DRYING OF SOYBEANS IN CONTINUOUS-FLOW DRYERS AND FIXED-BED DRYING SYSTEMS

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A DISSERTATION

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Agricultural Engineering

1981

ABSTRACT

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The drying of soybeans from different initial moisture contents in different drying systems has been studied.

About 50 percent of the United States soybean production is crushed by American soybean processing plants. The beans are dried from about 12.5 to 10.5 percent wet basis before processing. Two commercial size crossflow dryers were tested for capacity and energy efficiency. The specific energy consumption ranged from 7,100 to 8,192 BTU per pound of water removed (16,515-19,055 kJ/kg). Simulation of the drying process was employed to analyse soybean crossflow drying and to modify the dryer. A decrease in the dryer and cooler airflow rates and a change of two dryer sections into tempering zones resulted in a predicted savings of 67.9 percent in energy.

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Single- and multi-stage concurrentflow drying were experimentally tested in a laboratory dryer and further analyzed by computer simulation. In the 12.5 to 10.5 percent moisture content range, presently available concurrentflow dryers require about 50 percent of the energy presently needed by commercial crossflow dryers for drying soybeans; also, concurrentflow dryers will result in a more uniform and better dried product.

The effect of tempering was analyzed for both crossflow and concurrentflow drying. By converting drying stages 5 and 3 in the 6-stage crossflow dryer into tempering zones, the specific energy consumption was reduced by 39.8 percent without affecting the dryer capacity. Concurrentflow soybean dryers should have tempering zones after each drying stage. Compared to a concurrentflow corn dryer, the tempering zones in a similar soybean dryer should be reduced in height from 15.0 to 10.0 feet (4.6 to 3.1 m).

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The MSU Fixed-Bed Drying Model was solved using a new method of solution. The new version requires less computer time in low-temperature drying simulation. Low-temperature soybean drying for Brazil was found to be feasible if the ambient air is heated by 5.0 degrees Farenheit (2.8 degrees Celsius) and the airflow rate is increased to 1.5 cubic feet per minute per bushel (1.6 m3/min-ton).

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ACKNOWLEDGMENTS

The author wishes to express his deepest gratitude to Dr. Fred W. Bakker-Arkema, a teacher, advisor, and friend, for his moral and technical support since 1977.

The author is thankful to Dr. James V. Beck, Dr. Roger C. Brook, and Dr. Gary Van Ee for serving on the guidance committee.

Thankful acknowledgments is extended to Dr. L. Copeland for his help with the soybean germination tests, to Mr. Robert Schaffin who kindly provided the soybeans for the laboratory tests, and to the Gold Kist, Inc. personnel who made possible the commercial drying tests.

The author thanks the Ferrel-Ross - Blount Agribussines for providing funds for this research. The author is also indebted to the Brazilian Government and the Federal University of Vicosa for allowing the author to come to the United States and for the financial support during most of this work.

A very special thanks goes to the faculty, staff, and graduate students of the Michigan State University Department of Agricultural Engineering. Without them the author would never be a proud Spartan.

To

Maria Dolores

Marcelo

Polyana

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LIST OF SYMBOLS

a	area to volume ration, ft2/ft3
bu	bushels
C	degrees Celsius
Ca	specific heat of air, BTU/lb-F
cfm	cubic feet per minute
Cp	specific heat of soybeans, BTU/lb-F
cuft	cubic foot
Cv	specific heat of vapor, BTU/lb-F
Cw	specific heat of water, BTU/lb-F
D	diffusion coefficient, ft2/hr
Delr	increment in soybean radius, ft
Delt	drying time increment, hr
F	degrees Farenheit
ft	foot
ft2	square foot
ft3	cubic foot
Ga	airflow rate, lb/hr-ft2
Gp	soybean flow rate, bu/hr-ft2
h	heat transfer coefficient, BTU/hr-ft2-F
H	air humidity ratio, lb/lb
Hfg	heat of vaporization, BTU/lb
Hin	ambient air humidity ratio, lb/lb
HP	horsepower

hr	hour
i	soybean position coordinate
j	drying time (diffusion)
Ka	air thermal conductivity, BTU/hr-ft-F
kg	kilogram
kJ	kilo Joule
lb	pound
m	meter
M	moisture content, decimal dry basis
Me	equilibrium moisture content, dec. db
Mo	initial moisture content, dec. db
Mr	Moisture ratio ((M-Me)/(Mo-Me))
m2	meter square
m3	cubic meter
Nu	Nusselt number, dimensionless
PI	3.141592654
Pr	Prandlt number, dimensionless
Pv	vapor pressure, kgf/kg
Pvs	saturation vapor pressure,kgf/kg
Qa	airflow rate, cfm/bu
r	soybean radial coordinate, ft
Re	Reynolds number, dimensionless
RH	air relative humidity, decimal
RHe	equilibrium relative humidity,dec.
RHOP	soybean density, lb/bu

Ro	equivalent soybean radius, ft
sqft	square foot
SP	static pressure, inches of water
t	drying time, hours
T	air temperature, deg. F
Tamb	ambient air temperature, deg. F
TH	soybean temperature, deg. F
THabs	absolute soybean temp., deg. F
Tinlet	inlet drying air temp., deg. F
ton	metric ton (36.75 bu)
Ua	kinematic viscosity, ft2/hr
wb	wet basis
x	bed width coordinate(crossflow), ft
y	bed height coordinate, ft

CHAPTER 1

I N T R O D U C T I O N

Soybean (Glicine max ,L.,Merril) is widely used throughout the world as animal feed as well as human food. Its high nutritious value, especially in protein, makes it a very important element in animal rations. Its importance as a supplement in human diet in which soybean can be consumed in different forms such as soymilk, tofu, and soyflour, is growing rapidly.

1.1 Production and Importance of Soybeans

Soybeans are grown throughout the world. However, the largest production is in the United States which accounts for 64 percent of the world total. Brazil and China produce 26 percent. The world soybean production is summarized in Table 1.

More than 600,000 farmers grow soybeans in the United States. A record amount of more than 2.2 billion bushels (about 62 million metric tons) was harvested in 1979. Of this, 770 million bushels (21 million tons) were exported as beans, 1.1 million tons as oil, and 6.1 million tons as oilseed cake and meal, in total generating over $7.8 billion. These numbers make soybeans the second crop by volume in the United States and the first agricultural commodity in cash revenue.

TABLE 1: World soybean production in 1,000 bushels (1,000 metric tons).

CONTINENT/COUNTRY	PRODUCTION(1979/1980)
North America	2,314,772 (62,987)
South America	721,660 (19,637)
Europe	19,845 (540)
Soviet Union	22,050 (600)
Africa	5,770 (157)
Asia	461,654 (12,562)
Oceania	3,675 (100)
World Total	3,549,389 (96,582)

Source: Soya Bluebook 1980, American Soybean Association.

1.2 Drying of Soybeans

American farmers can usually leave soybeans in the field until a moisture content of approximately 11 percent is reached, thus avoiding artificial drying of the beans. Conventional in-field drying is usually satisfactory to maintain the soybean quality in storage. However, it is a weather dependent technique and often leads to excessive losses because of the brittleness of the pods and bean stalk. Under unfavorable conditions of humid weather, the beans suffer deterioration prior to the harvest.

The alternative to natural drying in the field is forced air artificial drying which is a safer method for decreasing the excessive moisture in the crop. The forced air drying rate is a function of the air temperature and relative humidity, soybean moisture content, soybean equilibrium moisture content, and mass flow rate. Variety and history under wnhich the beans are grown sometimes affect the drying rate.

Basically, the drying process can be divided in two categories: low- and high-temperature drying.

Low-temperature drying is a common practice among American farmers when the bean moisture content is too high for safe storage. In this process, little or no heat is added to the ambient air. In the case where the drying temperature is raised a few degrees, electricity and liquid propane are the most used forms of energy. With the advent of the energy crisis, solar energy and biomass were intensively investigated as alternative energy sources. Natural air drying (no heat added) may take so long (especially when the soybean initial moisture content is high and the weather is unfavorable) that some deterioration may take place before the desired moisture is reached.

High-temperature drying is a faster process and is less dependent upon the weather conditions than low-temperature dehydration. It is mainly practiced in the processing industry. In 1979, the 94 processing mills in the United States crushed more than one billion bushels (about 30 million metric tons) of soybeans (almost 50 percent of the total American production). Before the crushing process the moisture content of the beans must be reduced from the normal storage level to about 10 percent. To accomplish this, high-capacity high-temperature dryers are used.

Among the high-temperature commercial grain dryer configurations the crossflow design is the most common. It is a relatively simple design and produces an end product of acceptable quality. The main disadvantage of the conventional crossflow dryer is the high amount of energy required to remove moisture. Recently, concurrentflow dryers has been introduced. They are of more complicated design than the crossflow dryer but the dried product is of better quality. Concurrentflow dryers require less energy per unit of water removed as compared to other continuous flow dryers mainly because higher drying air temperatures can be used.

In the United States grain dryers are designed, rated and advertised as corn dryers. No specific soybean dryer has yet been marketed. The result is that the American soybean processing industry is not using the most suitable equipment for its drying needs but is fulfilling its drying demand with corn dryers which have different characteristics than those needed for soybeans. As a consequence, drying of soybeans at high temperatures is accomplished at the expense of high energy requirements. It shall be shown in this thesis that if specially designed soybean dryers become available to the processing industry it is possible to reduce the amount of energy consumed at the soybean processing plants to about half of the present requirement.

In Brazil, soybeans are usually harvested at moisture contents higher than in the United States (16 to 20 percent). Weather conditions are also less favorable at harvesting time and during subsequent storage.

Soybeans must be artificially dried. Drying is done almost completely at high temperatures at elevators, cooperatives, and processing plants. On-farm drying and storage is practiced very little. The Brazilian government prohibited the use of petroleum derivates for artificial drying of agricultural products (Jornal de Armazenagem, 1980), adding a serious constraint to the development of efficient drying systems.

CHAPTER 2

O B J E C T I V E S

In this study, emphasis shall be placed upon drying techniques which have been employed in the soybean processing industry and upon those that shall be recommended as highly desired. A technique will be selected as desired if it fulfills two conditions: the end product is of good quality and the consumption of energy is low.

The broad goal of this thesis is to develop efficient soybean drying systems. The specific objectives are:

1. <u>Determination of the major drying parameters for soybeans.</u>

In the United States, on-farm as well as commercial sized dryers are commonly designed as corn dryers. Thus, the drying parameters (e.g., airflow rate, burner size, column length and thickness, drying temperature, etc.) will be selected to optimize the drying of soybeans and not necessarily of a commodity such as corn or wheat (Bakker-Arkema *et al.* ,1980).

2. Improvement of computer models for simulating soybean drying.

A crossflow computer program will be updated by employing a four-equation drying model (Brooker et al.,1974). Previously, three equations were used based upon the assumption that the air and product temperatures are the same during the dehydration process.

3. Substitution of a thin-layer equation by a diffusion equation in the drying models.

Grain drying models usually employ thin-layer equations to predict the moisture behavior in the drying process. In this study, a diffusion equation will be used, instead. The use of diffusion type equations in the simulation drying models allows simulation of tempering or steeping zones in a dryer. These zones are of primary importance because they lead to significant energy savings and product quality improvement during the drying process.

4. Dimensioning of continuous flow dryers and fixed-bed drying systems.

The successful and intelligent use of the three previous conditions will give realistic simulation drying models which will help grain dryer manufacturers to design optimum soybean dryers for on-farm as well as for processing plant use. Designs for efficient continuous flow dryers and fixed-bed drying systems will be proposed.

5. <u>Speculating on the best methods of drying soybeans in Brazil.</u>

Although Brazil has different weather, sociological and economical conditions than the United States, the drying techniques here developed will be considered for successful adoption to Brazil through making the proper adaptation.

CHAPTER 3

L I T E R A T U R E   R E V I E W

3.1 Drying Developments in Soybeans

Drying is the process of removing excess moisture from a product to prevent deterioration during subsequent storage. In the United States, drying of soybeans has in the past only been necessary when inclement weather had occured during the harvest period. The beans were left to dry in the field until the moisture content had reached approximately 11 percent. Mature beans left exposed to damp weather develop a dark brown color and a chalky texture. The oil from weather damaged soybeans is often not of edible grade.

Artificial drying of soybeans offers advantages which merit consideration even when weather conditions make its use not required. The chance of losses through bad weather is reduced and it permits early harvest, minimizing mechanical damage by the combine reel and cutterbar (Rodda, 1974).

Soybean drying has not been studied as intensively as corn drying. Nevertheless, soybeans have successfully been dried and stored on farms after some adjustments had been made in airflow rate and heat input.

Depending on the utilization purpose, different drying techniques may be applied to soybeans. For seeds, natural air drying at airflow rates of 2-3 cubic feet per minute per bushel (2.1-3.1 m3/min-ton) is adequate for drying soybeans with initial moisture contents up to 16 percent (Rodda, 1974). Under unfavorable weather harvesting conditions supplemental heat must be added to the drying air. Soybean seed technologists suggest airflow rates of 10 cubic feet per minute per bushel (10.4 m3/min-ton) with a relative humidity of 40 percent or higher after heating. The air temperature should not exced 110 F (43.3 C) (Rodda,1974). Low-temperature in-bin drying with the air temperature raised by 5 to 10 degrees Farenheit (2.8-5.6 C) is a rather widely used method. The bin is filled to a depth of about 16 feet (4.9 meters) and an airflow of approximately 2 cubic feet per minute per bushel (2.1 m3/min-ton) is employed.

In-bin batch drying is also practiced. In this method, the temperature rise is limited to 15 degrees F (about 8 degrees C) at a maximum soybean depth on the order of 10 cubic feet per minute per bushel (10.4 cubic meter per minute per metric ton). The result is a relatively uniform moisture of the beans although the drying process is slow. Matthes and Welch (1974) dried high moisture soybean seed (at 22 percent wet basis) using in-bin drying. They recommended airflow rates no lower than 9-12 cubic feet per minute per bushel (9.4-12.5 m3/min-ton) at 110 F (43.3 C). Faster batch drying can be attained when the air is heated 50 to 70 F (28 to 40 C), the airflow rate adjusted to 40-50 cubic feet per minute per bushel (41.6-52.0 m3/min-ton) and the bed depth limited to 2 feet (0.6 meters) (Barre,1974).

Roberts and Brooker (1975) used a sweep auger at the bottom of the bin in conjunction with a vertical auger (i.e., in-bin counterflow drying) to recirculate the grain and to obtain a more uniform moisture content throughout the batch. Sabbah et al. (1976) tested a reversed-direction-air-flow technique which resulted in a more uniform final bed moisture content, lower germination losses, and less seed coat cracking as compared to conventional batch-in-bin drying.

If soybeans are dried for commercial use the air can be heated up to 140 F (60 C) in batch drying (McKenzie, 1972). At 190 F (87.8 C) reduction in oil yield has been observed (Rodda,1974;Barre,1974). Kalchik (1977) dried soybeans at temperatures up to 450 F

(232.2 C) using a laboratory-scale concurrent flow drier without observing a reduction in oil yield or oil quality.

Drying of soybeans in processing plants is accomplished by means of large continuous flow dryers. Soybeans are dehydrated to moisture levels below those required for storage. Because the beans are subsequently crushed, cracking of the bean coats and cotyledons is of no importance and in fact is desired. Drying air temperatures of about 200 F (93.3 C) are commonly used with crossflow dryers (Madison, 1980). Crossflow dryers are by far the most popular dryers used in processing plants. In fact, no reference could be found in the literature of other dryer design being used in the soybean processing industry.

Kalchik (1977) tested a laboratory-size concurrent flow dryer and found that it is possible to reduce soybean moisture content from 13 percent to 9 percent requiring only 1500 BTU per pound of water removed (3490 kJ/kg). This is a much better figure than those currently obtained with crossflow dryers (Madison, 1980) which are of the order of 7000 BTU/lb (16,286 kJ/kg).

In reviewing the commercial literature it is clear that there are no commercial soybean dryers in the market. What is available are corn dryers which are adapted to soybeans. For the on-farm soybean dryers, such parameters as airflow, air temperature, static pressure,etc., should be modified. There is a need for on-farm tests comparing alternative forms of the drying/storing of soybeans similar to those which have been conducted on corn by the Agricultural Engineering Department of Michigan State University.

Since continuous flow dryers are designed as corn dryers in the United States, they are over-designed and over-rated when used for soybeans due to the different drying characteristics of the two products. This makes such dryers inefficient when employed as soybean dryers.

3.2 Drying Equations

3.2.1 Thin-layer and diffusion equations

Thin-layer equations are of critical importance in simulation drying models. The equations are obtained from thin-layer experiments in which a small quantity of the original product is dried. In drying simulation, the entire drying bed is assumed to consist of a series of thin layers of the product. An accurate equation describing the moisture behavior of the thin layers is thus essential in order to accurately simulate the multi-layer drying process.

Sabbah *et al.* (1976,1977,1979) developed a thin-layer drying equation for soybeans based on the premise that the mechanisms which control the drying rate are diffusion within the seed and mass convection at its surface. Two governing equations for convection and mass diffusion developed in the range of 90-110 F (32.2-43.3 C) were coupled, resulting in the following semi-empirical equation:

MR = 0.608*(exp(-K2*t)*(exp(-K1*t) +
0.25*exp(-4*K1*t))+exp(-K2*t) (1)

The variable K1 is evaluated from:

K1 = 4*PI**2*D/d**2 (2)

The term d in equation (2) is the equivalent seed diameter, assuming the seed to be a sphere. This assumption has been validated by Chu and Hustrulid (1968) who found that two solids of different shapes can be considered equivalent for drying if their volume-to-surface-area ratios are the same, provided none

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[1] In this study, the equations and data from the literature are presented and published. The number of significant figures in the constants and data may not be consistent.

of the solids are original spheres. The equivalent seed diameter of soybeans can be obtained from the following empirical equation:

$$d = 0.6279 + 0.1255*M \quad (3)$$

$$d = cm$$

The mass diffusion coefficient D in Equation (1) is given by:

$$D = (0.0493*exp(-0.59/(Mo-Me)) + 0.0181*(M-Me))*exp(-3137.6/(TH+273.13) \quad (4)$$

$$D = cm2/sec$$

The convection parameter K2 is defined as:

$$K2 = GF * AF * GAF \quad (5)$$

where GF is the grain factor:

$$GF = a*S/B \quad (6)$$

$$a = 558.99 - 196.19*M \quad (7)$$

$$B = 675.10 + 464.54*M \quad (8)$$

$$S = 1.0 \text{ (shape factor)}$$

The air factor AF is expressed by:

$$AF = 1.342E-6*Ga/RH*(TH+272.13)**1.54/(0.514+0.0036*TH)**0.67 \quad (9)$$

and GAF, the grain-air factor, by:

$$GAF = x*Re**-y*(RHe-RH)/(M-Me) \quad (10)$$

where:

$$x = 0.91 \quad \text{and} \quad y = 0.51 \quad \text{for} \quad Re \leq 50.0$$

and

$$x = 0.61 \quad \text{and} \quad y = 0.41 \quad \text{for} \quad Re > 50.0$$

Equations (1) through (10) were originally written in SI units.

The Sabbah equations were developed with a reversed-air drying system. A careful examination of the equations showed, however, that the moisture ratio in Equation (1) does not decrease below 0.73, no matter how large the drying time becomes. Thus, the Sabbah equations for thin-layer soybean drying can not be employed in deep-bed simulation models.

