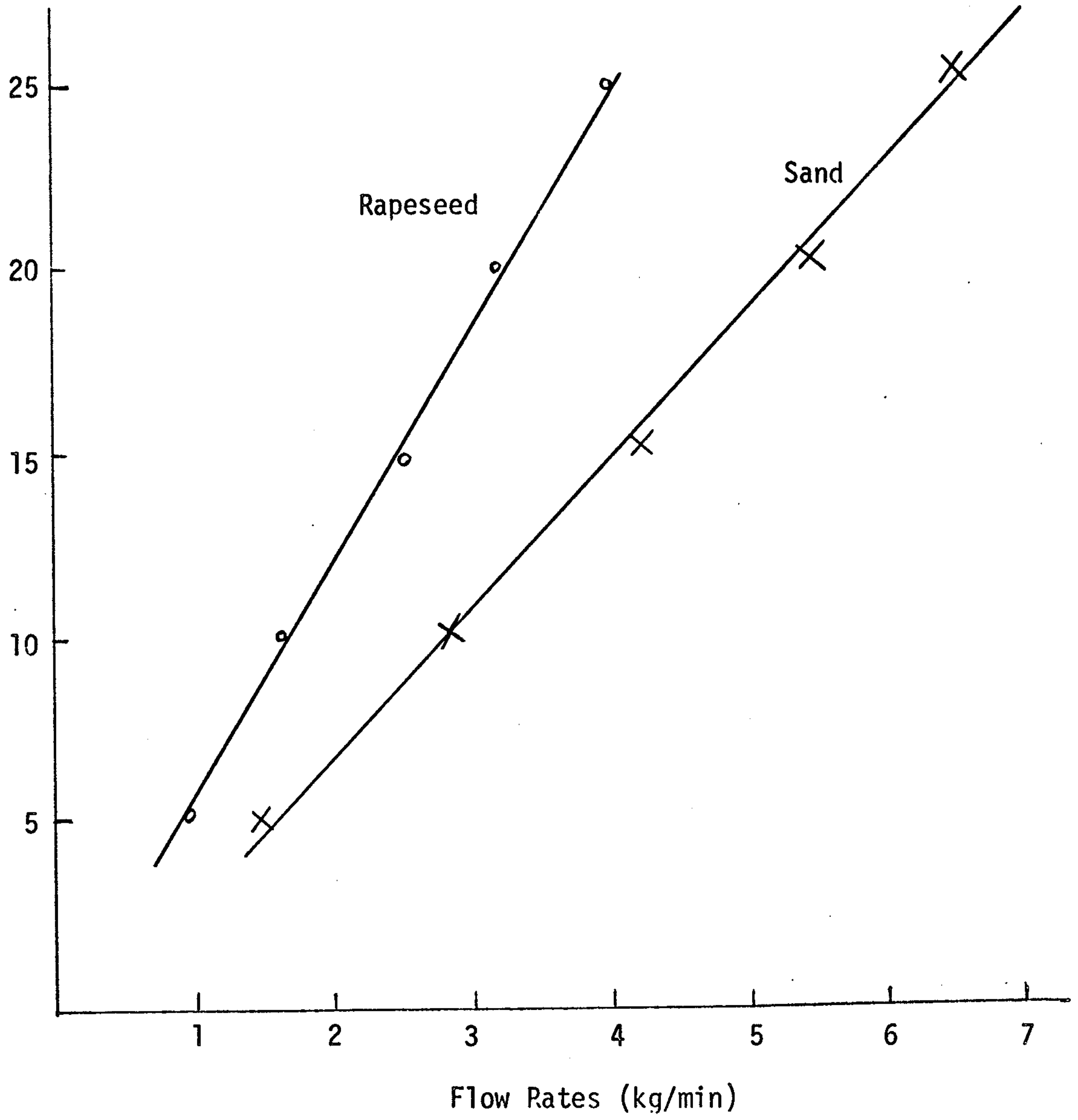

Fig. 5.5 Flow rates of sand and rapeseed vs. control settings of the metering head device.

a trial run, hand sieving, and then weighing each fraction.