A semi-theoretical drying equation with a logarithmic behavior was presented by Brooker _et al._ in 1974:

$$MR = \exp(-k*t) \tag{11}$$

Overhults _et al._ (1973) observed that a logarithmic drying model of the type in Equation (11) does not adequately describe the thin-layer drying process for soybeans. The following modified logarithmic model was proposed:

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[2] The units corresponding to each variable are given in the List of Symbols, except for those specifically indicated.

$$MR = \exp(-(k*t)**n) \tag{12}$$

where k and n are drying constants described by:

$$n = 0.3529 + 0.00136*TH \tag{13}$$

if Mo < 20 percent, w.b.

$$\ln k = 11.752 - 7912.7/THabs \tag{14}$$

if 20 < Mo < 23 percent

$$\ln k = 10.906 - 7357.0/THabs \tag{15}$$

if 23 < Mo < 33 percent, w.b.

$$\ln k = 10.375 - 6779.3/THabs \tag{16}$$

The Overhults equation is the only empirical drying equation for soybeans which was developed at temperatures in the 200 F (93.3 C) range. This fact along with the high initial moisture contents of the tested soybeans makes it a suitable equation to be employed in simulating high temperature continuous flow dryers.

In order to avoid the use of three different equations for evaluating the drying parameter k in the Overhults' equation, White et al. (1978) derived two empirical equations for n and k :

$$n = 0.33 + 0.0025*RH + 0.003*TH \tag{17}$$

$$k = -0.207 + 3.57*10^{-3}*TH + 2.16*10^{-3}*Mo + 2.61*10^{-3}*RH + 3.202*10^{-6}*Mo*TH \tag{18}$$

where

RH = relative humidity, percent

TH = temperature, degrees Celsius

Mo = initial moisture content, percent dry basis

Initial moisture contents for the White *et al.* experiments varied from 16 to 24 percent wet basis, and air temperatures ranged from 86 to 158 F (30 - 70 C) at dew point temperatures of 46.4 to 100.4 F (8 - 38 C). However, when Equations (17) and (18) are used as the drying constants in Equation (12), it is observed that the moisture ratio decreases as the relative humidity increases. Because the opposite effect is expected, Equations (17) and (18) can not be used.

Pinheiro Filho (1976) investigated intermittent soybean drying and developed empirical equations to evaluate the parameters n and k in the Overhults equation at two initial moisture contents (15 and 19 percent wet basis) and at two drying temperatures of 89.6 and 130 F (32 and 54.5 C). The following relations were reported:

$$n = 0.552 + 1.7742/TH \qquad (19)$$

$$\ln k = -3.5187 + 0.03333*TH \qquad (20)$$

Pinheiro Filho pointed out that some restrictions must be placed on Equations (19) and (20) because of the small number of experiments on which the regression was based.

Roa and Macedo (1976) derived a thin-layer drying equation for carioca beans:

$$MR = \exp(-m(Pvs - Pv)^{n} \cdot t^{q}) \qquad (21)$$

where m, n and q are drying constants for the product.

Rossi and Roa (1980) estimated the drying constants of the Equation (21) for soybeans. The following values were obtained at 118 F (47.7 C) and 28 percent relative humidity:

$m = 0.01448$

$n = 0.47088$

$q = 0.51168$

Although the authors do not present any restriction to Equation (21), it was developed at only one drying condition, which limits its application.

Contrary to the thin-layer equations which assume that the product has the same moisture content at any point within the kernel at one time, diffusion-type equations model a moisture gradient inside the seed. Besides describing the drying process in a more realistic way, diffusion equations allow simulation of tempering (steeping) zones in a dryer.

Molecular diffusion has generally been accepted as the controlling mechanism of convection drying of biological materials during the falling-rate drying period. Bakker-Arkema and Hall (1965) investigated the effects of boundary conditions in solving the diffusion equation for drying forage wafers. It was found that the drying process could be better described by assuming that the two wafer surface concentrations vary exponentially with time. It was also claimed that the physical phenomenon of an exponential surface-moisture-content is likely to be observed in grains and legumes if some drying points are determined sooner than usually done after the start of drying.

Wang and Hall (1961) concluded that the diffusion equation with concentration as the driving force is adequate to describe the moisture movement in a medium if its temperature is uniform. For the non-uniform case, simultaneous equations of moisture and heat diffusion are needed to describe moisture migration in the medium.

Whitaker et al. (1969) studied diffusion in spherical bodies with a concentration dependent diffusion coefficient. It was noticed that a moisture-movement-heat-transfer mathematical model was needed to characterize the heat-moisture diffusion.

Young and Whitaker (1971) stated that:

> "in order to accurately describe moisture transfer within a bulk of material and to explain the effects of drying on the quality of the material, the moisture transfer within individual particles of the material should be understood and accurately repesented by a matehematical model. In the most general case, the transfer of heat and moisture must be

> considered simultaneously in order to accurately describe the transport processes within the material".

They used Fick's second law of diffusion and vapor-concentration gradients within the pores of the material as the driving force. According to the authors, the vapor-concentration gradients seemed to be the best mechanism for describing moisture transfer within a composite body of different hygroscopic properties.

Sabbah _et al._ (1976,1977,1979) developed a diffusion equation for soybeans (Equation (4)) for simulating a reversed-direction airflow drying in a fixed bed. The drying rate was assumed to be a function of the mass diffusion within the bean and mass convection at its surface. The diffusion was used as a thin-layer equation parameter instead of a coefficient in the mathematical model of diffusion.

Misra and Young (1978,1980) investigated the effects of shrinkage on moisture diffusion during drying of remoistened soybeans. Soybeans were dried under sixteen different environmental conditions of four dry-bulb temperatures ranging from 95 to 203 F (35 to 95 C) and four dew-point temperatures varying from 50 to 77 F (10 to 25 C). The diffusion coefficient D was modeled using the Arrhenius equation:

$$D = A*\exp(-B/TH) \tag{22}$$

where

D = diffusion coefficient, m2/hr

TH = absolute temperature, degrees Kelvin

A = 0.04694372

B = 3437.16

Equation (22) is less empirical in nature. Several investigators employed the Arrhenius analogy to develop diffusion equations for other agricultural products (Pabis and Henderson, 1961).

There are many other thin-layer and diffusion equations available in the literature for crops other than soybeans. Although they are for other products, they have been derived under similar conditons and assumptions than the soybean equations discussed above. It seems, however, that due to the much larger number of investigations made with other commodities, and especially with corn, soybean equations are often limited to application in narrow temperature and moisture content ranges.

3.2.2 Equilibrium moisture content equations

Several equations are available for determining the equilibrium moisture content of soybeans. Some have a general form and can be used for different agricultural products by varying one or more coefficients in the equations. Others have been specifically derived for soybeans.

Equilibrium moisture content is the moisture content of the material after it has been exposed to a particular environment for an indefinetely long period of time. Its availability in accurate form is of critical importance in drying simulation. Unfortunately variations in the equilibrium moisture content values reported for soybeans at the same relative humidity and temperature are common. A few probable causes for the variations are: 1) different varieties with different growth histories; 2) differences in the methodology applied; 3) inadequate measurement of the moisture content, and 4) difficulties in controlling temperature and relative humidity during the tests.

The best known equilibrium moisture content equation for a biological material is a semi-logarithmic thermodynamic relationship developed by Henderson (1952):

1 - RH = exp(-A*TH*Me**B) (23)

where A and B are product constants and T is expressed in degrees Rankine. Henderson determined the values of A and

B as, respectively, 0.000052 and 1.52 for soybeans at 77 F (25 C).

Alam (1972) re-evaluated the product constants of Equation (23) for soybeans. At 77 F (25 C) they were found to be A = 0.00004667 and B = 1.48234. He also evaluated the constants for soybeans in the Sabbah equilibrium moisture content equation:

$$Me = a*RH**b/TH**c \qquad (24)$$

where

a = 0.0001617

b = 2.85274

c = 0.189376

Me = equilibrium moisture content, percent dry basis

RH = relative humidity, percent

Equations (23) and (24) do not satisfactorily predict the equilibrium moisture content in the entire range of relative humidities.

Alam (1972) developed a third order polynomial equation to describe soybean equilibrium moisture content:

$$\begin{aligned} Me = {} & c1 + c2**RH + c3*T + c4*RH*T + c5*RH**2 + \\ & c6*RH**2*T+c7*T**2+c8*RH*T**2+c9*RH**2*T**2+ \\ & c10*RH**3 + c11*RH**3*T + c12*RH**3*T**2 + \\ & c13*T**3 + c14*RH*T**3 + c15*RH**2*T**3 + \\ & c16*RH**3*T**3 \qquad (25) \end{aligned}$$

where

T = temperature, degrees Celsius

RH = relative humidity, percent

Me = equilibrium moisture content, percent wet basis

c1 = 2.98305	c9 = 0.000005206
c2 = 0.29107	c10 = 0.000075358
c3 = -0.10662	c11 = 0.0000023991
c4 = 0.01251400	c12 = -0.000000036882
c5 = -0.006551	c13 = -0.000004801
c6 = -0.00034487	c14 = 0.00000068246
c7 = 0.0000131125	c15 = -0.000000019123
c8 = -0.00018787	c16 = 0.00000000013494

Although this equation was developed over the entire range of relative humidities and temperatures between 41 and 131 F (5 to 55 C) the results obtained by this author could not duplicate the Alam results.

A general equilibrium moisture content equation for grains was proposed by Pfost _et al._ (1976):

$$Me = E - F*\ln(R*(TH + C)*\ln RH) \qquad (26)$$

where, for soybeans:

E = 0.375314

F = 0.066816

C = 24.576

R = 1.987 cal/kg-K - universal gas constant

Negative Me values were observed at low relative humidities and temperatures between 50 and 130 F (10 to 54.4 C)

Pfost _et al._ (1976) calculated the constants for the Henderson-Thompson equilibrium moisture content equation for soybeans:

$$Me = \ln(1-RH)/(-k*(TH + C)*100*N) \qquad (27)$$

where

k = 0.000503633

C = 43.016

N = 1.3628

TH = temperature, degrees Celsius.

Equation (27) does not present the characteristic sigmoidal shape of the equilibrium moisture content curves for biological products.

Roa _et al._ (1977) proposed the following general equilibrium moisture content equation:

$$Me = (p1*RH + p2*RH**2 + p3*RH**3) * \exp((q0 +(q1*RH + q2*RH**2 + q3*RH**3 + q4*RH**4)*(TH + q5)) \qquad (28)$$

where TH is the temperature in degrees Celsius.

Rossi and Roa (1980) evaluated the constants in Equation (28) for soybeans:

p1 = 0.469448 q2 = -0.22417

p2 = -0.295153 q3 = 0.46542

p3 = 0.170480 q4 = 0.24788

q0 = -0.006910 q5 = 32.0800

q1 = -0.224170

The drying conditions under which the coefficients of Equation (28) have been developed were not mentioned by the authors.

Silva (in Kalchik *et al.* (1979)) using published equilibrium moisture data for corn developed the following equation:

Me = a*RH**b/lnTH if 0.0 < RH < 52.0 (29)

Me = c*exp(RH*d)/lnTH if 52 < RH <99.9 (30)

where

Me = equilibrium moisture content, percent wet basis

RH = relative humidity, percent.

The soybean coefficients for Equations (29) and (30) have been determined by Silva and Dalpasquale (1979):

a = 6.208060

b = 0.027377

c = 3.961830

d = 0.491880

For soybeans, the transition relative humidity between Equations (29) and (39) was set at 55 percent. Me is expressed in percent dry basis. Equations (29) and (30) predict satisfactorily the equilibrium moisture content in the entire range of relative humidities.

Many of the equilibrium moisture content equations reviewed in this study were plotted for different temperatures and relative humidities by Dalpasquale (1979). The reader is referred to that study for a more thoroughly comparison among the equations.

3.3 Drying Effects on Soybean Quality

According to Brooker _et al._ (1974) high quality grain has the following properties:

1. appropriate low and uniform moisture content;
2. low percentage of broken and damaged kernels;
3. low susceptibility to breakage;
4. high test weight;
5. high starch content;
6. high oil recovery;
7. high protein quality;
8. high viability;
9. low mold count; and
10. high nutritive value.

For soybeans, all but property (5) are important. However, not all quality factors are of interest to every user.

Soybean field and harvest losses may be reduced if the beans are harvested at a moisture content of about 16 percent (Byg and Johnson, 1970). Drying will be necessary to reduce the beans moisture content to approximately 11 percent as required for safe long-term storage.

Ramstad and Geddes (1942) investigated the effects of moisture content, temperature, length of storage, aeration, split beans, and microorganisms on soybean quality. The latter were found to be responsible for heating and other damages in wet beans. It was observed that higher microbiological growth occured in split beans than in whole beans. A larger surface area and the absence of the seedcoat were mentioned as possible reasons.

The loss of seed viability in soybeans has been studied by Milner and Geddes (1946). They related growth of fungy to increases in fatty acids and associated biochemical changes in stored soybeans. Chemical changes were directly proportional to the moisture content and mold growth.

Holmer and Carter (1952) found that soybean seeds can be safely stored for one year with only a sligh decrease in viability if the moisture content is less than 10 percent.

Delouche (1975) studied the effects of damage, temperature, and moisture content on germination of soybeans. Sound soybeans showed a germination potential of 84 percent against only 15 percent for damaged beans after 12 months of storage. Soybeans stored at 50 F (10 C) and 9.4 percent moisture showed a germination of 94 percent after 10 years . In fact, germination increased from 93 percent after 6 months in storage to 98 percent after 2 years. At 68 F (20 C) and at the same moisture, germination was at 90 percent after the beans had been stored for 5 years but dropped to zero percent after 10 years. At 13.9 percent of moisture and 50 F (10 C) soybeans displayed a 92 percentage of germination after 3 years of storage.

Chanchai _et al._ (1976) investigated the influence of heated air drying on soybean impact damage. The results showed that drying with heated air can lead to significant cracking damage to the soybeans. Subsequent impact damage during handling was related to drying air temperature: the higher the air temperature the higher the amount of splits, cracked beans, and total damage after impact. Hall (1974) studying damage caused by handling of soybeans, observed that artificial drying will not cause an increase in damage during handling. A similar observation was made by Matthes and Welch (1974) who concluded that it is feasible to dry high moisture content soybean seeds with heated air and obtain a product of acceptable quality.

White _et al._ (1976) reported that the physical damage of soybeans when dried with heated air can have pronounced effects on their long term storability and quality. Soybeans dried with high air temperatures are more prone to mold development and, also, to an increase in the fatty acid content.

White _et al._ (1980) carried out thin-layer drying experiments with the objective of determining the relationship between the drying parameters and the development of seedcoat and cotyledon damage. Three initial moisture contents (16, 20, and 24 percent), five drying temperatures varying from 86 to 158 F (30 - 70 C) and seven dew-point temperatures ranging from 46.4 to 100.4 F (8 - 38 C) were employed. They observed that seedcoat and cotyledon cracks are highly correlated to the initial moisture content and relative humidity but the drying air temperature did not significantly affect the prediction of those characteristics. Cracks of the seedcoat were absent only at relative humidities of 50 percent or higher.

Sabbah *et al.* (1976,1977) applied the reversed-direction-air-flow technique to a batch-in-bin drying system. They claimed considerable improvement in soybean seed quality over conventional one-direction-airflow drying. In their system, the final moisture content was almost uniform throughout the bed because of the periodical reversal of the airflow direction. Also, fewer overdried and underdried seeds were observed. As a consequence, less cracking and mold activity inside the bean mass was detected. The avoidance of mechanical stirring equipment was mentioned as another advantage of the drying method.

Pfost (1975) studied the effects of varietal and environmental factors on the cracking of soybeans. Seventeen varieties were dried with air varying from 90 to 150 F (32.2 - 65.6 C) and significant diferences were found among them. In general, cracking decreased with an increase in the final moisture content and relative humidity of the drying air, and increased with an increase in air temperature, drying rate, and initial moisture content. For any given variety, the most significant factor affecting cracking was the relative humidity of the drying air. It was also observed that most of the cracks formed during the first five minutes of drying.

Ting *et al.* (1978,1980) investigated the occurence and extent of drying damage in remoistened soybeans at different depths in a laboratory-scale deep-bed dryer. Soybeans have been dried in batches up to 2.0 feet (0.6 meter) deep using drying air temperatures of 122 and 149 F (50-65 C) and airflow rates of 20 and 40 cfm/sqft (0.102-0.203 m3/s-m2). The position of the soybeans in the bed was found to be the most significant factor affecting the drying damage. The farther the soybeans were located from the air inlet, the lower the damage. Besides the position in the drying bed, initial moiture content, airflow rate, and air temperature were all found to significantly affect the drying damage.

Soybean seeds which did not decrease in quality during the drying process still can be deleteriously affected if subsequent handling and storage operations are not properly performed. Rodda and Ravalo (1978) stored soybeans in four types of containers at ambient temperatures, and in sealed metal containers at constant temperatures. Samples at low initial moisture contents maintained the original quality characteristics satisfactorily under tropical conditions. On the other hand, samples with poor initial quality did not store well even at temperatures as low as 37.4 F (3 C). Rodda *et al.* (1980) concluded that it is essential to reduce and to maintain the soybean moisture content during storage if viability of the seed is to be maintained.

Paulsen (1978) reported that in decreasing the soybean moisture content from 17 to 8 percent the average compressure force required to cause seedcoat rupture decreased. He found the energy per unit volume absorbed by the soybeans prior to the seedcoat rupture (thoughness) to be maximum in the moisture range of 11 to 14 percent. It was also observed that the smaller the soybean seed the greater its resistance to seedcoat crack.

Haghighi and Segerlind (1978) performed a numerical study of the stress crack formation in the soybean kernels resulting from moisture and temperature gradients during drying. It was reported that tangential stress in the kernels change from compressive to tensile stress as it approaches the surface. There the tensile stress reaches its peak in one hour and then decays slowly.

Misra and Young (1978,1980) employed a finite-element procedure in determining soybean stresses during artificial drying. Elastic properties were assumed but did not adequately predict the stresses in soybeans. Viscoelastic properties were suggested as more appropriate in soybean stress prediction.

Mensah *et al.* (1980) found that the soybean seedcoat is a viscoelastic material and it can be modeled as a generalized Maxwell model. They stated that the soybean seedcoat is anisotropic with respect to ultimate stress and relaxation modulus, i.e., it exhibits higher values of both properties when loaded perpendicular to the hilum than it does when loaded parallel to the hilum. Higher values were also found for low equilibrium relative humidities and/or low temperatures.

Famili *et al.* (1980) studied the effects of compression strain on soybean germination, average hypocotyl length, and percent of cracked and broken beans at four moisture levels (10.8 to 19.2 percent dry basis) at three compression orientations. Increasing compression strain or decreasing the bean moisture content resulted in lowering the percent germination and average hypocotyl length.

Miller *et al.* (1979) employed a Stein breakage tester to determine breakage susceptibiity in soybeans. Breakage increased as temperature or moisture content decreased. It was also determined that the breakage susceptibility of a mixture of sound and breakage-prone soybeans could be calculated from both the proportion and breakage susceptibility of the components in the mixture.

It should be noted that soybean quality may be affected when the crop is still in the field. Harvesting, drying, handling, and storage can be deleterious to the bean quality if not properly performed. Quality can not be improved by any of these precesses but can be preserved during their execution if proper engineering techniques are applied.

CHAPTER 4

DRYING MODELING AND SIMULATION

A grain dryer is a device which uses ambient air and a heat source to create a flow of heated air to remove water from the drying product. It can have several configurations according to the air and product flow directions: crossflow, concurrentflow, counterflow, and cascade. A grain dryer can operate on a stationary (fixed-bed) or on flowing beds (continuous flow).

Grain dryer performance can be affected by a number of parameters, including: (1) the air temperature and relative humidity, (2) the initial and final moisture content of the product, (3) the initial grain temperature, (4) the throughput of the dryer, (5) the resistance to airflow through the grain mass, (6) the design of the burner, fans, and ducting systems, and (7) the grain variety. All of these parameters act together and their proper design and management enable one to determine the most suitable equipment for specific drying needs.

The drying air temperature is the most easily manageable parameter in a drying system. It drastically affects the drying efficiency and quality of the finished product. In conjunction with the grain and air flows, it is responsible for the amount of water removed in a dryer.

The initial moisture content affects the drying rate. The higher the moisture content, the faster the drying rate in terms of water removed per unit of energy. At high moisture contents the adsorption forces of the water molecules held by the soybean cell structure are less than in the low moisture range. As a result, an increasing percentage of the available heat is utilized to evaporate the moisture in the grain.

The throughput of the dryer can influence the drying rate and the efficiency of the process, and the quality of the end product. If the grainflow is increased, the quality of the end product is usually improved, the specific energy efficiency (the energy required to remove a unit of water) decreases (more energy is necessary per unit of water removed) along with the amount of water evaporated. Underdrying may occur. If the grainflow rate is decreased, a reversing of these trends is likely to occur.

The pressure drop across a drying bed (usually known as the airflow resistance and referred to as static pressure) significantly affects the rate of airflow and thus the drying rate. For a given fan size, the cleaner the mass, the higher the airflow and thus the drying rate.

It has been speculated that different corn varieties dry at different rates (Keener and Glenn, 1978). Bakker-Arkema et al. (1978) defined the "hybrid drying factor" which accounts for the characteristic drying behavior of a lot of corn. The hybrid factor is defined as the ratio of the specific drying rate to the standard drying rate of a lot of corn. It is expected that other agricultural commodities such as soybeans behave in a similar way.

4.1 Crossflow Dryer

Crossflow dryers, often called screen-column dryers, are the most widely used grain dryers. Their simple construction and operating principles, and their lower first cost compared to other types of grain dryers are responsible for this popularity.

Crossflow dryers are availabe in several configurations; the tower type is the most common commercial type. Some crossflow dryers are of horizontal construction with the grain columns located on the two sides of the plenum. They can be operated as batch, multi-stage, or as continuous flow dryers and can be stacked one above the other if higher capacities need to be met. Stacking the units in modules greatly enhances the operation flexibility of the dryers (Hawk et al. ,1978). Each module of the stack can be operated at the same temperature, or at different temperatures. Some intermediate units may at times be used without heat in order to act as a tempering zone. The unit at the very bottom is normally used as a cooler.

In a conventional crossflow dryer, grain and air flow in perpendicular directions. Grain near the air inlet tends to overdry and overheat. Grain near the air exhaust tends to remain wet. The moisture gradient across a 12-inch column can be as large as 20 percent (Gustafson and Morey, 1980).

The optimization of a crossflow grain dryer performance can be achieved throught proper management of the dryer design parameters (column height, length and thickness, and grain discharge rate) and operational parameters (air temperature and velocity). The length of the dryer affects only its total capacity due to moisture and temperature symmetry in that dimension. Column height and discharge rate determine the residence time of the grain in the dryer. Thus, in the optimization process of a crossflow dryer there are four main parameters: two design parameters, column thichness and residence time, and two operational parameters, airflow and drying temperature (Thompson, 1967).

The simple construction and easy operation of crossflow dryers have some drawbacks. Bakker-Arkema et al. (1978) observed the following points:

1) the fuel and fan operation costs are reduced by decreasing the airflow rate at a constant temperature or by increasing the drying air temperature at a constant airflow rate;

2) the temperature and grain moisture gradients are reduced by increasing the airflow rate at a constant temperature or by decreasing the air temperature at constant airflow rate.

Some attempts to decrease the grain moisture and temperature gradients without greatly affecting dryer capacity and efficiency have been made. Converse (1972), Lerew et al. (1972), Paulsen and Thompson (1973) and Morey and Cloud (1973) investigated the effect of reversing the airflow direction halfway through the drying section. Although the approach resulted in a slight decrease in efficiency and capacity, a reduction of 60 to 75 percent in the moisture content gradient was observed.

A major improvement in the basic crossflow grain dryer design has been the recycling of part of the exhaust air. Usually, around 50 percent of the total air is recirculated when drying corn. Saturated air from the first drying section is exhausted to the environment. Air leaving the remaining drying sections is mixed with the exhaust air from the cooling section and the mixture is directed to the burner for re-use. Lerew _et al._ (1972) reported a 50 percent reduction in energy per unit of water removed in a modified (air recycling and reversing) crossflow corn dryer as compared to the basic model. Bakker-Arkema _et al._ (1972) found the modified crossflow corn dryer more energy efficient than an early version of the concurrentflow dryer. The superior performance was associated to recirculaton of 50 percent of the total air employed. Bauer _et al._ (1977) found a 30 percent saving in energy usage by recirculating about 50 percent of the total air in a modified crossflow corn dryer. Bakker-Arkema _et al._ (1979) tested a modified and a conventional crossflow corn dryer. The modified version was observed to be 42 percent more energy efficient than the basic crossflow model.

In some crossflow grain dryer models, the reversing of the airflow direction is not possible because the burner is surrounded by the columns of the dryer. In such dryers, a grain-turning device which splits the grain columns and switches drier and wetter grain can be installed (Hawk et al. ,1978).

The latest addition to crossflow dryers is the tempering or steeping zones. The addition of a tempering section (or of several sections), was until recently an exclusive feature of concurrentflow dryers. The effect of tempering on the product quality has not yet been totally answered in crossflow drying.

4.1.1 Model development

Different crossflow dryer models have been proposed. Thompson (1967) developed a semi-theoretical, algebraic type model which has been successfully used. The model is based on heat and mass balances at the kernel surface. A thin-layer equation describes the moisture transfer. Computer solution is required.

A more theoretical and general model has been developed by researchers at Michigan State University (MSU) starting in 1966. The model is based on the fundamental laws of heat and mass transfer and, because of its theoretical nature, it is described by a rather complicated system of partial differential equations. A digital computer is needed to numerically solve the system of equations. Besides crossflow, the MSU grain drying models contains concurrentflow, conterflow, and fixed-bed programs.

Bakker-Arkema _et al._ (1974) simulated a conventional crossflow dryer using the Michigan State University crossflow model. Severe oscillaton and stability problems were encoutered.

Bakker-Arkema _et al._ (1977) made a significant change in the basic MSU model in the simulation of in-bin solar drying. It was observed that the air and product temperatures could be set equal at low airflow rates as used in solar drying. The same assumption was later extended to crossflow drying simulation with a considerable reduction in computer time was claimed (Dalpasquale, 1979). However, in commercial sized crossflow dryers the equal-temperature assumption is violated at the air inlet and might lead to errors in the drying predictions.

Brooker _et al._ (1974) presented the Michigan State University crossflow drying model:

$$\partial T/\partial x = -h*a*(T-TH)/(Ga*(Ca+Cv*H)) \tag{31}$$

$$\partial TH/\partial y = h*a*(T-TH)/(Ga*(Cp+Cw*M)) - Hfg+Cv*(T-TH)/(Ga*(Cp+Cw*M))*Ga*\partial H/\partial x \tag{32}$$

$$\partial H/\partial x = -Gp/Ga * \partial M/\partial x \tag{33}$$

$$\partial M/\partial t = \text{an appropriate drying equation} \tag{34}$$

A better representation of the drying process is likely to be obtained if Equation (34) is replaced by a diffusion-type equation. Besides describing drying in a more fundamental way it is possible to simulate tempering zones in the dryer and investigate the stresses which occur inside the kernel due to moisture differences.

The model used in this thesis is composed of Equations (31),(32),(33) and the following spherical diffusion equation (Crank, 1979):

$$\partial M/\partial t = D/r{*}{*}2{*}\partial/\partial r{*}(r{*}{*}2{*}\partial M/\partial r) \tag{35}$$

In developing the MSU crossflow drying model, the following assumptions have been made (Brooker _et al._ , 1974):

1. There is no volume shrinkage during the drying process;

2. The dryer walls are adiabatic with negligible heat capacity;

3. The heat capacities of the drying product and of the moist air are constants over short periods of time;

4. There is no temperature gradient within the individual grain particles;

5. $\partial T/\partial t$ and $\partial H/\partial t$ are insignificant as compared to $\partial T/\partial x$ and $\partial H/\partial x$;

6. All transfer processes are reversible without hysteresis;

7. The grainflow and airflow are uniform (plug-type);

8. Crossflow drying is a steady-state process.

Although there is no analytical solution to the MSU drying model, it can be numerically solved. Equations (31), (32) and (33) can be solved using backward differences. Numerical solution of Equation (35) becomes:

(Mi,j-Mi-1,j)/Delt = D/i*Delr**2*((i+1)*Mi+1,j - 2*i*Mi,j + (i-1)*Mi-1,j),
i≠0 (36)

(M1,j-Mo,j)/Delt = 6/Delr**2*(Mi,j - Mo,j),
i=0 (37)

4.1.2 Auxiliary equations

The solution of the system of partial differential equations which constitutes the MSU crossflow model requires knowledge of several air and drying product properties. Some properties are recalculated at each time step, others are constant in regard to temperature and/or moisture content.

4.1.2.1 Equilibrium moisture content

The mathematical description of the equilibrium moisture content of biological products is of great importance in grain dryer simulation. Most of the proposed equations have limitations. In this present study, Equations (29) and (30) are used together with the coefficients determined by Silva and Dalpasquale (1979). These equations are plotted in Figure 1 for five temperatures. The curves present the characteristic sigmoidal behavior and can be used in the entire range of relative humidities.

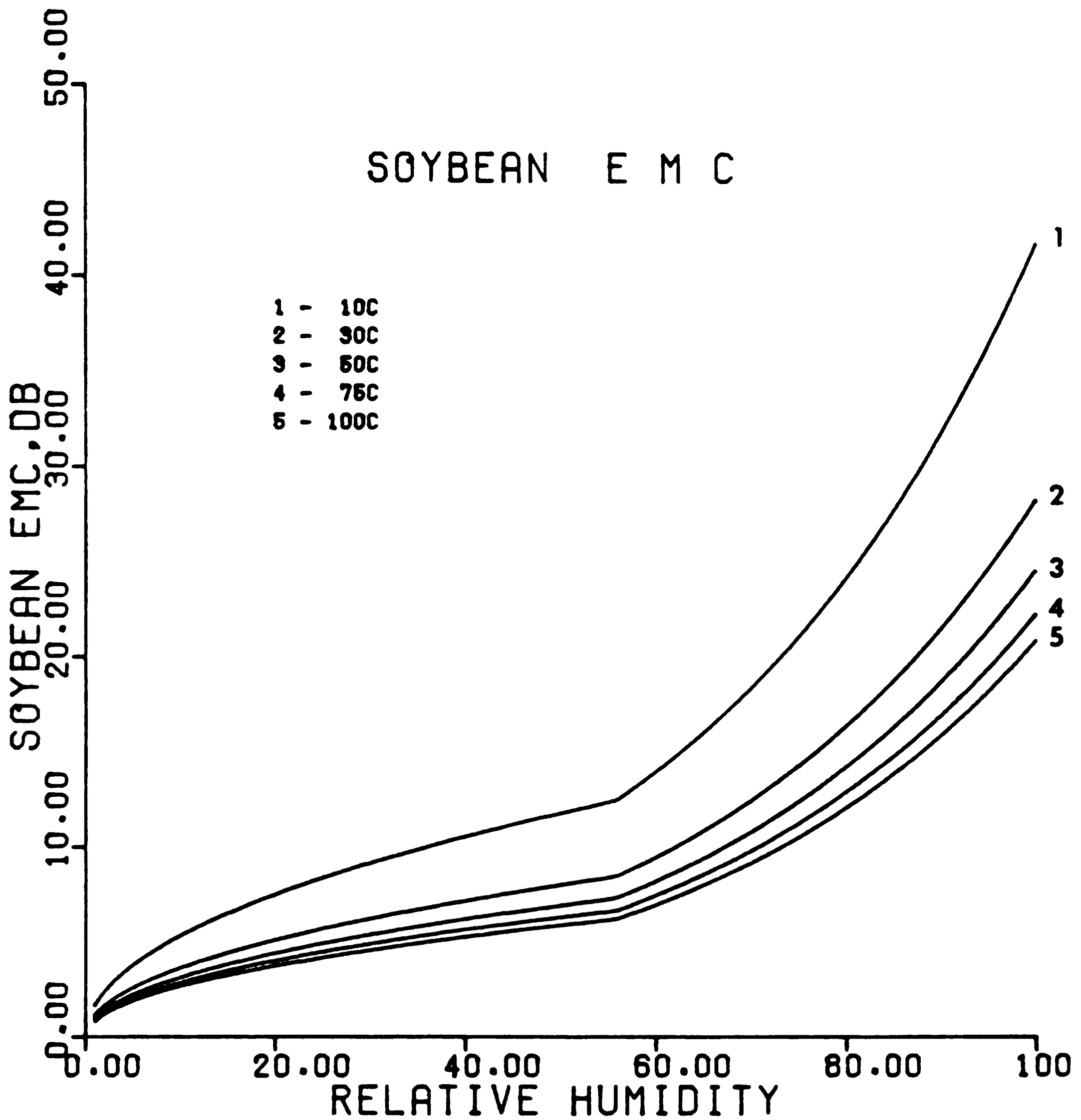

FIGURE 1: Soybean equilibrium moisture content according to Silva's equation.

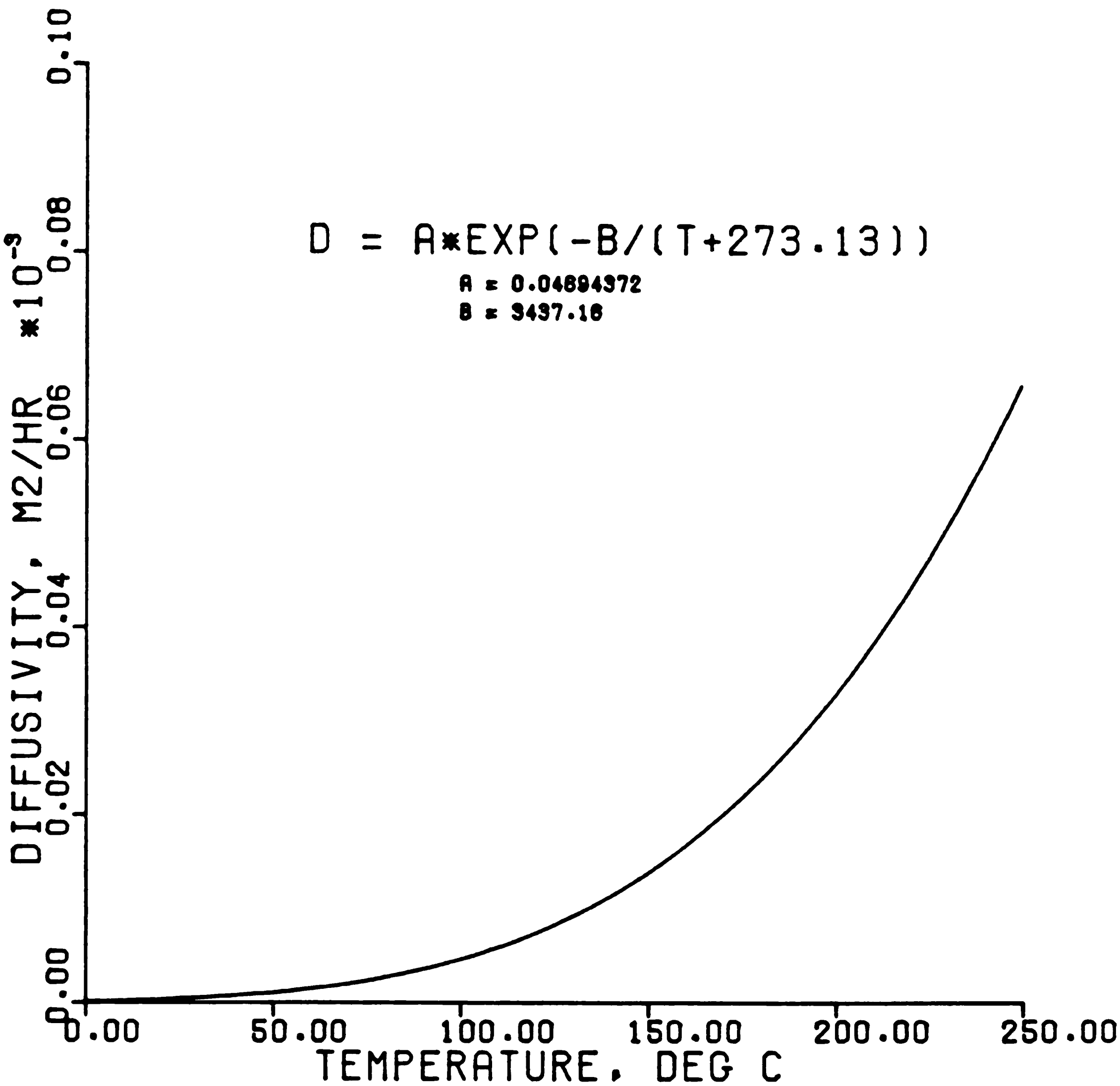

FIGURE 2: Soybean diffusion equation as developed by Misra and Young.

4.1.2.2 Diffusion coefficient

In the first stage of the crossflow simulation program, Equation (5), the Sabbah diffusion equation, was employed. The Misra and Young diffusion equation (Equation(22)) was also tested and preferred over Equation (5). Misra and Young employed Arrhenius analogy to develop the temperature dependence of their diffusion coefficient. Equation (22) is presented in Figure 2.

4.1.2.3 Specific heat

Watts and Bilanski (1970) measured the specific heat of soybeans using a calorimeter. It was found that at 7.4 percent moisture content the specific heat was fairly constant at 0.45 BTU per pound per degree Farenheit (0.58 kJ/kg-C) in the temperature range of 86.4 to 262.0 F (30.2 - 127.8 C).

Alam (1972) carried out specific heat determinations of soybeans by a calorimetric procedure. The specific heat values obtained at various moisture levels were linearly related, resulting in the following

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[3] See footnote [1] in Chapter 3 on significant figures.

empirical equation:

$$Cp = 0.39123 + 0.45057*M \qquad (38)$$

Equation (38) is graphycally presented in Figure 3.