The adjustable legs of the dryer were set such that there was a drop of 8.9 cm (3½ in) over the 3.7 m (12 ft) length of frame, giving the cylinder a slope of approximately 1½ degrees. With the anglular velocity of the rotating cylinder set at 13 rpm, the residence time of the sand-rapeseed mixture in the drying section of the prototype was found to be 30 seconds. This 30 second residence time remained constant for all drying tests while the mixture ratios and initial sand temperatures were varied.

Sand temperature was measured at three different location of the prototype. The initial sand temperature T_1, was taken by a copper-constantan thermocouple probe mounted at the sand discharge port of the metering head device. This represented the temperature of the sand which would initially come in contact with the rapeseed and begin the drying process. A copper-constantan thermocouple mounted in the sand collecting hopper beneath the separating section measured the temperature of sand upon completion of the drying process (T_2). A copper constantan thermocouple was also installed at the top of the sand heating hopper to measure the final sand temperature before reheating (T_3). All three thermocouples were connected through a switching box to a model 590TC Digitec digital thermocouple thermometer which displayed the temperature directly in degrees Celsius with a repeatability and resolution of 0.1°C (Fig. 5.6). This instrument has a built in ice point and calibration adjustment. The temperature of the rapeseed as it left the cooling section of the dryer was measured with a mercury-in-glass therometer.

Fig. 5.6 Switching box connected to digital thermocouple thermometer and Halross moisture meter.

The procedure for each drying trial consists of the following:

1. turn on all heaters and allow approximately 10 minutes for sand to heat up,
2. set sand flow rate and allow heated sand to flow through system for another 10 minutes thereby permitting a warm-up period for the system,
3. after determining the initial moisture content of the rapeseed, set the rapeseed flow rate for desired ratio,
4. record sand temperature T_1, T_2, and T_3, and
5. collect about a 250 g sample of dried rapeseed from discharge point of dryer.

The samples of dried rapeseed were collected in plastic bags, sealed and allowed to cool for 24 hours in a atmospheric temperature of about 18°C (65°F) before the final moisture contents were determined. Tests were then conducted to assess any changes in the quality of the rapeseed samples.

5.4 Quality Tests on Rapeseed

Tests on the quality of the rapeseed samples were conducted by the Plant Science Department of the University of Manitoba. The specific factors which were evaluated were germination quality, oil content, fatty acid composition, and protein content.

CHAPTER VI

RESULTS AND DISCUSSION

Drying with a solid heat transfer medium using various initial sand temperatures and mixing ratios, reduced the moisture content of rapeseed by 3.0 percent to 5.8 percent during a 30-second drying period as shown by the results in Table 6.1. An increase in the severity of drying by the use of higher initial sand temperatures and/or greater sand-to-to-rapeseed ratios increased the percentage of moisture removed from the rapeseed. Raising the initial sand temperature increased the severity of drying to a greater extent than an increase in the sand-to-rapeseed mixture ratios. The quantity of moisture removed was approximately constant for a given initial sand temperature throughtout the range of mixture ratios investigated as shown in Fig. 6.1. For example, at an initial sand temperature of 170°C and mixture ratios of 2:1, 2.6:1, 3:1, and 4:1, the moisture content of rapeseed was decreased by about 4.2 percent. Variations in the amount of moisture removed at a given temperature, are probably the result of different initial moisture contents of the samples since moisture removal becomes increasingly more difficult at lower moisture contents. The amount of moisture removed was found to be greater with an increase in the initial sand temperature.