4.1.2.4 Latent heat of vaporization

The energy required to evaporate moisture from a product is called the latent heat of vaporization. Othmer (1940) proposed the following equation for the latent heat of vaporization for grains:

$$Hfg = Hfg'*(1 + A*exp(B*M)) \qquad (39)$$

Alam and Shove (1973) determined the constants A and B for Equation (39) from equilibrium moisture content data for soybeans in the range of 5.7 to 27.5 percent dry basis and at temperatures from 41 to 131 F (5 - 55 C):

$$Hfg = (2502.1 - 2.386*TH)*$$

$$(1 + 0.216*exp(-6.233*M)) \qquad (40)$$

$$Hfg = kJ/kg$$

Hfg' in Equation (39) is the latent heat of vaporization for free water as a function of the soybean temperature. Its mathematical representation in Equation (40) was derived by Rodrigues-Arias (1956).

The effects of soybean temperature and moisture content on the latent heat of vaporization can be observed in Figure 4.

4.1.2.5 Heat transfer coefficient

If the soybean kernel is represented by a sphere of equivalent radius, its convective heat transfer coefficient can be calculated from standard heat transfer equations for spheres. McAdams (1954) proposed the following equation for heat transfer between a flowing gas and a sphere:

$$Nu = 0.37*Re**0.6 \tag{41}$$

where

$$Nu = 2*h*Ro/Ka \tag{42}$$

$$Re = 2*Ga*Ro/Ua \tag{43}$$

Ngoddy *et al.* (1966) made use of an equation for packed beds of spheres based on the Colburn-j factor to describe heat transfer in beds of pea beans.

$$j = Nu/(Re*Pr**0.333) = 0.992*Re**0.34 \tag{44}$$

or

$$Nu = 0.992*Re**0.66*Pr**0.333 \tag{45}$$

The constants for pea beans can be used for calculating the convective heat transfer coefficient of soybeans. Averaged values are employed for the thermal conductivity, the dynamic viscosity and Prandtl number of the air (Holdman, 1976).

4.1.2.6 Energy and static pressure

The energy to heat the drying air can be calculated from an enthalpy balance on the air flowing through the heater:

$$E = (Ga*(Ca + Cv*Hin)*(Tinlet - Tamb)) \quad (46)$$

The burner efficiency is assumed to be 100 percent.

Pressure drop evaluation is based on the Shedd curve for soybeans which is represented by the following pressure-flow relationship (Brook, 1977):

$$Qa = A*(SP/x)**B \quad (47)$$

where, for soybeans:

$A = 75.2$

$B = 1/1.431$

Rearranging Equation (47) gives:

$$SP = x*(Qa/75.2)**1.431 \quad (48)$$

4.1.2.7 Air and soybean properties

A psychrometric computer model developed by Lerew (1972) allows the calculation of a property of the moist air given any other two independent properties. The model, known as SYCHART, is stored on a permanet file on the CDC Cyber 750 computer at Michigan State University.

Some soybean and air properties are treated as constants in this thesis. They are listed in Table 2.

TABLE 2: Air and soybean property constants

PROPERTY		
Dry bulk density	929.0 kg/m3	58.0 lb/cu ft
Spec.surface area	1,522.3 m2/m3	464.0 ft2/cu ft
Spec.heat dry air	1,013.0 kJ/kg-C	0.24 BTU/lb-F
Spec.heat water	1,884.0 kJ/kg-C	0.45 BTU/lb-F

Source: Brook (1977)

To be able to operate economically a crossflow dryer must have the following characteristics: (1) air recycling, (2) air reversal, and (3) tempering or steeping. Such a dryer is simulated in this thesis. A schematic of the dryer is pictured in Figure 5.

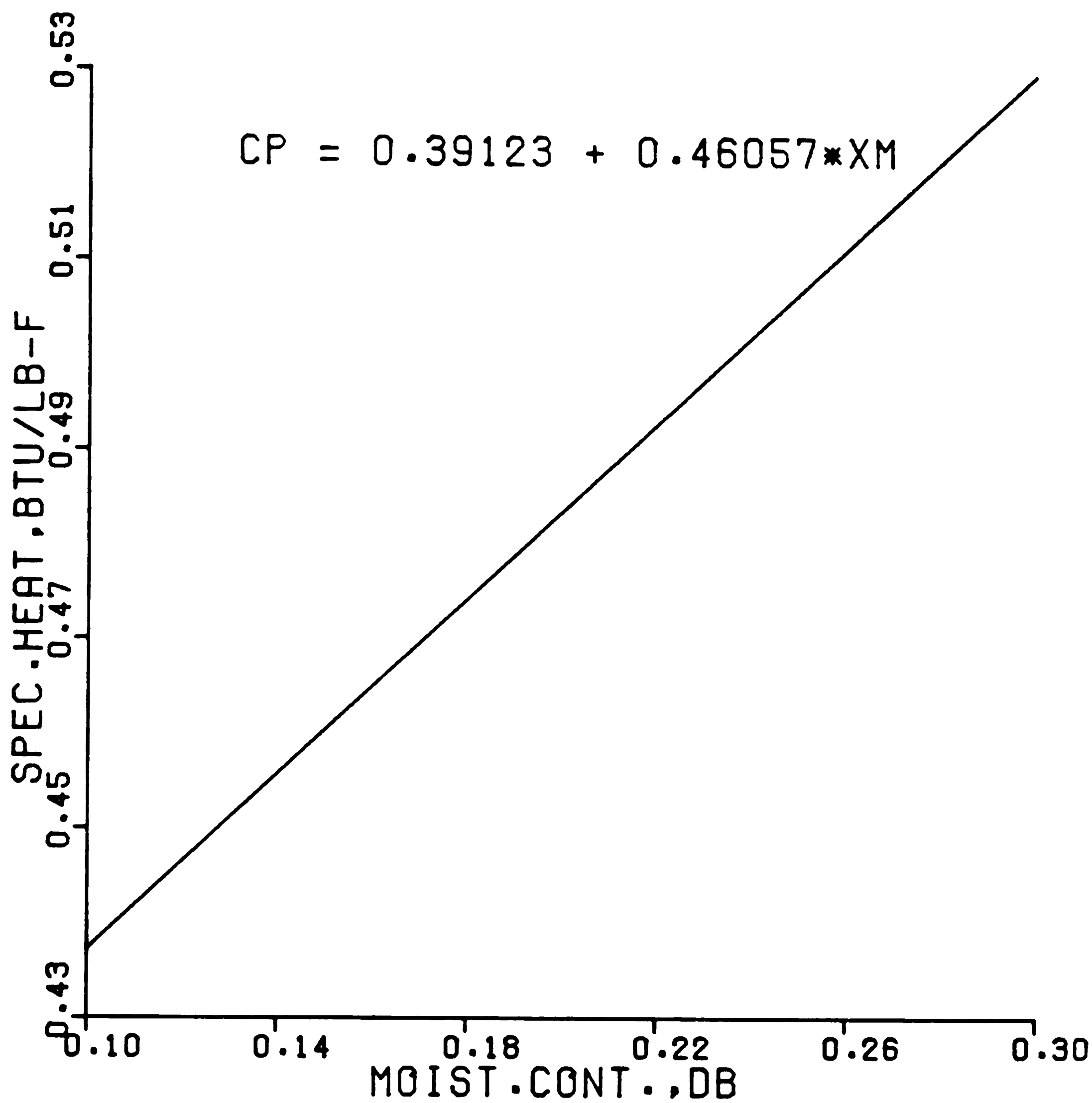

FIGURE 3: Specific heat of soybeans according to equation developed by Sabbah.

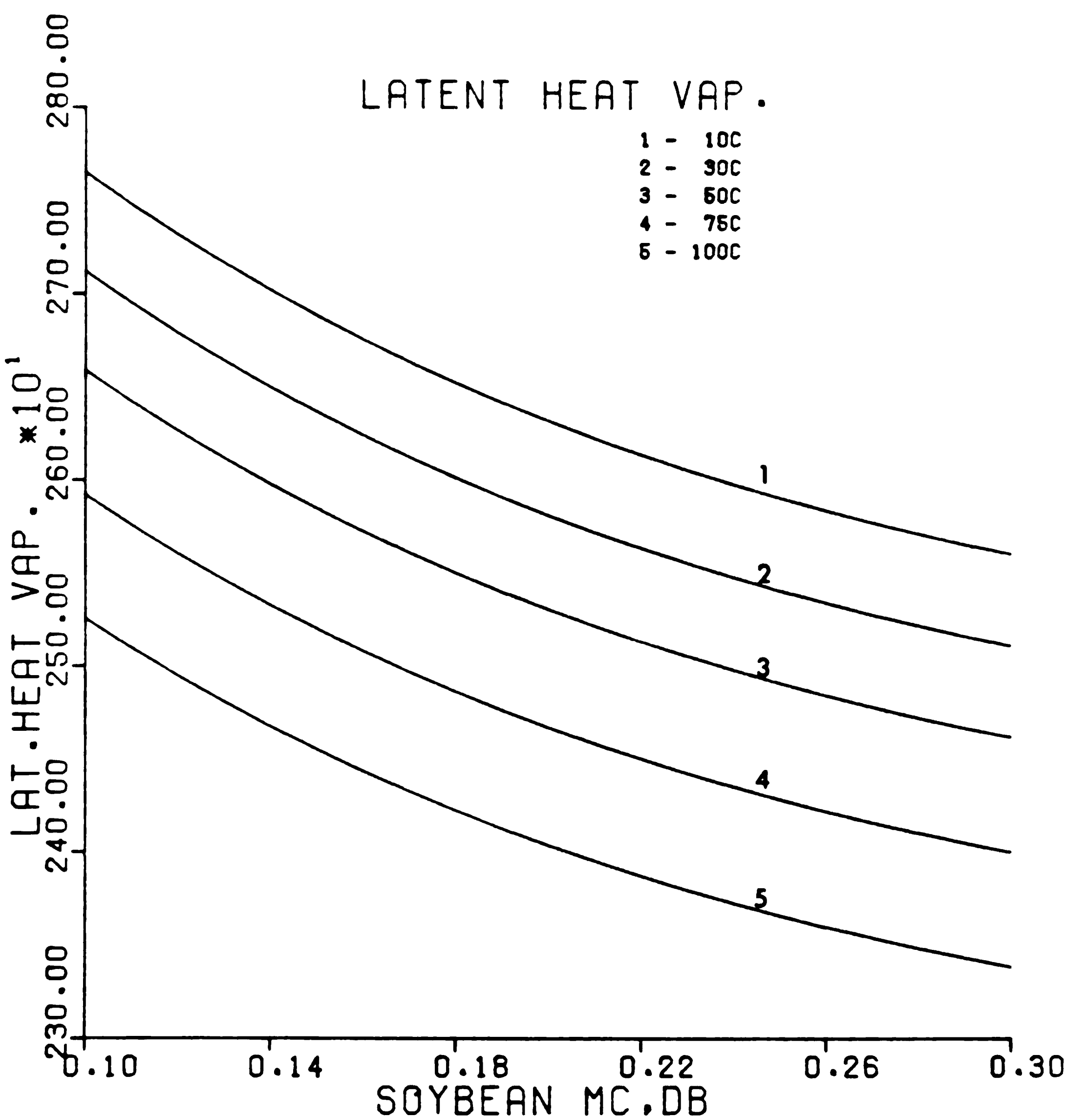

FIGURE 4: Heat of vaporization for soybeans according to equation developed by Sabbah.

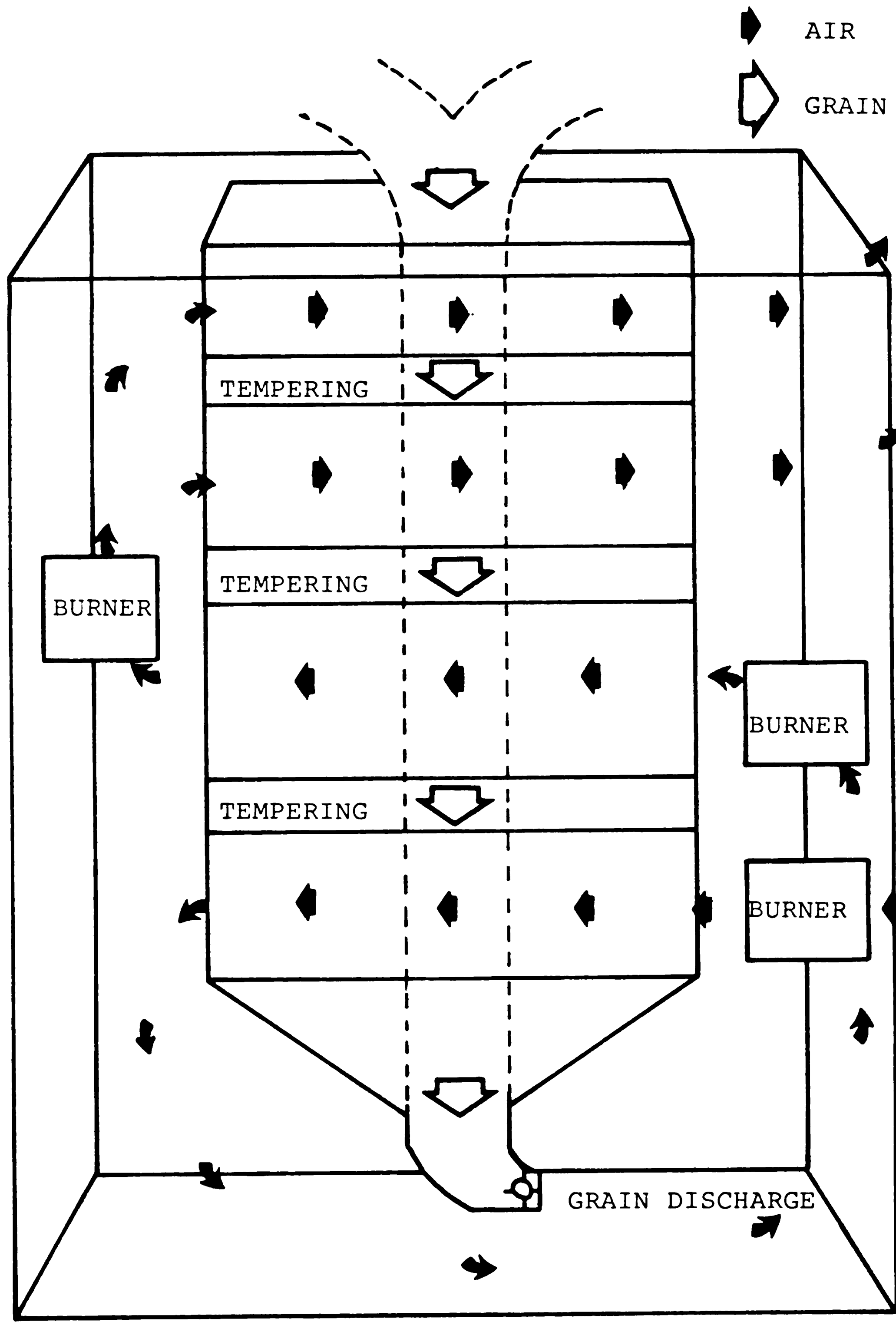

FIGURE 5: Schematic of a crossflow dryer with air recycling, air reversal, and tempering.

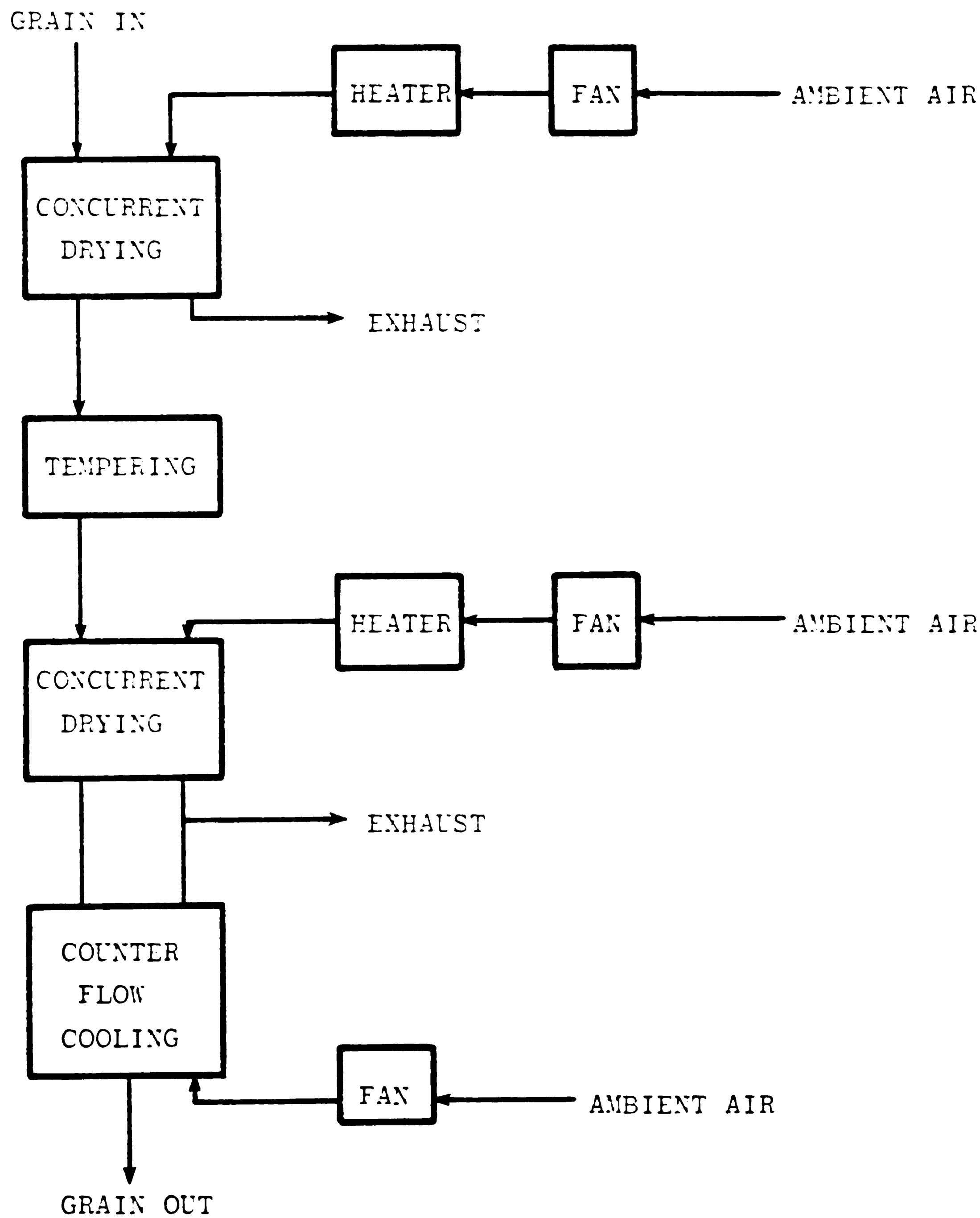

Figure 6: Block diagram of a 2-stage concurrent flow dryer with counterflow cooler (Brook, 1977).

4.2 Concurrentflow Dryer

Concurrentflow drying is a relatively new grain drying technique which has only recently become commercially available. Its principle, however, has long been known (Muhlbauer *et al.*, 1978). Low-cost energy and less expensive dryer configurations have delayed marketing of the concurrentflow dryer. Its high specific energy efficiency has been responsible for its increasing popularity, especially with the advent of the energy crisis.