The effect of the rapid moisture removal on the quality of the final product was evaulated by measuring possible changes in germinability, protein content, oil content, and fatty acid composition of the dried rapeseed samples. The germinability of the undried sample was found to be very high with 99 percent of the kernels showing penetration of the pericarp-testa by the coleorhiza after only 40 hours. The heated treated samples, however, showed no indication of germination after a week,

Table 6.1

Drying Results Using A Solid Heat Transfer Medium

SAND:RAPE RATIO	T_1(°C)	T_2(°C)	T_3(°C)	MC_i	MC_f	ΔMC	DRYING EFF.	OIL CONTENT	PROTEIN CONTENT
2:1	135	70	61	13.5	10.2	3.3	85.2		
	150	66	57	13.5	10.3	3.2	64.0	51.2	17.8
	150	60	54	15.0	11.7	3.3	62.8		
	170	76	65	15.0	10.8	4.2	75.9	51.4	17.6
2.6:1	130	68	63	13.5	10.5	3.0	62.8		
	150	80	73	13.5	10.1	3.4	63.5		
	170	102	88	13.5	9.3	4.2	79.9		
	180	87	78	13.5	9.6	3.9	54.3	51.1	17.8
3:1	130	70	65	15.0	11.3	3.7	68.0		
	170	85	82	15.0	10.7	4.3	55.6		
	190	100	95	15.0	9.2	5.8	70.0	46.7	23.0
4:1	125	68	55	13.7	10.7	3.0	45.2	47.7	22.5
	140	75	62	13.7	10.3	3.4	44.7		
	150	78	65	13.7	10.0	3.7	44.2		
	165	86	73	13.7	9.6	4.1	44.4		
	170	92	78	13.7	9.5	4.2	45.7		
	170	84	73	15.0	10.3	4.7	43.4	47.5	23.0
5:1	120	74	63	13.7	10.6	3.1	46.5	47.5	22.8
	135	72	65	13.7	10.5	3.2	34.8		
	155	91	77	13.7	9.6	4.1	43.7	47.5	22.7
	170	83	62	14.5	8.8	5.7	43.7		
	190	91	86	14.5	9.2	5.3	35.6	46.8	23.2
						Control Sample:		46.5*	23.0*

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* indicates results from an average of three trials.

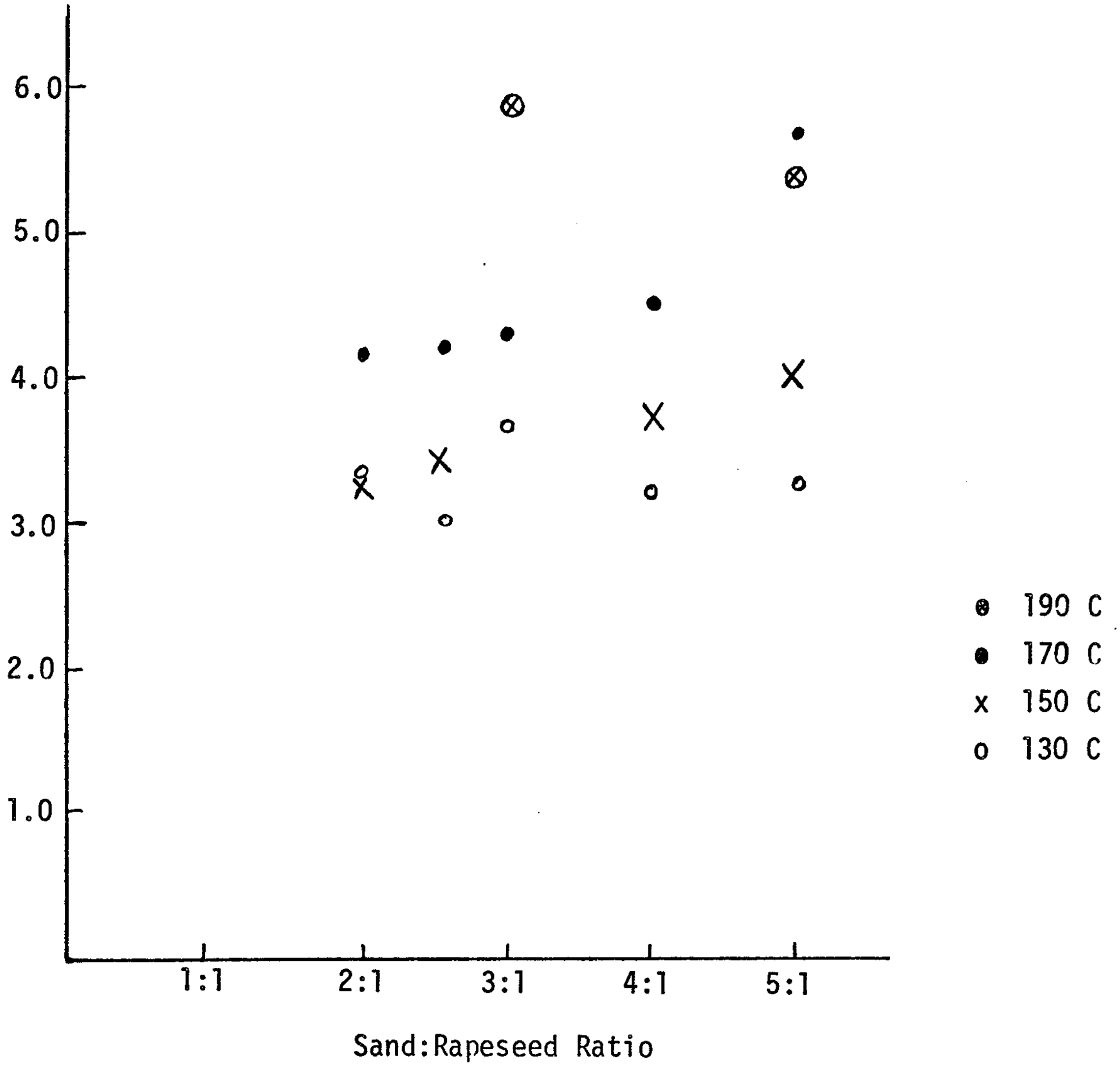

Fig. 6.1 The effect of mixture ratios on the moisture reduction at various initial sand temperatures.

indicating that the viability of the seed had been destroyed. Scientific literature states that temperatures above 43°C (110°F) should not be used for drying seed grain and destruction of the germinability was expected to occue due to the high temperatures employed in the drying trials.

The protein content of the undried sample of rapeseed was found to be 23.0 percent, db. Drying rapeseed at the higher sand-to-rapeseed ratios of 3:1, 4:1, and 5:1 and at initial sand temperatures ranging from 120°C to 190°C showed no change in the protein content. Rapeseed which was dried at the lower ratios of 2:1 and 2.6:1 and at initial sand temperatures of 150°C to 180°C had a protein content of approximately 17.8%, a decrease of almost 25 percent. This decrease in protein content is possibly due to the destruction of the heat sensitive amino acids such as lysine, arginine, tryptophan, methionine, and cystine. The specific amino acids which may have been destroyed were not determined but the decrease in the protein content indicates that some definite destruction has occurred. It also seems that this protein loss is not dependent upon the temperature of the solid medium but upon the sand-to-rapeseed ratio. One possible explanation for this may be that at the higher sand-to-rapeseed ratio the sand particles surround the rapeseed kernels for a larger percentage of the residence time. This would retard moisture diffusion from the surface of the rapeseed kernels, resulting in a slower drying rate and less damage to the protein content. Using lower sand-to rapeseed ratios, moisture diffusion from the rapeseed kernel may be faster since there is less sand surrounding the kernel to restrict the moisture movement. The result would be rapid drying rate, causing changes in, or destruction of some amino acids. The high temperatures employed in the drying process may also drive off other volatile substances or destroy other constituents of the rapeseed and perhaps reduce the dry matter weight of the kernels.

The dried rapeseed samples showing a decrease in protein content had a corresponding increase in the percentage oil content. Assuming that the amount of oil contained within the kernel remained constant, the apparent increase in the oil content percentage can be partially attributed to the possible reduction in the dry matter weight due to the loss of protein, volatile substances, and other constituents of rapeseed. However, almost an 8 percent reduction of the dry matter weight would be required to account completely for the oil content increase. Since this does not seem possible, the reason for the increase in oil content percentage cannot be fully explained. The fact that the oil content percentage did increase would probably indicate that no oil was lost due to the drying treatment at the lower ratios.