In a concurrentflow dryer, grain and air both flow in the same direction through the dryer, as illustrated in Figure 6. High rates of evaporation occur at the very top of the dryer because the hottest air encounters the wettest grain. The intensive heat and mass transfer which takes place at the grain/air inlet causes a rapid reduction in the air temperature and moisture content of the drying product. The product temperature remains considerably below the air temperature in the inlet region of the dryer (Farmer *et al.*, 1972). As the air and grain move through the dryer, their temperatures equilibrate. As a consequence, the driving forces governing the drying process decrease due to the cooling of the drying air, the increase in the air relative humidity, and increase in the product equilibrium moisture content.

All kernels undergo the same treatment in a concurrentflow dryer. Thus, there is no moisture gradient present among the kernels as is the case for a crossflow dryer. The continuous decrease of the product temperature through the last portion of the drying bed aliviates the drying stresses and reduces stress cracking and mechanical damage during subsequent handling.

The basic concurrentflow dryer consists of a single concurrentflow drying section with one counterflow cooling section. The one-stage models have limited capacity if moisture removal is over ten points. They also subject the product to a relatively severe drying treatment because of the low grain velocities (Bakker-Arkema *et al.* , 1977).

More recently, multi-stage concurrentflow dryers have been developed. Staging of the drying sections permits the use of higher inlet air temperatures and higher grain velocities. Another important feature of the multi-stage concurentflow dryer is the presence of steeping (tempering) zones between two consecutive drying sections. In these zones, moisture diffuses throughout the warm kernel and the drying stresses are further reduced. Bakker-Arkema *et al.* (1977) reported that staging along with tempering increases the dryer capacity and the end product is of better quality.

Counterflow cooling has usually been combined with concurrentflow drying. Cold ambient air first encounters the coldest grain, thus limiting the thermal stresses (Gygax *et al.*, 1974). Counterflow cooling is a high thermal efficient process.

Carrano (1970), Gygax *et al.* (1974) and Kline (1977) described three laboratory-size one-stage concurrentflow dryers. The dryer presented by Kline was used by Kalchik (1977) who dried soybeans at 450 F (232.2 C) without affecting the oil yield and quality of the beans. Soybeans were dried for seeds in the same dryer by Dalpasquale (1979). An end product of acceptable quality was reported.

Muhlbauer *et al.* (1971) described the drying of high moisture shelled corn in a concurrentflow dryer with counterflow cooler. The nutritive value of the corn did not significantly change at air temperatures below 428 F (220 C). It was predicted that the thermal damage at higher temperatures could be avoided by appropriately balancing the air and grainflow rates. Similar conclusions were drawn by Ahmadnia (1977) and Bakker-Arkema *et al.* (1977) when drying soft wheat.

Walker (1977) conducted a series of rice drying experiments with the Kline model one-stage concurrentflow dryer. He concluded that rice could be successfully dried in a concurrentflow dryer at temperatures as high as 120 F (48.9 C) without affecting the head yield.

Westelaken and Bakker-Arkema (1978) described single-stage and multi-stage concurrentflow commercial dryers. The following advantages of the two- and three-stage models over the one-stage dryer were reported: (1) increased capacity, (2) improved grain quality, (3) greater flexibility for adaptation to various crops, and (4) improved thermal efficiency. Muhlbauer *et al.* (1978) came to similar conclusions in comparing single- and multi-stage concurrentflow dryers.

4.2.1 Model development

Thompson *et al.* (1969) and Bakker-Arkema *et al.* (1974) modeled one-stage concurrentflow steady-state grain drying. Non-diffusion type empirical equation were used in these models. Brook (1977) simulated multi-stage concurrentflow drying using the MSU model. A diffusion type equation was employed in order to properly model the change in the kernel moisture distribution in the steeping zones between two drying sections.

In this thesis, the MSU concurrentflow drying model is used. The basic equations which describe the model are (Bakker-Arkema _et al._, 1974):

dT/dx = -h*a*(T-TH)/(Ga*(Ca+Cv*H)) (49)

dTH/dx = h*a*(T-TH)/(Ga*(Cp+Cw*M)) -

Hfg+Cv*(T-TH)/(Ga*(Cp+Cw*M))*Ga*dH/dx (50)

dH/dx = -Gp/Ga*dM/dt (51)

dM/dt = an appropriate thin-layer equation (52)

Equation (35), the diffusion equation for a sphere, is substituted (in this thesis) for Equation (52) after transforming it into a set of coupled ordinary differential equations by the method of lines (Carver, 1976).

Equations (49), (50), (51), and (35) were solved numerically with the help of a digital computer. A fourth-order single-step Runge-Kutta integration algorithm was used in conjunction with an Adams-Moulton technique for starting the integration. The step size was automatically adjusted using a relative error checking. The kernel average moisture content was determined by employing a volumetric approach, i.e., the moisture content at each kernel node was multiplied by the volume corresponding to that node. The average kernel moisture content was then found by adding these products and dividing them by the total volume of the kernel. A description of the method can be found in Brook (1977).

4.2.2 Auxiliary equations and constants

Equations (38) through (48) were employed as the auxiliary equations. The constants in Table 2 were used with this model.

Brook and Bakker-Arkema (1977,1980) used a dynamic programming optimization scheme for finding the optimum operational parameters and dimensions of a multi-stage concurrentflow dryer. They concluded that the single-stage dryer is more expensive to operate than the multi-stage concurrentflow dryer on a per unit of column area basis.

In the latest version of commercial three-stage concurrentflow dryers, the air from the last drying stage and the cooling stage can be recycled to the heater of the first stage (Blount, 1981). High inlet air temperatures allow the re-use of the air (Hawk *et al.* 1978).

Soybeans for seed or processing can also be dried in multi-stage concurrentflow dryers. The determination of the design and operational requirements to successfully accomplish this task is one of the objectives in this study.

4.3 Fixed-Bed Drying Systems

The sharp increase in agricultural production in the United States after World War II was responsible for the increase in on-farm storage.

Another aspect which greatly contributed to this development was the adoption of shelled corn harvesting. Steel bins were selected as storage structures and thus, drying systems became mandatory.

The first on-farm grain drying systems used low airflow rates (around 1.0 cfm/bu or about 1.0 m3/min-ton) with unheated air, very similar in nature to the drying systems available today. In fact, Brooker et al. (1978) mentioned that there seems to be a cyclical pattern in the grain drying practices and procedures since World War II.

On-farm storage has been intensively studied. Although the majority of the research dealt with corn, other agricultural commodities, including soybeans, have been investigated.

4.3.1 Model development

The first deep bed drying model was proposed by Hukill (1947). It is empirical in nature but is still used because of its satisfactory drying prediction and short computer time required in the simulation process. Boyce (1966) developed an early computer simulation model. The MSU drying models which started with a fixed-bed program were also developed in 1966. These programs are the most rigorous from the heat and mass transport viewpoint, along with the hybrid computer model developed by Hamdy and Barre (1970). Bloome (1969) presented a simplified corn drying model in which near equilibrium conditions was assumed between corn and the drying air. Bloome's model required less computer time than other models available at that time. Alam (1972) simulated fixed-bed soybean drying using Bloome's procedure. The simulation results showed good agreement between experimental and simulated data.

The MSU fixed-bed grain drying model has been previously solved (Bakker-Arkema *et al.*, 1974). The early version is suitable only for short-run batch-in-bin drying. In this thesis, a different approach has been taken in the simulation program (see Calculation procedure on page 69).

The fixed-bed model employed in this study simulates the following drying techniques: (19) natural air drying, (2) low-temperature drying, (3) reversing of the airflow direction at any time during drying, and (4) batch-in-bin drying.

The MSU fixed-bed drying model as used in this study in modified form is described by (Bakker-Arkema *et al.*, 1978):

$$\partial T/\partial x = -h*a*(T-TH)/(Gp*(Ca+Cv*H)) \qquad (53)$$

$$\partial TH/\partial t = h*a*(T-TH)/(Gp*(Cp+Cw*M)) - Hfg+Cv*(T-TH)/(Gp*(Cp+Cw*M))*Ga*\partial H/\partial x \qquad (54)$$

$$\partial H/\partial x = -RHOP/Ga*\partial M/\partial t \qquad (55)$$

$$\partial M/\partial t = \text{an appropriate drying equation} \qquad (56)$$

Equaton (56) is substituted by Equation (35), the diffusion equation for a sphere, in this study.

The MSU fixed-bed grain drying model does not account for hysteresis. Alam (1972) reported that in low-temperature drying hysteresis can be neglected without involving significant errors in the drying simulation process.

4.3.2 Auxiliary equations and constants

Equations (38) through (48), the auxiliary equations for the crossflow and concurrentflow drying programs, were also used in the fixed-bed program. The constants from Table 2 were used.

4.3.3 Calculation procedure

Equations (53) through (56) are numerically solved using backward differences. Equation (53) is the first to be evaluated. The product temperature TH and the air temperature T from the previous position are used as initial guesses. Next, Equation (54) is evaluated using the product temperature TH and the air humidity ratio H from the previous position and the product moisture content M from the previous time as the initial guesses. Equation (55) is then evaluated after the moisture content has been calculated from Equation (56). Equations (53), (54) and (56) are then re-evaluated using these values. The same sequence is used to evaluate Equations (31) through (34).

CHAPTER 5

EXPERIMENTAL INVESTIGATIONS

In this thesis, data was collected from three sources: (1) a commercial crossflow dryer was tested in a commercial soybean processing plant; (2) soybeans were dried in a laboratory-size concurrentflow dryer, and (3) natural air soybean drying data was collected directly from the literature.

5.1 Commercial Crossflow Drying Tests

A series of four soybean drying tests was conducted on two Ferrel-Ross FR-3000 continuous flow crossflow dryers, at the Gold Kist, Inc. processing plant at Decatur, Alabama, during the month of February, 1980. The dryer performance characteristics were evaluated, especially the effects of recirculating part of the drying and cooling air. A computer drying model was later checked against these results.

Three crossflow dryers were available at the plant site. They were installed side by side and numbered dryer No. 1, dryer No. 2, and dryer No. 3 from east to west, respectively. In dryer No. 1, the air is partially recycled. Thermocouples for air temperature determination and probes for static pressure measurement were installed in dryer No. 1. Dryers 1 and 3 were tested for capacity and energy efficiency only.

Four soybean drying tests were conducted. Dryer No. 1 was used in the first three tests. The difference among the tests was the degree of recycling part of the air. Test No. 4 was performed in dryer No. 3 which is a standard crossflow dryer (no air recirculation).

5.1.1 The dryer

The FR-3000 consists of six drying/cooling sections, each with a length of 7.9 feet (2.4 meters) and a house which contains the burner and the cooling and heating fans. The grain column thickness is uniform (12 inches or 0.30 meters) and has a width of 10.7 feet (3.3 meters). The FR-3000 has six grain columns. The total cross-sectional area of the grain columns per section is 64.0 square feet (5.9 m2). A schematic of the dryer is pictured in Figure 7.

Soybeans enter the dryer in section 6 and leave from section 1. Sections 1 and 2 are cooling sections; sections 3 through 6 are heating (drying) sections.

The soybean moisture content is controlled by regulating the grainflow rate at the discharge auger at the bottom of the dryer.

The airflow direction is reversed once in the FR-3000 between the fourth and fifth sections. In the air recirculation model (dryer No. 1) the exhaust air from drying stages 5 and 6 is directly discharged to the atmosphere as is the case for the first stage (cooling air). Exhaust air from sections 2, 3, and 4 is recirculated to the heaters before being re-used. No air was recirculated in dryer No. 3 at the time of the tests.

The FR-3000 dryer power requirement is about 316.5 HP (849,650 kJ). Two 50 HP (134,226 kJ) motors drive the cooling fans, two 100 HP (268,452 kJ) motors power the heating fans. Also, one 15 HP (40,268 kJ) motor drives the oil thermo blower, and one 1.5 HP (4,027 kJ) motor is required for the discharge auger. The heating fuel can be No. 2 oil or liquid propane gas.

5.1.2 Instrumentation

The following parameters need to be measured for the performance evaluation of a grain dryer:

1. grain moisture content before and after drying;
2. grain initial and final temperatures;
3. grain intial and final test weight;
4. grain intial and final quality;
5. drying capacity in wet bushels per hour (ton/hr);
6. ambient and drying temperatures and relative humidities;
7. airflow rate; and
8. energy consumption (fuel and electricity).

The total weight (or bushels) dried was determined by taping the bins in which the soybeans were dumped. Although this procedure may lead to small errors, it was the only option available at the drying site. In order to reduce the error, sounding was done by Gold Kist personnel who had extensive experience with this procedure.

The grainflow rate was determined by dividing the total weight dried by the number of hours of each test.

The soybean moisture contents were measured with a calibrated GAC II Dickey-John moisture meter. Moisture content readings were also made by the dryer operator using a Motomco moisture tester. The results were checked and showed excellent agreement. Samples were collected before and after drying every half-hour during the tests. An arithmatic average was used to calculate the average inlet and outlet moisture contents.

Air and grain temperatures were measured with copper-constantan thermocouples in conjunction with a Fluke data logger. A total of eighty (80) thermocouples monitored the temperatures in and around the dryer at one-half hour intervals. The temperatures were recorded directly on tape with a Techtron magnectic tape recorder. The tapes were decoded and the temperature values stored as permanent files on a CYBER 750 computer at Michigan State University. A Calcomp plotter, driven by the CYBER, was employed to plot the temperatures.

The test weight and temperature of the soybean samples were determined at the same time as the moisture content by a GAC II Dickey-John moisture meter. For each sample, this instrument reads the moisture content, the test weight, and the soybean sample temperature.

The relative humidity of the ambient air was obtained with a dry-bulb-wet-bulb thermometer.

The airflow rates were not determined experimentally. Instead, fan curves provided by the manufacturer were used in conjunction with the experimentally measured static pressures, to calcualte the airflow rates in the heating and cooling sections.

Oil consumption was measured hourly with a flow meter.

5.1.3 Procedure

Three 24-hour drying tests were conducted using dryer No. 1 and one 23-hour test using dryer No. 3. The tests were run continuously.

The average inlet moisture content varied from 11.4 percent to 12.1 percent (wet basis); the inlet test weight ranged from 53.7 to 54.5 pounds per bushel (859.6 to 873.3 kg/m3). The soybean flow rate was varied from 40.9 to 44.6 dry bushel per hour per square foot (10,929 to 12,0442 kg/hr-m2) which translates in a capacity of 2,617 to 2,853 dry bushels per hour (64,967 to 71,564 kg/hr).

The ambient temperatures were relatively cold for Alabama conditions during the first two tests when the average dry bulb temperature was 35.0 F (1.7 C). For the last two tests, the ambient conditions were more moderate (the dry bulb temperature was about 54.0 F (12.2 C)).

The drying air temperature was set at 175. F (79.4 C) for all four tests. However, the average temperature readings for the drying stages were about 190. F (87.8 C) for the first and third tests and about 200. F (93.3 C) for the second test in dryer No. 1. The test in dryer No. 3 was also run at a set temperature of 175. F (79.4 C) but no direct temperature measurements were taken in the drying air with thermocouples.

5.2 Laboratory Concurrentflow Drying Tests

Soybeans of the variety HCF 200 were dried in a series of eight tests conducted in a pilot-scale concurrentflow dryer in the Processing Laboratory in the Agricultural Engineering Departament of Michigan State University. The specific energy consumption was evaluated and the quality (cracks, splits, breakage susceptibility, and germination) of the beans was determined.

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[4] The decimal place figures were uncertain for those numbers ending by a dot (.).

5.2.1 The dryer

The laboratory-size dryer consists of a single-stage concurrentflow dryer with a counterflow cooling section. The cross-sectional area of the dryer is 1.0 square foot (0.09 m2); the drying section has a length of 3.0 feet (0.9 meter). The counterflow cooling section is 2.0 feet (0.6 meter) long with a cross-sectional area of also 1.0 square foot (0.09 m2). According to Kalchik (1977), 5.9 bushels (0.21 m3) of soybeans are required to fill the dryer. An additional 2.4 bushels (0.08 m3) are needed to fill the cooler and the cross auger which connects the concurrentflow drying section to the counterflow cooling section.

Soybeans are converged into the dryer with a bucket elevator which carries the beans to the top of the dryer. They flow by gravity through the concurrentflow drying section. At the bottom of the dryer, the beans are moved to the cooling section by means of an auger. Another auger removes the beans from the cooler. The dried product can be diverted from the dryer if cooling is not necessary at the exit of the cross auger.

The power requirement of the concurrentflow dryer is about 18.5 HP (49,664 kJ). One 1.5 HP (4,027 kJ) motor drives the heating fan, one 2 HP (5,369 kJ) motor powers the cooling fan, one 5 HP (13,423 kJ) motor drives the bucket elevator, and one 5 HP (13,423 kJ) motor is used for the discharge auger. The cross auger is driven by a variable speed 5 HP (13,423 kJ) DC motor.

A schematic of the dryer is presented in Figure 8.

5.2.2 Instrumentation

The total number of bushels dried in each test was determined before the start of the tests. The drying time was monitored and the grainflow rate was evaluated from these two quantities.

The moisture content of the soybeans were initially determined by the oven method according to the Service and Regulatory Announcements No. 147 of the United States Department of Agriculture. A GAC II Dickey-John moisture meter was later used when excellent agreement with the oven results was known. Besides the moisture content, the meter provides the soybean test weight and temperature.

The drying air temperature was measured by means of a thermometer placed in the plenum. A total of eleven (11) copper-constantan thermocouples were installed in and around the dryer to monitor air and grain temperatures. The thermocouples were attached to a Texas Instruments twenty-four channel temperature recorder.

The relative humidities of the ambient and exhaust air were obtained with the dry- and wet-bulb thermocouples at the air inlet and outlet.

The airflow rates were determined with a hot wire anemometer and double checked by making an energy balance in the dryer.

The consumption of liquid propane was measured by the difference in the tank weight before and after each run. Soybean germination tests were conducted in the laboratory of the Crop ans Soil Sciences Department at Michigan State University. Three replications of 100 seeds were performed. Soybeans were left in the germinator for seven days.

The breakage tests were performed with a Stein Breakage Tester using a time cycle of four minutes (Miller et al. ,1979) and a 8/64 (0.003 meter) diameter round hole sieve. Two replications of 0.1 kg were used.

Cracks and splits were evaluated as a percentage by weight basis in samples of 100 grams. For the purpose of this thesis, soybeans are classified as falling in one of the following categories:

1. undamaged - no visual evidence of physical damage;

2. <u>cracked</u> - a crack in the seedcoat of the soybeans with the seedcoat still on and the cotyledons intact;

3. <u>split</u> - a crack which has advanced to the cotyledons, with the seedcoat off and the cotyledons separated into two individual parts, and small broken or fracturated parts of the beans.

5.2.3 Procedure

To initiate the drying process, the concurrent section was filled with soybeans which would not be tested. The fan, the cross auger, the burner, and the temperature recorder were switched on. The cooler was not used and the beans diverted back to the bucket elevator. This "closed loop" was maintained until the warm-up of the dryer which took from 20 to 30 minutes for all tests. When the dryer was assumed to be running in a steady state, wet soybeans started to enter the dryer. At that time, the gas tank weight was read and the drying time was set to zero. Samples were periodically taken at the inlet and outlet of the dryer; the temperature recorder was kept on during the entire course of a test. At the end of the drying process, the gas tank weight and the time were recorded. If multi-stage concurrent drying was to be simulated, the beans were left to temper in a container for a period equivalent to a 15 feet (4.6 meters) tempering zone before being put back into the dryer. The cooler was not used in any of the tests. After drying, the soybeans were stored in a room at 40 F (4.4 C) until the quality tests could be performed.