The fatty acid composition of the rapeseed was not affected by the various drying trials. Analysis of both undried and dried samples of rapeseed showed that fatty acids having 16 and 18 carbon atoms such as palmitic, oleic, linoleic, and linolenic accounted for 97.5 percent of the fatty acids. Those having 20 carbon atoms such as eicocenoic constituted about 2 percent while the remaining .5 percent was erucic acid having 22 carbon atoms. Although some small changes in the fatty acid composition could have occurred due to the rapid, high temperature drying process, no significant change was detected.

Drying efficiencies were calculated for each trial using the relationship expressed in Chapter 4.2.

$$\text{drying efficiency} = \frac{\text{HEAT UTILIZED TO REMOVE WATER}}{\text{HEAT AVAILABLE FOR DRYING}}$$

$$= \frac{W\ h_{fg}}{Ms\ Cp\ \Delta T}$$

where

w = weight of water removed, Kg

h_{fg} = latent heat of vaporization, 640 cal/gm

Ms = quantity of sand, Kg

Cp = specific heat of sand, 0.21 cal/g-°C

ΔT = temperature change of sand in drying section, °C

The calcuated drying efficiencies of the various trials ranged from 34.8 percent to 85.2 percent, as shown in Table 6.1. The initial sand temperature had little effect on the drying efficiency for a given sand-to-rapeseed ratio. Using a mixture ratio of 4:1, the drying efficiency varied only from 43.4 percent to 45.7 percent when initial sand temperature ranged from 125°C to 170°C. Throughout the temperature range investigated, the drying efficiency remained almost constant for a given mixture ratio. At the lower sand-to-rapeseed ratios, drying efficiency was greater but decreased as the mixture ratios increases. The average drying efficiency for trials using a 2:1 mixture ratio was 71.5 percent but decreased to 40.9 percent for the trials using a 5:1 mixture ratio. Drying at the higher ratios may be less efficient because of the slower drying rate which is thought to occur when moisture diffusion from the rapeseed kernels is restricted by the surrouding sand. The higher drying rates associated with the use of low mixture ratios would permit utilization of the heat for evaporation of mositure from the rapeseed, rather than allowing the heat to be carried out the cylinder or the air flow from the fan or being lost to the ambient atmosphere by radiation from the drying section. Although no figures were found on the drying efficiencies of heated air systems for drying rapeseed, efficiencies of 51.2 to 57.5 percent were reported for drying field shelled corn from 25.1 percent to 14.6 percent (22).

Fuel efficiency was calculated using the relationship expressed in Chapter 4.2.

$$\text{fuel efficiency} = \frac{\text{HEAT UTILIZED TO REMOVE WATER}}{\text{HEAT CONTENT OF FUEL SUPPLIED}}$$

where

$$= \frac{W\ h_{fg}}{C\ I\ V}$$

where

W = weight of water removed, Kg

h_{fg} = latent heat of vaporization, 640 cal/gm

C = constant = 859,184 cal/Kw-hr

I = current flow, amperes

V = voltage, volts

The current drawn by the prototype under operating conditions was measured with an ammeter and found to be 90 amperes. With the voltage being 230 volts, the power being consumed by the prototype dryer with all the electric heating elements and motors operating would be 20.7 Kilowatts.

After the warmup period, the power supplied to the dryer had to be controlled to maintain an equilibrium between the heat being used in the removal of moisture and the heat supplied by the electric heaters to the sand. This requires that the power be regulated to keep a constant initial sand temperature for a given sand-to-rapeseed ratio with a constant amount of moisture being removed from the rapeseed. Measurement of the power being consumed could then be used to calculate the true fuel efficiency of the system.

The equilibrium conditions required for the determination of the true fuel efficiency could not be carried out in the drying trials for two reasons:

1. A shortage of a large supply of rapeseed at a constant, high moisture content which would be required for the dryer operation until an equilibrium would be reached.
2. Lack of an accurate method for continuous control of power as only three specific settings were possible on the prototype.

Assuming that the maximum power of 20.7 kilowatts was required for moisture removal during the drying trials, the highest fuel efficiency achieved would be 29 percent. This is significantly lower than the fuel efficiencies reported for heated air systems, however, due to the limitations of the prototype, the correctness of the fuel efficiency of the solid heat transfer medium is questionable and no definte value of fuel efficiency can be reported.