5.3 Fixed-Bed Drying

No experimental tests were run in order to verify the correspondent computer simulation model. Because the great majority of soybean drying research has been conducted in stationary beds, drying data available in the literature was used to verify the model. In this study, the results published by Alam (1972) were employed.

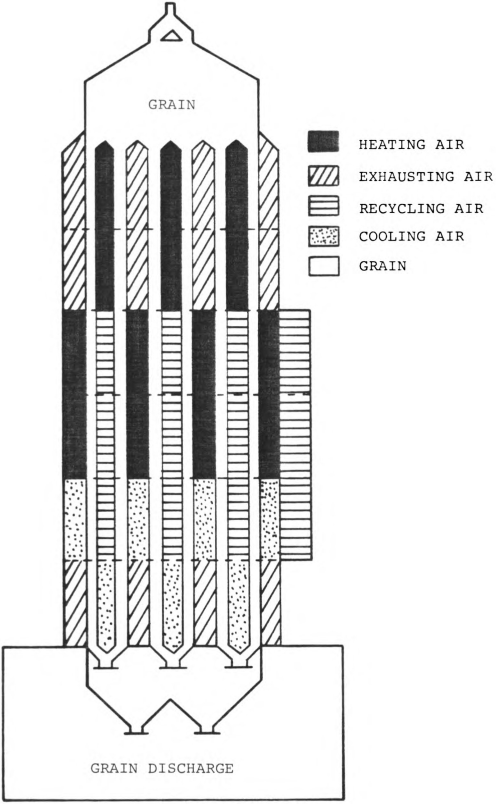

FIGURE 7: Schematic of the FR-3000 dryer.

Figure 8: Schematic of the pilot-scale concurrent flow dryer used in the laboratory, showing the thermocouple locations (dots) (Walker, 1978).

Legend:
1. Bucket elevator
2. Grain storage hopper
3. Natural grain airlock
4. Heating air and grain boundary area
5. Concurrent drying section
6. Dryer exhaust
7. Burner
8. Grain flow rate metering auger
9. AC motor
10. Cooler exhaust
11. Cooling section
12. Cooling air entrance
13. Cooling section discharge auger
14. Cooler base

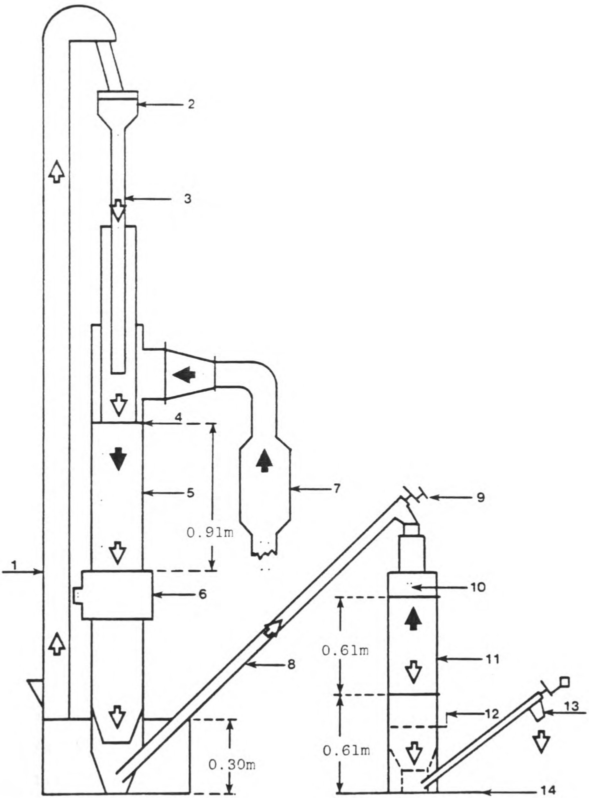

Figure 8: Schematic of the pilot-scale concurrent flow dryer used in the laboratory, showing the thermocouple locations (dots) (Walker, 1978).

CHAPTER 6

RESULTS AND DISCUSSIONS

The results of this study will be presented in the following order: (1) crossflow drying results, (2) concurrentflow drying results, and (3) fixed-bed drying results.

6.1 Crossflow Drying Results

A summary of the major experimental and simulated results is presented in Tables 3 through 6. They correspond to tests No. 1, No. 2, No. 3, and test No. 4. The agreement is excellent for all tests performed.

The dryer efficiency factor is defined as the ratio between the experimental and simulated specific energy consumption (energy used to heat the drying air)(Bakker-Arkema *et al.* ,1978). The FR-3000 efficiency factor averaged 1.34 for drying soybeans as compared to 1.69 for drying shelled corn (Bakker-Arkema *et al.* ,1979).

TABLE 3 : Experimental and simulated results for crossflow test No. 1.

DRYER PARAMETER VALUES	EXPERIMENTAL	SIMULATION
Drying air temperature, deg. F (deg. C)	195. (90.6)	195. (90.6)
Airflow in dryer sections, cfm/bu (m3/min-ton)	83. (86.4)	83. (86.4)
Airflow in cooler sections, cfm/bu (m3/min-ton)	23. (23.9)	23. (23.9)
Grainflow rate, bu/hr-sqft (ton/hr-m2)	42.6 (12.5)	42.6 (12.5)
Dryer height, ft (m)	31.4 (9.6)	31.4 (9.6)
Cooler height, ft (m)	15.7 (4.8)	15.7 (4.8)
Total dryer height, ft (m)	47.1 (14.4)	47.1 (14.4)
MCin, perc. wb	12.1	12.1
MCout Stage 5, perc. wb	-	11.9
MCout Stage 3, perc. wb	-	11.2
MCout Cooler, perc. wb	10.7	10.6
Spec. energy consumption, BTU/lb (kJ/kg)	7,790 (18,120)	5,341 (12,424)
Dryer efficiency factor	1.46	

TABLE 4 : Experimental and simulated results for crossflow test No. 2.

DRYER PARAMETER VALUES	EXPERIMENTAL	SIMULATION
Drying air temperature, deg. F (deg. C)	200. (93.3)	200. (93.3)
Airflow in dryer sections, cfm/bu (m3/min-ton)	83. (86.4)	83. (86.4)
Airflow in cooler sections, cfm/bu (m3/min-ton)	23. (23.9)	23. (23.9)
Grainflow rate, bu/hr-sqft (ton/hr-m2)	40.9 (12.0)	40.9 (12.0)
Dryer height, ft (m)	31.4 (9.6)	31.4 (9.6)
Cooler height, ft (m)	15.7 (4.8)	15.7 (4.8)
Total dryer height, ft (m)	47.1 (14.4)	47.1 (14.4)
MCin, perc. wb	12.1	12.1
MCout Stage 5, perc. wb	-	11.9
MCout Stage 3, perc. wb	-	11.1
MCout Cooler, perc. wb	10.5	10.5
Spec. energy consumption, BTU/lb (kJ/kg)	7,100 (16,515)	5,411 (12,586)
Dryer efficiency factor	1.31	

TABLE 5 : Experimental and simulated results for crossflow test No. 3.

DRYER PARAMETER VALUES	EXPERIMENTAL	SIMULATION
Drying air temperature, deg. F (deg. C)	190. (87.8)	190. (87.8)
Airflow in dryer sections, cfm/bu (m3/min-ton)	83. (86.4)	83. (86.4)
Airflow in cooler sections, cfm/bu (m3/min-ton)	23. (23.9)	23. (23.9)
Grainflow rate, bu/hr-sqft (ton/hr-m2)	44.6 (13.6)	44.6 (13.6)
Dryer height, ft (m)	31.4 (9.6)	31.4 (9.6)
Cooler height, ft (m)	15.7 (4.8)	15.7 (4.8)
Total dryer height, ft (m)	47.1 (14.4)	47.1 (14.4)
MCin, perc. wb	11.4	11.4
MCout Stage 5, perc. wb	-	11.3
MCout Stage 3, perc. wb	-	10.8
MCout Cooler, perc. wb	10.4	10.4
Spec. energy consumption, BTU/lb (kJ/kg)	8,192 (19,055)	6,627 (15,415)
Dryer efficiency factor	1.24	

TABLE 6 : Experimental and simulated results for crossflow test No. 4.

DRYER PARAMETER VALUES	EXPERIMENTAL	SIMULATION
Drying air temperature, deg. F (deg. C)	195. (90.6)	195. (90.6)
Airflow in dryer sections, cfm/bu (m3/min-ton)	83. (86.4)	83. (86.4)
Airflow in cooler sections, cfm/bu (m3/min-ton)	23. (23.9)	23. (23.9)
Grainflow rate, bu/hr-sqft (ton/hr-m2)	41.8 (12.7)	41.8 (12.7)
Dryer height, ft (m)	31.4 (9.6)	31.4 (9.6)
Cooler height, ft (m)	15.7 (4.8)	15.7 (4.8)
Total dryer height, ft (m)	47.1 (14.4)	47.1 (14.4)
MCin, perc. wb	11.8	11.8
MCout Stage 5, perc. wb	-	11.6
MCout Stage 3, perc. wb	-	10.9
MCout Cooler, perc. wb	10.24	10.4
Spec. energy consumption, BTU/lb (kJ/kg)	7,319 (17,024)	5,464 (12,710)
Dryer efficiency factor	1.34	

Figures 9 through 11 show the temperature measurements in the different dryer stages during test No. 2. For each dryer stage, the average inlet and average exhaust air temperatures are plotted. In the two cooling stages (stages 1 and 2, Figure 11) the curve at the top of the plot represents the average air exhaust temperature and the curve at the bottom represents the average air inlet temperature. For the drying stages (stages 3 through 6, Figures 9 and 10) the top curve is the average air drying temperature and the bottom curve is the average air exhaust temperature.

The uniformity of the temperature distribution in the drying and cooling stages are considered satisfactory. The temperature differences between the air entering and the air leaving the different drying stages display a characteristic trend, i.e., the temperature differences decrease as the soybeans move through the dryer. An exception is observed in stage 4 due to the air reversal which occurs between stages 4 and 5 (the high soybean temperature at the air exhaust side heats up the grain).

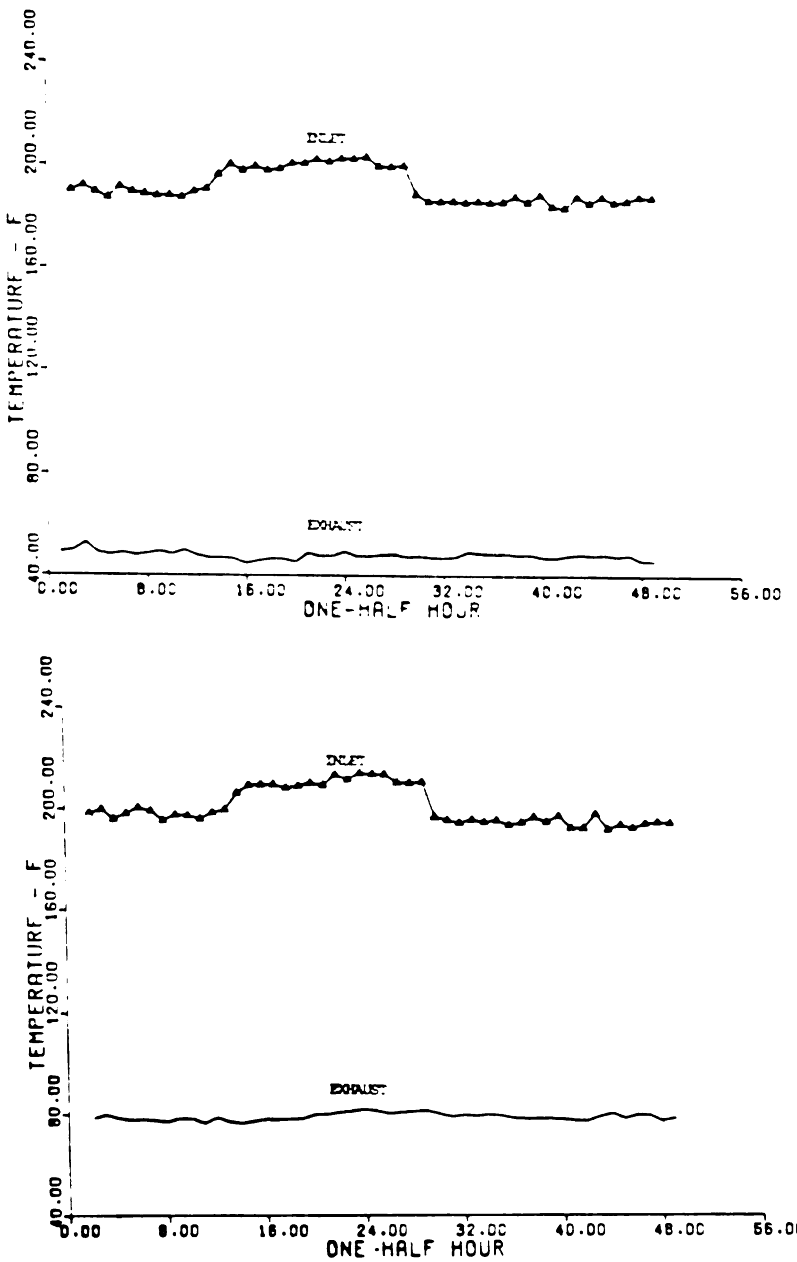

FIGURE 9: Inlet and exhaust air temperatures for drying stages No. 6 (top) and No. 5 (bottom).

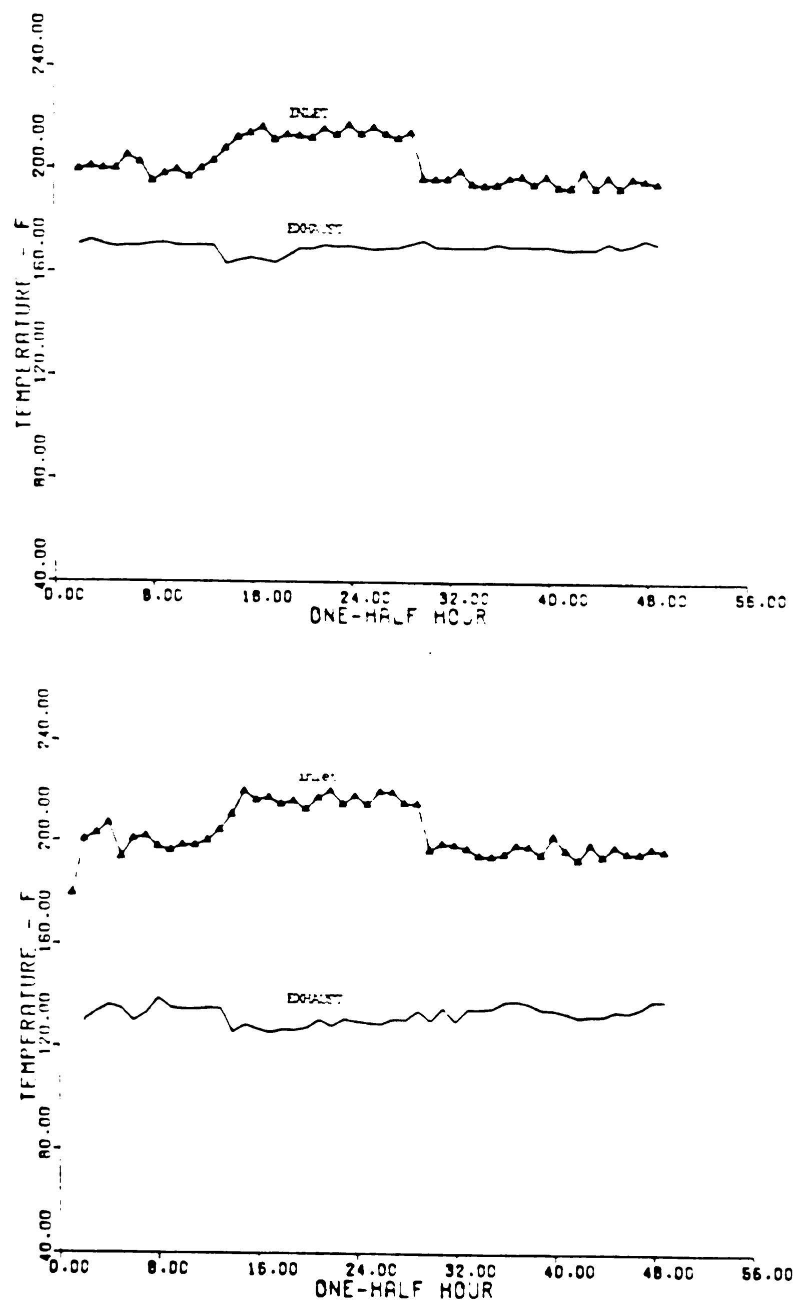

FIGURE 10: Inlet and exhaust air temperatures for drying stages No.4 (top) and No.3 (bottom).

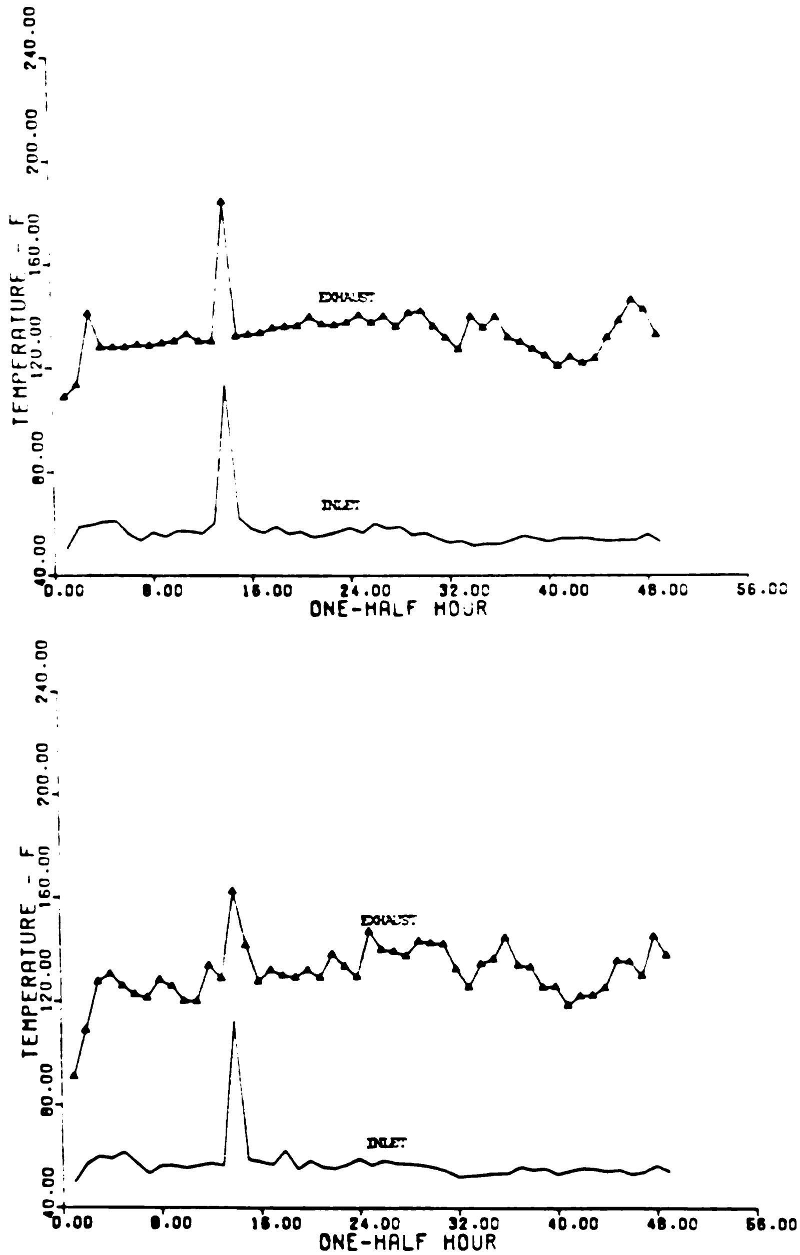

FIGURE 11: Exhaust and inlet air temperatures for cooling stages No.2 (top) and No.1 (bottom).