Considering the range of temperatures and sand-to-rapeseed mixture ratios tested during the drying trials, the optimum values for drying rapeseed appears to be an initial sand temperature in the range of 130°C to 190°C at a mixture ratio of 3:1.. At these conditions, there is no evidence of protein damage, a large percentage of moisture removal is possible, and the average drying efficiency of 64.5 percent using a 3:1 ratio is quite acceptable.

The theoretical airflow 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. Conditions of the air entering the dryer were assumed to be 18°C (65°F) and 70 percent relative humidity, while the conditions of the air leaving the dryer were assumed to be 30°C (86°F) and 100 percent relative humidity. The theoretical amount of moisture which can be picked up by this was determined from the psychrometric chart and was found to be 18.4 grams/ cubic meter (8.4 grains/cubic foot) of air. Since the maximum amount of moisture removed from the rapeseed during the drying trials was 0.136 Kg/min, a theoretical airflow of 7.08 m^3/min (250 cfm) would be required if the air leaving the dryer was saturated. It is recognized that the air leaving the dryer would be not saturated and that a larger fan capacity would be necessary. The 17.00 m^3/min (600 cfm) fan installed on the prototype should therefore have sufficient capacity and should not be a limiting factor in the drying process. The amount of cooling achieved in the cooling section could not be determined because of the difficulty in measuring the rapeseed temperature as it left the drying section. The temperature of the rapeseed as it left the prototype dryer was measured with a mercury-in-glass thermometer and found to vary from 40° to 50°C (104 to 122°F).

The prototype flow system for metering, mixing, separating, and sand reciruclation functions well. For the limited amount of drying done with t- the prototype, wear on the cylinder due to the abrasiveness of the sand was negligible. Visual observation of the dried rapeseed at the discharge point of the dryer showed no sand contamination but some dust and very small and cracked rapeseed kernels were observed in the sand. The cracked rapeseed kernels had a tendency to become embedded in the screening section and slightly reduce the available screening area. Grain with a high percentage of dockage would probably have to be cleaned prior to drying to reduce sand contamination and screen blockage.

CHAPTER VII

CONCLUSIONS

1. For the range of conditions in these tests, the amount of moisture removed increases with an increase in the initial temperature of solid heat transfer medium, but remains approximately constant throughout the various mixture ratios for a given initial sand temperature.

2. The viability of the rapeseed was completely destroyed by the various heat treatments used in the drying trials.

3. Drying at sand-to-rapeseed ratios of 2:1 and 2.6:1 causes a significant reduction in the protein content. The use of mixture ratios of 3:1, 4:1 and 5:1 does not reduce the protein content despite initial sand temperatures of up to 190°C.

4. Dried rapeseed showing a decrease in protein content had a corresponding increase in oil content percentage.

5. Fatty acid compositions were not affected by the various drying treatments.

6. The drying efficiency of the solid heat transfer medium increased as the sand-to-rapeseed ratio decreased from 5:1 to 2:1. For a given mixture ratio, the initial sand temperature had little effect on the drying efficiency.

7. The optimum condition for drying rapeseed using sand as the heat transfer medium is a sand-to-rapeseed ratio of 3:1 and a initial sand temperature range of 130°C to 190°C, based on the mixture ratios and temperatures used in the investigation.

CHAPTER VIII

RECOMMENDATIONS

The drying of rapeseed using a solid heat transfer medium could be extended to include other oilseed crops such as flax and sunflowers. The principle may also have application to the drying of cereal crops, although lower temperatures with a longer residence time may have to be employed to prevent damage to the milling and baking qualities of the grain. The drying of such grains as fababeans, soybeans and wild rice may be possible with this process. Increasing the temperature of the solid medium could accomplish the processes of roasting, puffing or popping of grains.

The use of other solid granular media, such as steel shot and salt, and the effect of various textures of the medium should be investigated. The properties of the solid heat transfer medium may have an effect on the efficiencies of the process as well as the quality of the dried grain. Depending upon texture and type of solid medium chosen, design modifications may be required on the prototype.