Both cooling stages display similar temperature distributions. The exhaust air temperatures have approximately the same average value (120 F or 48.9 C) which indicates that the cooling process is incomplete in the FR-3000 dryer.

The specific energy consumption in drying soybeans in the FR-3000 was 7,100 BTU per pound of water removed (16,515 kJ/kg) for the maximum air-recirculation test No. 2. When no air was recirculated (test No. 1) the specific energy consumption was 7,790 BTU per pound of water evaporated (18,120 kJ/kg). The recycling of part of the drying air resulted in about 10 percent savings in energy consumption. The energy consumption is very high compared to that of shelled corn. Bakker-Arkema _et al._ (1979) tested a FR-4500 with corn, with and without air-recycling, and measured specific energy consumption values of 2,180 and 3,100 BTU per pound of water removed (5,071 and 7,211 kJ/kg), respectively. Thus, for drying corn, only 30-40 percent as much energy per unit weight of water evaporated was required than for soybeans.

Three major factors appear to be responsible for the large difference in energy requirements in drying corn and soybeans in commercial crossflow dryers: (1) the low initial moisture content of the soybeans, (2) the small amount of moisture removed in drying the soybeans, and (3) the design of the dryer.

Soybeans for processing are stored at 12.5-13.0 percent moisture content and are dried in the processing plant to about 10.5 percent. In this low moisture content range, the water molecules are held tightly by the soybean cell structure and excessive energy is required to overcome these high adsorption forces. Shelled corn, on the other hand, is usually dried from 25-30 percent moisture down to around 15.0 percent. In this moisture content range, the heat of evaporation is close to that of free water, i.e., the adsorption forces are smaller than at lower moisture contents.

The small amount of water removed from soybeans in a processing plant translates in a much larger amount of sensible heat required to heat the soybean kernels than is the case of corn. This also contributes to high specific energy consumption values in drying soybeans for processing.

The third major reason for the high energy requirements of the FR-3000 in drying soybeans is the non-optimum design of the dryer. In the United States, grain dryers are primarily designed as corn dryers and not for soybeans which have totally different physical characteristics. The characteristics of particualr significance in drying are the static pressure and the initial moisture content of the drying product. Different grains display different values for those parameters, and thus the optimum dryer design is different for each product.

The FR-3000 tested was designed for drying corn. A less than favorable energy consumption rate should have been expected when the dryer was used with soybeans. The experimental results here reported have quantified the energy consumption rate as two to three times as large for soybeans as for corn. In order to diminish and eventually eliminate the difference in energy use, modifications in the design of the FR-3000 have been investigated through computer simulation.

6.1.1 Soybean crossflow dryer

The following points have been considered in the search for the optimum FR-3000 design as a soybean dryer: (1) the proposed modifications should be easy to implement in the basic dryer design and, (2) a stage to be added to or removed from the basic FR-3000 design is of 7.9 feet (2.4 m), i.e., the actual length of a stage in the original model. Test No. 2 presented in Table 4 is used as reference in the simualtion results.

The results for the first proposed design are tabulated in Table 7. The modifications are: (1) to reduce the airflow rate from 83. to 45. cubic feet per minute per bushel (46.8 m3/min-ton) in the drying stages; (2) to increase the airflow rate from 23. to 45. cubic feet per minute per bushel (46.8 m3/min-ton) in the cooling stages; and (3) to augment the cooler height to 23.5 feet (7.2 m) (one stage is added to the cooler). The throughput of the dryer was not affected by these modifications but the actual specific energy consumption decreased from 7,100 to 4,565 BTU per pound of water removed (10,619 kJ/kg), a 35.7 percent savings in energy. The reduction in the specific energy consumption reflects the fact that the drying rate does not increase indefinitely with increasing airflow rates. Rather, the drying rate may be limited by the rate of drying inside the bean kernels (thus by the moisture diffusion inside the beans). In such cases, the drying air will have low relative humidities at the exit side of the drying column which indicates that drying capacity of the air is waisted.

The effects of tempering has been investigated in the second proposed design. In this case, the drying parameters and the design parameters were not changed. Instead, drying stages 3 and 5 were changed to tempering zones. In this design, soybeans are heated in stage 6, tempered in stage 5, dried in stage 4, once again tempered in stage 3, and cooled in the last two stages. Table 8 presents the simulated results for the second proposed design. It can be seen that the dryer capacity has not been altered but the specific energy consumption has been reduced by 39.8 percent from 7,100 to 4,344 BTU per pound of water removed (10,105 kJ/kg). The superior energy efficiency of this design is due to the moisture diffusion inside the beans during the tempering process. The moisture gradients formed during drying are reduced in the steeping zone and as a consequence, the rate of moisture removal is increased when subsequent drying or cooling takes place.

The third proposed design for the FR-3000 combines the advantages of the two previous ones. The necessary modifications in the basic design are: (1) stages 4 and 6 are changed to tempering stages; (2) the airflow rate is

TABLE 7 : Proposed design No. 1 - crossflow dryer.

DRYER PARAMETER VALUES	SIMULATION
Drying air temperature, deg. F (deg. C)	200. (93.3)
Airflow in dryer sections, cfm/bu (m3/min-ton)	45. (46.8)
Airflow in cooler sections, cfm/bu (m3/min-ton)	45. (46.8)
Grainflow rate, bu/hr-sqft (ton/hr-m2)	40.9 (12.0)
Dryer height, ft (m)	31.4 (9.6)
Cooler height, ft (m)	23.5 (7.2)
Total dryer height, ft (m)	54.9 (16.8)
MCin, perc. wb	12.1
MCout Stage 6, perc. wb	11.9
MCout Stage 4, perc. wb	11.3
MCout Cooler, perc. wb	10.7
Spec. energy consumption, BTU/lb (kJ/kg)	3,407 (7,925)
Actual spec. energy cons., BTU/lb (kJ/kg)	4,565 (10,619)
Energy saving, perc.	35.7

TABLE 8 : Proposed design No. 2 - crossflow dryer.

DRYER PARAMETER VALUES	SIMULATION
Drying air temperature, deg. F (deg. C)	200. (93.3)
Airflow in dryer sections, cfm/bu (m3/min-ton)	83. (86.4)
Airflow in cooler sections, cfm/bu (m3/min-ton)	23. (23.9)
Grainflow rate, bu/hr-sqft (ton/hr-m2)	40.9 (12.0)
Dryer height, (6 + 4) ft (m)	15.7 (4.8)
Tempering height, (5 + 3) ft (m)	15.7 (4.8)
Cooler height, ft (m)	15.7 (4.8)
Total dryer height, ft (m)	47.1 (14.4)
MCin, perc. wb	12.1
MCout Stage 6, perc. wb	12.1
MCout Stage 4, perc. wb	11.7
MCout Cooler, perc. wb	10.7
Spec. energy consumption, BTU/lb (kJ/kg)	3,242 (7,541)
Actual spec. energy cons., BTU/lb (kJ/kg)	4,344 (10,105)
Energy saving, perc.	39.8

TABLE 9 : Proposed design No. 3 - crossflow dryer.

DRYER PARAMETER VALUES	SIMULATION
Drying air temperature, deg. F (deg. C)	200. (93.3)
Airflow in dryer sections, cfm/bu (m3/min-ton)	45. (46.8)
Airflow in cooler sections, cfm/bu (m3/min-ton)	45. (46.8)
Grainflow rate, bu/hr-sqft (ton/hr-m2)	40.9 (12.0)
Dryer height, (7 + 5) ft (m)	15.7 (4.8)
Tempering height, (6 + 4) ft (m)	15.7 (4.8)
Cooler height, ft (m)	23.5 (7.2)
Total dryer height, ft (m)	54.9 (16.8)
MCin, perc. wb	12.1
MCout Stage 7, perc. wb	12.1
MCout Stage 5, perc. wb	11.8
MCout Cooler, perc. wb	10.7
Spec. energy consumption, BTU/lb (kJ/kg)	1,701 (3,957)
Actual spec. energy cons., BTU/lb (kJ/kg)	2,279 (5,302)
Energy saving, perc.	67.9

reduced from 83. to 45. cubic feet per minute per bushel (46.8 m3/min-ton) in the drying stages; (3) the airflow rate is increased from 23. to 45. cubic feet per minute per bushel (46.8 m3/min-ton) in the cooler stages; and (4) one stage is added to the cooler (the total cooler length is 23.5 feet (7.2 m)). The results in Table 9 show that the actual specific energy consumption decreased from 7,100 to 2,279 BTU per pound of water evaporated (5,302 kJ/kg). This represents 67.9 savings in energy.

In order to better quantify the energy savings it is assumed that the average soybean moisture content dried in a soybean processing plant in the United States is 12.1 percent wet basis with a test wight of 56.0 pounds per bushel (721.0 kg/m3). Around 52.5 million gallons of No. 2 oil are required to dry one billion bushels of soybeans (the approximate amount of soybeans presently crushed in the United States (Soya Bluebook, 1980)) to 10.5 percent if dryers of conventional FR-3000 type would be used. By modifying the FR-3000 according to proposed design no. 3, the amount of No. 2 oil necessary to dry this volume of soybeans will be reduced to 16.8 million gallons, i.e., more than 35 million gallons of fuel would be saved.

Besides the high specific energy consumption when drying soybeans, the FR-3000 did not meet its specifications for capacity during the tests performed.

In order to obtain a throughput of 3,000 bushels per hour (about 82 ton/hr) the soybean flow rate must be around 47 bushels per hour per square foot (13.8 ton/hr-m2). Table 10 contains the design parameters and the drying parameters for a FR-3000 which will dry soybeans from 12.5 percent down to 10.5 percent at a rate of 3,000 bushels per hour (82 ton/hr). The dryer is an eight-stage dryer with three drying sections (stages 8, 6, and 4), three tempering sections (stages 7, 5, and 3), and the cooler is composed of stages 1 and 2. The airflow rate in the dryer stages is 45. cubic feet per minute per bushel (46.8 m3/min-ton) and 40. cubic feet per minute per bushel (41.6 m3/min-ton) in the cooler stages. Standard conditions (air temperature of 60.0 F (15.6 C), soybean temperature of 60.0 F (15.6 C), and relative humidity of 60 percent) were used in the simulated design. The predicted specific energy consumption is 1,860 BTU per pound of water removed (4,327 kJ/kg) which makes the FR-3000 an energy efficient soybean dryer.

It has been shown in this section that soybeans can be efficiently dried at processing plants with crossflow dryers. In order to accomplish such a task the dryer must have been designed specifically for

TABLE 10 : Proposed design No. 4 - crossflow dryer.

DRYER PARAMETER VALUES	SIMULATION
Drying air temperature, deg. F (deg. C)	200. (93.3)
Airflow in dryer sections, cfm/bu (m3/min-ton)	45. (46.8)
Airflow in cooler sections, cfm/bu (m3/min-ton)	40. (41.6)
Grainflow rate, bu/hr-sqft (ton/hr-m2)	47.0 (13.8)
Dryer height, (8+6+4) ft (m)	23.5 (7.2)
Tempering height, (7+5+3) ft (m)	23.5 (7.2)
Cooler height, ft (m)	23.5 (7.2)
Total dryer height, ft (m)	62.7 (19.2)
MCin, perc. wb	12.5
MCout Stage 4, perc. wb	11.5
MCout Cooler, perc. wb	10.4
Spec. energy consumption, BTU/lb (kJ/kg)	1,380 (3,229)
Actual spec. energy cons., BTU/lb (kJ/kg)	1,860 (4,327)

soybean. A dryer which is designed for one grain and is employed to dry another one most likely will be over-rated and inefficient in terms of specific energy consumption.

6.2 Concurrentflow Drying Results

The analysis of the concurrentflow dryer is based upon the data acquired during the tests run in the laboratory and on computer simulation tests. The calculations assume LP gas to have 19,444 BTU per pound (45,227 kJ/kg).

Two broad goals were pursued with the concurrentflow drying tests: (1) the soybeans should be dried to a final moisture content of 13.0 percent wet basis, and (2) the viablity of the beans should not be affected so that the soybeans could be used for seed. It is of interest to mention that quality does not have the same meaning for the soybean processor and for the soybean seed producer. For seed, soybeans must have a high germination percentage (usually above 90 percent) without excessive cracks and splits. For processing soybeans must have high protein content and the oil yield must be high and of edible quality. No quality tests were conducted for the crossflow drying tests because quality is not affected under the drying conditions under which the tests were run (Madison, 1980).

The major experimental results are summarized in Tables 11 through 19. In the first four tests the airflow rate was 114 cubic feet per minute per square foot (34.8 m3/min-m2); in the last four tests the airflow rate was 86 cubic feet per minute per square foot (26.2 m3/min-m2). The bed depth was 3.0 feet (0.9 m) for all tests. For the multi-stage drying tests, the tempering length was 15.0 feet (4.6 m). No cooling was performed for any laboratory test.

Test No. 1 is a one-stage concurrentflow drying test. A two-stage concurrentflow dryer was experimentally simulated in test No. 2. In the remaining tests, three-stage concurrentflow dryers were experimentally simulated. The soybean flow rate and the drying air temperature were varied from test to test.

The experimental drying air temperature and the soybean flow rate are presented in Tables 11 and 12, respectively. The soybean temperatures before drying and after each drying section are in Table 13.

The results in Table 14 indicate that overdrying occured in the first five tests. The quality results for the same tests show a high percentage of cracks (Table 17), a substantial decrease in germination (Table 18), and a susceptibility to breakage higher than for the other concurrentflow tests (Table 19). The split percentage was low for all tests conducted in the laboratory.

It is worthy to mention that at 200.0 F (93.3 C) (test No. 1) the germination percentage of the soybeans decreased to 53 percent and at 400.0 F (204.4 C) (test No. 8) the germination percentage decreased to 77 percent. This indicates that the air temperature is not the sole factor affecting the soybean quality in concurrentflow drying but rather a combination of the drying air temperature and the soybean flow rate.

TABLE 11: Drying air temperatures, deg. F (deg. C).

TEST No.	FIRST STAGE	SEC.STAGE	THIRD STAGE
1	200.0(93.3)		
2	250.0(121.1)	200.0(93.3)	
3	300.0(148.9)	250.0(121.1)	200.0(93.3)
4	350.0(176.7)	300.0(148.9)	200.0(93.3)
5	350.0(176.7)	300.0(148.9)	200.0(93.3)
6	350.0(176.7)	300.0(148.9)	200.0(93.3)
7	350.0(176.7)	280.0(137.8)	200.0(93.3)
8	400.0(204.4)	300.0(148.9)	200.0(93.3)

TABLE 12: Soybean flow rate, bu/hr-sqft (ton/hr-m2).

TEST No.	FIRST STAGE	SEC.STAGE	THIRD STAGE
1	2.2(0.6)		
2	4.4(1.3)	4.4(1.3)	
3	5.4(1.6)	5.8(1.7)	6.7(2.0)
4	9.7(2.8)	9.7(2.8)	10.5(3.1)
5	8.6(2.5)	9.3(2.7)	9.8(2.9)
6	10.5(3.1)	10.4(3.1)	11.0(3.2)
7	13.6(4.0)	15.0(4.4)	16.6(4.9)
8	16.5(4.8)	18.7(5.5)	18.7(5.5)

TABLE 13: Dryer outlet temperatures of soybeans, deg. F (deg. C), dried in one-, two-, and three-stage concurrentflow dryers.

TEST No.	IN	OUT FIRST STAGE	OUT SEC.STAGE	OUT THIRD STAGE
1	46.4(8.0)	100.4(38.0)		
2	46.4(8.0)	100.4(38.0)	95.0(35.0)	
3	59.9(15.5)	100.4(38.0)	100.4(38.0)	100.4(38.0)
4	37.4(3.0)	92.3(33.5)	100.4(38.0)	95.0(35.0)
5	38.3(3.5)	83.3(28.5)	95.9(35.5)	91.4(33.0)
6	36.5(2.5)	78.8(26.0)	90.5(32.5)	91.4(33.0)
7	33.8(1.0)	73.4(23.0)	86.0(30.0)	87.8(31.0)
8	49.6(9.8)	80.6(27.0)	91.4(33.0)	93.2(34.0)

TABLE 14: Soybean moisture content, percentage wb.(*)

TEST No.	IN	OUT FIRST STAGE	SEC.STAGE	THIRD STAGE
1	16.4	11.0		
2	16.4	13.5	11.3	
3	15.8	12.6	10.4	9.1
4	16.0	14.1	12.0	10.5
5	15.9	14.3	12.8	11.7
6	16.3	14.9	13.7	12.9
7	15.9	15.0	14.2	13.7
8	15.2	14.5	13.8	13.3

(*) without cooling of the soybeans.

TABLE 15: Soybean test weight, lb/cuft.

TEST No.	IN	OUT FIRST STAGE	SEC.STAGE	THIRD STAGE
1	56.5	54.4		
2	56.6	54.8	54.4	
3	56.6	55.3	54.5	54.3
4	56.2	55.6	55.1	54.4
5	56.5	55.9	55.5	55.1
6	56.4	56.1	55.9	55.7
7	56.6	56.3	56.5	56.3
8	56.6	56.7	56.4	56.4

TABLE 16: Percentage of splits.(*)

TEST No.	IN	OUT FIRST STAGE	OUT SEC.STAGE	OUT THIRD STAGE
1	0.48	2.84		
2	0.67	1.56	2.21	
3	0.32	1.28	2.57	2.97
4	0.56	2.03	2.59	4.20
5	0.46	1.72	2.05	3.67
6	0.47	0.90	2.02	3.50
7	0.80	2.44	2.08	2.28
8	0.18	0.68	3.43	3.08

(*) without cooling in the counterflow cooler.

TABLE 17: Percentage of cracks.(*)

TEST No.	IN	OUT FIRST STAGE	OUT SEC.STAGE	OUT THIRD STAGE
1	0.00	31.82		
2	0.00	26.37	37.48	
3	0.82	35.50	53.79	58.09
4	0.00	21.99	51.64	51.63
5	0.00	16.13	38.11	36.23
6	0.00	11.55	25.49	28.68
7	0.00	7.43	14.71	13.04
8	0.00	6.33	11.85	12.09

(*) without cooling in the counterflow cooler.

TABLE 18: Percentage of germination.(*)

TEST No.	IN	OUT FIRST STAGE	SEC.STAGE	THIRD STAGE
1	96	53		
2	97	62	40	
3	96	51	32	29
4	94	55	39	38
5	92	67	48	52
6	95	75	62	60
7	95	79	70	65
8	96	77	75	71

(*) without cooling in the counterflow cooler.

TABLE 19: Stein breakage results (percentage).