The design of the current prototype should be altered to accommodate a different method for the recycling of the solid medium. The present system, utilizing an elevator leg, requires a vertical height of over 3.05 m (10 ft). The long distance over which the sand is recycled increases the heat loss of the process, thereby reducing the fuel efficiency.

Electrical heating elements were used in the prototype for experimental purposes although commercial models would employ some type of heat exchanger.

Future drying trials should also have recorded measurements of the air conditions leaving the dryer as well as amino acid analysis of the dried grain.

REFERENCES

(1) ALTSCHUL, A.M. 1958. Processed plant protein foodstuffs. Acadmic Press Inc. Publishers, New York.

(2) ANDERSON, J.A. and ALCOCK, A.W. 1954. Storage of cereal grains and their products. Published by The American Association of Cereal Chemists.

(3) APPELQVIST, L.A. and OHLSON, R. 1972. Rapeseed cultivation, composition, processing and utilization. Elsevier Publishing Co.

(4) BROOKER, D.B., BAKKER-ARKEMA, F.W. and HALL, C.W. 1974. Drying cereal grains. The AVI Publishing Co. Inc.

(5) BURRELL, N.J. 1970. Conditions for safe grain storage. Home-Grown Cereals Authority, Haymarket House, Oxendon St., London, SW1 ENG.

(6) CANADA AGRICULTURE. 1971. Publication #1448, What you should know about oilseed crops.

(7) CHANCELLOR, W.J. 1968. A simple grain dryer using conducted heat. ASAE Transactions General Edition 11(6):857.

(8) CHIN SHU CHEN and JOHNSON, W.H. 1969. Kinetics of moisture movement in hydroscopic materials (I. Theoretical considerations of drying phenomena). ASAE Transactions.

(9) CHRISTENSON, C.M. 1974. Storage of cereal grains and their products. Published by American Association of Cereal Chemists, St. Paul, Minnesota.

(10) FRIESEN, O.H. 1973. Grain Drying. Publication #1497, Canada Department of Agriculture.

(11) GORDON, A.G. 1971. The germination resistance test - a new test for cereals. Can. J. Plant Science 51:181-183.

(12) HALL, C.W. 1957. Drying farm crops. Published by Agr. Consulting Ass. Inc.

(13) HAMBY, M.Y. and BARRE, H.J. 1969. Evaluating film coefficients in single kernel drying. ASAE Transactions.

(14) JOHNSON, H.K. and DALE, A.C. 1954. Heat required to vaporize moisture. Agricultural Engineering.

(15) KAHN, A.V. 1969. Semiannual substantive report #9. International Rice Research Institute, Los Banos, Laguna, Philipines.

(16) KREITH, F. 1969. Principles of heat transfer. International Textbook Co., Scranton, Pennsylvania.

(17) MCKNIGHT, K.E. and MOYSEY, E.B. 1971. The effect of temperature and airflow rate on the quality of dried rapeseed. ASAE 1971 Annual Meeting.

(18) KAGHAVAN, G.D.V. and HARPER, J.M. 1973. Drying agricultural materials in an agitated granular bed. Paper #73-320, presented to the 1973 Annual Meeting of ASAE.

(19) RAGHAVAN, G.D.V., HARPER, J.M. and HABERSTROTH, R.D. 1972. A study of heat transfer using granular media. Paper #72-892, presented to the 1972 Winter Meeting of ASAE.

(20) RAPESEED ASSOCIATION OF CANADA. 1970. Publication #8, Rapeseed, Canada's "Cinderella" crop. Winnipeg, Manitoba.

(21) SCHULER, R.T. and ZIMMERMAN, D.C. 1972. The effect of drying on sunflower seed oil quantity and quality. ASAE 1972 Winter Meeting.

(22) SINHA, R.N. and MUIR, W.E. 1973. Grain storage: part of a system. The AVI Publishing Co. Inc.

(23) TKACHUK, R. and IRVINE, G.N. 1969. Amino acid composition of cereals and oilseed meals. Cereal Chemistry, March 1969, Vol. 46, No. 2, pp. 206-218.