TEST No.	IN	OUT FIRST STAGE	OUT SEC.STAGE	OUT THIRD STAGE
1	4.4	9.5		
2	3.4	6.9	8.3	
3	3.4	6.9	9.3	11.0
4	2.0	5.5	7.6	10.0
5	2.6	4.8	7.0	8.3
6	0.4	3.1	4.9	6.2
7	0.5	2.1	3.4	4.3
8	0.5	2.0	3.4	4.6

The final moisture content of the soybeans was around 13 percent for tests No. 6, No. 7, and No. 8. Better end product quality was obtained after each test. It can be observed in Tables 16 through 19 that the best quality results were obtained with test No. 8 in spite of the higher drying air temperatures in the first and second stages. The Stein breakage results in Table 19 were similar for tests No. 7 and No. 8. This is not a contradiction from the previous quality results but was caused by the lower soybean moisture content for test No. 8 (the beans were left to dry one week longer than the other tests). It can be seen that the drying air temperature is not the main factor responsible for quality deterioration of the drying product. The grain flow rate (the residence time) plays an important role when quality needs to be considered. In fact, the drying air temperature and the grainflow rate act together and their fine-tunning is essential in concurrentflow drying of sensitive products. Improper adjustment of these two parameters may lead to a dried product of poor quality.

TABLE 20: Simulated soybean moisture content, percent wb.

TEST No.	IN	OUT FIRST STAGE	OUT SEC.STAGE	OUT THIRD STAGE
1	16.4	11.5		
2	16.4	13.5	10.0	
3	15.8	12.7	9.1	6.9
4	16.0	14.7	12.5	10.6
5	15.9	14.8	13.0	11.4
6	16.3	15.6	14.2	12.7
7	15.9	15.5	14.8	14.1
8	15.2	14.7	14.1	13.3

TABLE 21: Experimental and simulated specific energy consumption, BTU/lb (kJ/kg).

TEST No.	EXPERIMENTAL	SIMULATED	EFFIC.FACTOR
1	3,127(7,273)	2,061(4,794)	1.52
2	4,256(9,900)	1,896(4,410)	2.24
3	3,880(9,025)	1,841(4,282)	2.11
4	3,146(7,318)	2,012(4,680)	1.56
5	3,324(7,731)	1,951(4,538)	1.70
6	3,472(8,076)	2,091(4,864)	1.66
7	4,175(9,711)	2,814(6,545)	1.48
8	4,210(9,793)	2,575(5,989)	1.63
		Average	1.74

A computer program was used to simulate the tests run in the laboratory. Table 20 contains the simulated soybean moisture content results for all the concurrentflow tests. The final moisture content did not agree well in the first three tests but for tests No. 4 through No. 8 the agreement is satisfactory. Better moisture prediction could have been obtained if a larger volume of soybeans would be dried in each test.

The amount of soybeans dried in each test was low. It varied from 281 pounds (127.5 kg) to 1,006 pounds (456 kg) with an average of 671 pounds (304 kg). Any variation in the drying conditions would be least noticeable if the test were run for a longer time period.

The experimental and simulated specific energy consumption results are pictured in Table 21. The efficiency factor varied from 1.52 to 2.24 with an average of 1.74. No explanation was found for the high efficienty factors obtained in tests No. 2 and No. 3.

The dryer efficiency factor indicates the amount of heat loss in the drying process. In a well insulated dryer, the efficiency factor should have a value close to 1.0.

The average efficiency factor for the laboratory concurrentflow dryer is higher than the value obtained with crossflow drying but it should be remembered that the laboratory tests involved small amounts of soybeans as compared to thousands of bushels for the crossflow field tests and the laboratory dryer was not insulated.

Tempering has been shown to be highly desirable in high temperature crossflow soybean drying when the initial moisture content of the beans is around 12.5 percent. The effect of tempering on the soybean drying rate at higher moisture contents was analyzed by applying the concurrentflow computer program.

Tables 23 and 24 contain the results of a three-stage concurrentflow dryer at 20.0 and 16.0 percent initial moisture content. The dimensions of the drying and cooling stages and the airflows are those of a commercial three-stage concurrentflow dryer (see Table 22). In Table 25 the results for a commercial two-stage concurrentflow dryer is presented. It can be seen that at high initial moisture contents (16-20 percent wet basis) the soybean drying rate increases significantly with increasing tempering height. At a low initial moisture content (12.5 percent) the soybean drying rate was less sensitive to changes in the tempering height. At high initial moisture contents there is a compromise mainly between the tempering height and dryer capacity. At low initial moisture contents, the compromise is between tempering height and specific energy consumption. At all levels of initial moisture content, however, the use of one additional tempering stage between the last drying section and the cooler is beneficial as evidenced in Tables 23 through 25.

Tables 26 and 27 contain thin-layer drying simulation results for soybeans and corn at four temperatures and for four hours. At all temperatures, soybeans were predicted to dry faster than corn. In Table 28 three-stage concurrentflow soybean and corn drying simulation results are presented. Identical drying conditions were used for both products but the soybean results showed a lower final moisture content (11.0 percent).

The high drying rates characteristic of soybeans indicate that concurrentflow corn dryers are not optimum designed for soybean drying. It is recommmended that the use of a 10-foot tempering zone after each drying section in concurrentflow soybean dryers is considered.

TABLE 22: Drying parameters and dimensions of a commercial three-stage concurrentflow corn dryer.

DRYING PARAMETER VALUES	
FIRST STAGE	
Airflow rate, cfm/ft2 (m3/min-m2)	150.0 (45.7)
Dryer length, ft (m)	3.5 (1.1)
SECOND STAGE	
Airflow rate, cfm/ft2 (m3/min-m2)	135.0 (41.2)
Dryer length, ft (m)	4.5 (1.4)
THIRD STAGE	
Airflow rate, cfm/ft2 (m3/min-m2)	110.0 (33.5)
COOLER	
Airflow rate, cfm/ft2 (m3/min-m2)	100.0 (30.5)
Cooler length, ft (m)	3.0 (0.9) (*)

(*) The commercial dryer has a cooling section of 5.0 ft.

TABLE 23: Effect of tempering on soybean drying rate in a three-stage concurrentflow dryer (*).

DRYING PAR. VALUES	S I M U L A T I O N				
FIRST STAGE					
Drying air temp., deg. F (deg. C)			400.0 (204.4)		
MCin, perc. wb	20.0	20.0	20.0	20.0	20.0
MCout, perc. wb	18.7	18.7	18.7	18.7	18.7
Tempering length, ft (m)	20.0 (6.1)	15.0 (4.6)	10.0 (3.1)	5.0 (1.5)	0.0 (0.0)
SECOND STAGE					
Drying air temp., deg. F (deg. C)			300.0 (148.9)		
MCout, perc. wb	16.8	16.8	16.9	17.0	17.1
Tempering length, ft (m)	20.0 (6.1)	15.0 (4.6)	10.0 (3.1)	5.0 (1.5)	0.0 (0.0)
THIRD STAGE					
Drying air temp., deg F (deg. C)			200.0 (93.3)		
MCout, perc. wb	15.2	15.3	15.5	15.7	16.0
Tempering length ft (m)	20.0 (6.1)	15.0 (4.6)	10.0 (3.1)	5.0 (1.5)	0.0 (0.0)
COOLER					
MCout, perc. wb	14.4	14.5	14.8	15.1	15.6
Grainflow rate, bu/hr-ft2 (ton/hr-m2)			17.0 (5.0)		
Theoretical spec. energy consump. BTU/lb (kJ/kg)	1,384 (3,219)	1,421 (3,305)	1,477 (3,436)	1,572 (3,657)	1,745 (4,059)

(*) The dimensions of the drying/cooling stages and the airflow rates are those presented in Table 22.

TABLE 24: Effect of tempering on soybean drying rate in a three-stage concurrentflow dryer (*).

DRYING PAR. VALUES	S I M U L A T I O N				
FIRST STAGE					
Drying air temp., deg. F (deg. C)			400.0 (204.4)		
MCin, perc. wb	16.0	16.0	16.0	16.0	16.0
MCout, perc. wb	14.7	14.7	14.7	14.7	14.7
Tempering length, ft (m)	20.0 (6.1)	15.0 (4.6)	10.0 (3.1)	5.0 (1.5)	0.0 (0.0)
SECOND STAGE					
Drying air temp., deg. F (deg. C)			300.0 (148.9)		
MCout, perc. wb	12.6	12.7	12.8	12.9	13.0
Tempering length, ft (m)	20.0 (6.1)	15.0 (4.6)	10.0 (3.1)	5.0 (1.5)	0.0 (0.0)
THIRD STAGE					
Drying air temp., deg F (deg. C)			200.0 (93.3)		
MCout, perc. wb	10.9	11.1	11.2	11.5	11.8
Tempering length ft (m)	20.0 (6.1)	15.0 (4.6)	10.0 (3.1)	5.0 (1.5)	0.0 (0.0)
COOLER					
MCout, perc. wb	10.2	10.4	10.6	10.9	11.5
Grainflow rate, bu/hr-ft2 (ton/hr-m2)			16.0 (4.7)		
Theoretical spec. energy consump. BTU/lb (kJ/kg)	1,575 (3,664)	1,609 (3,743)	1,666 (3,875)	1,767 (4,110)	1,971 (4,585)

(*) The dimensions of the drying/cooling stages and the airflow rates are those presented in Table 22.

TABLE 25: Effect of tempering on soybean drying rate in a two-stage concurrentflow dryer (*).

DRYING PAR. VALUES	S I M U L A T I O N				
FIRST STAGE					
Drying air temp., deg. F (deg. C)			250.0 (121.1)		
MCin, perc. wb	12.5	12.5	12.5	12.5	12.5
MCout, perc. wb	11.9	11.9	11.9	11.9	11.9
Tempering length, ft (m)	20.0 (6.1)	15.0 (4.6)	10.0 (3.1)	5.0 (1.5)	0.0 (0.0)
SECOND STAGE					
Drying air temp., deg. F (deg. C)			200.0 (93.3)		
MCout, perc. wb	10.9	10.9	11.0	11.0	11.1
Tempering length, ft (m)	20.0 (6.1)	15.0 (4.6)	10.0 (3.1)	5.0 (1.5)	0.0 (0.0)
COOLER					
MCout, perc. wb	10.4	10.4	10.5	10.6	10.8
Grainflow rate, bu/hr-ft2 (ton/hr-m2)			8.0 (2.4)		
Theoretical spec. energy consump. BTU/lb (kJ/kg)	1,759 (4,092)	1,796 (4,178)	1,859 (4,324)	1,971 (4,585)	2,189 (5,092)

(*) The dimensions of the drying/cooling stages are those in Table 22. The airflow rate in the drying sections was 60.0 cfm/ft2 (18.3 m3/min-m2) and 45.0 cfm/ft2 (13.7 m3/min-m2) in the cooling section.

TABLE 26: Soybean and corn moisture content according to the Overhults and Thompson thin-layer equations, respectively.

DRYING TIME (hrs)	DRYING TEMPERATURES 250.0 F (121.1 C) SOYBEANS	250.0 F (121.1 C) CORN	200.0 F (93.3 C) SOYBEANS	200.0 F (93.3 C) CORN
0.0	16.0	16.0	16.0	16.0
0.4	10.2	11.4	12.1	13.0
0.8	8.1	8.9	10.6	11.5
1.2	6.7	7.3	9.6	10.4
1.6	5.7	6.2	8.8	9.5
2.0	5.0	5.3	8.1	8.9
2.4	4.4	4.7	7.6	8.3
2.8	3.9	4.1	7.1	7.8
3.2	3.5	3.7	6.7	7.4
3.6	3.2	3.4	6.4	7.0
4.0	2.9	3.1	6.0	6.6

TABLE 27: Soybean and corn moisture content according to the Overhults and Thompson thin-layer equations, respectively.

DRYING TIME (hrs)	DRYING TEMPERATURES 100.0 F (37.8 C) SOYBEANS	CORN	70.0 F (21.1 C) SOYBEANS	CORN
0.0	16.0	16.0	16.0	16.0
0.4	13.3	13.8	13.8	14.8
0.8	12.3	13.5	13.1	14.3
1.2	11.7	12.9	12.6	13.9
1.6	11.1	12.4	12.2	13.6
2.0	10.7	11.9	11.8	13.3
2.4	10.3	11.6	11.5	13.0
2.8	10.0	11.3	11.3	12.8
3.2	9.7	11.0	11.0	12.6
3.6	9.4	10.7	10.8	12.4
4.0	9.1	10.5	10.6	12.2

TABLE 28: Soybean and corn drying in three-stage concurrentflow dryer at 17.0 bu/hr-ft2 (5.0 ton/hr-m2).

DRYING PARAMETER VALUES	SOYBEANS	CORN
FIRST STAGE		
Drying air temperature, deg. F (deg. C)	400.0 (204.4)	400.0 (204.4)
Airflow rate, cfm/ft2 (m3/min-m2)	150.0 (45.7)	150.0 (45.7)
Dryer length, ft (m)	3.5 (1.1)	3.5 (1.1)
Tempering length, ft (m)	15.0 (4.6)	15.0 (4.6)
MCin, percent,wb	16.0	16.0
MCout, perc. wb	14.8	15.1
SECOND STAGE		
Drying air temperature, deg. F (deg. C)	300.0 (148.9)	300.0 (148.9)
Airflow rate, cfm/ft2 (m3/min-m2)	135.0 (41.2)	135.0 (41.2)
Dryer length, ft (m)	4.6 (1.4)	4.5 (1.4)
Tempering length, ft (m)	15.0 (4.6)	15.0 (4.6)
MCout, perc. wb	13.0	13.9
THIRD STAGE		
Drying air temperature, deg. F (deg. C)	200.0 (93.3)	200.0 (93.3)
Airflow rate, cfm/ft2 (m3/min-m2)	110.0 (33.59	110.0 (33.5)
Dryer length, ft (m)	5.0 (1.5)	5.0 (1.5)
MCout, perc. wb	11.4	13.1
COOLER		
Airflow rate, cfm/ft2 (m3/min-m2)	100.0 (30.5)	100.0 (30.5)
Cooler length, ft (m)	5.0 (1.5)	5.0 (1.5)
MCout, perc. wb	11.0	12.8
Theoretical specific energy consumption BTU/lb (kJ/kg)	1,686 (3,922)	2,595 (6,036)

6.2.1 Soybean concurrentflow dryer

Three two-stage concurrentflow dryer designs are proposed for soybean processing plants in Tables 29 through 31. The difference among the three designs are the airflow and the grainflow rates. The theoretical specific energy consumption decreased from 2,180 to 1,859 BTU per pound of water removed (5,071 to 4,324 kJ/kg) while the dryer capacity decreased from 15.0 to 8.0 bushels per hour per square foot (4.4 to 2.4 ton/hr-m2). It can be seen that capacity was sacrificed for the dryer thermal efficiency.

6.3 Sensitivity Analysis

Sensitivity analyses were conducted with the crossflow and concurrentflow drying results. Table 32 shows the accuracy of the measured parameters accepted in this study.

Two tests were run with crossflow and two with concurrentflow dryer simulation programs. In both cases, the upper limit condition indicates that the accuracy as presented in Table 32 is added to the respective drying parameter; for the lower limit case, the accuracy was subtracted from the respective drying parameter.

TABLE 29: Proposed design No. 1.

DRYING PARAMETER VALUES	SIMULATION
FIRST STAGE	
Drying air temperature, deg. F (deg. C)	250.0 (121.1)
Airflow rate, cfm/ft2 (m3/min-m2)	135.0 (41.2)
Dryer length, ft (m)	3.5 (1.1)
Tempering length, ft (m)	10.0 (3.1)
MCin, percent, wb	12.5
MCout, perc. wb	12.0
SECOND STAGE	
Drying air temperature, deg. F (deg.C. C)	200.0 (93.3)
Airflow rate, cfm/ft2 (m3/min-m2)	110.0 (33.5)
Dryer length, ft (m)	4.5 (1.4)
Tempering length, ft (m)	10.0 (3.1)
MCout, perc. wb	11.1
COOLER	
Airflow rate, cfm/ft2 (m3/min-m2)	100.0 (30.5)
Cooler length, ft (m)	5.0 (1.5)
MCout, perc. wb	10.6
Grainflow rate bu/hr-ft2 (ton/hr-m2)	15.0 (4.4)
Theoretical specific energy consumption, BTU/lb (kJ/kg)	2,180 (5,071)

TABLE 30: Proposed design No. 2.

DRYING PARAMETER VALUES	SIMULATION
FIRST STAGE	
Drying air temperature, deg. F (deg. C)	250.0 (121.1)
Airflow rate, cfm/ft2 (m3/min-m2)	110.0 (33.5)
Dryer length, ft (m)	3.5 (1.1)
Tempering length, ft (m)	10.0 (3.1)
MCin, percent, wb	12.5
MCout, perc. wb	11.8
SECOND STAGE	
Drying air temperature, deg. F (deg.C. C)	200.0 (93.3)
Airflow rate, cfm/ft2 (m3/min-m2)	80.0 (24.4)
Dryer length, ft (m)	4.5 (1.4)
Tempering length, ft (m)	10.0 (3.1)
MCout, perc. wb	11.0
COOLER	
Airflow rate, cfm/ft2 (m3/min-m2)	60.0 (18.3)
Cooler length, ft (m)	5.0 (1.5)
MCout, perc. wb	10.5
Grainflow rate bu/hr-ft2 (ton/hr-m2)	12.0 (3.5)
Theoretical specific energy consumption, BTU/lb (kJ/kg)	2,010 (4,675)

TABLE 31: Proposed design No. 3.

DRYING PARAMETER VALUES	SIMULATION
FIRST STAGE	
Drying air temperature, deg. F (deg. C)	250.0 (121.1)
Airflow rate, cfm/ft2 (m3/min-m2)	60.0 (18.3)
Dryer length, ft (m)	3.5 (1.1)
Tempering length, ft (m)	10.0 (3.1)
MCin, percent, wb	12.5
MCout, perc. wb	11.9
SECOND STAGE	
Drying air temperature, deg. F (deg.C. C)	200.0 (93.3)
Airflow rate, cfm/ft2 (m3/min-m2)	60.0 (18.3)
Dryer length, ft (m)	4.5 (1.4)
Tempering length, ft (m)	10.0 (3.1)
MCout, perc. wb	11.0
COOLER	
Airflow rate, cfm/ft2 (m3/min-m2)	45.0 (13.7)
Cooler length, ft (m)	5.0 (1.5)
MCout, perc. wb	10.5
Grainflow rate bu/hr-ft2 (ton/hr-m2)	8.0 (2.4)
Theoretical specific energy consumption, BTU/lb (kJ/kg)	1,859 (4,324)

TABLE 32: Accepted accuracy of the measured parameters in grain dryer design.

MEASURED PARAMETERS	ACCURACY
Moisture content, percent	+/- 0.2
Temperature, deg. F	+/- 1.5
Test wight, lb/ft3	+/- 0.5
Relative humidity, percent	+/- 5.0
Grainflow rate, bu/hr-ft2	+/- 1.0
Airflow rate, cfm/bu	+/-10.0

TABLE 33: Crossflow soybean drying results at the higher and lower limit conditions, using the crossflow proposed design No. 4 - Table 10.

DRYER PARAMETER VALUES	UPPER LIMITS	LOWER LIMITS
Drying air temperature, deg. F (deg. C)	201.5 (94.2)	198.5 (92.5)
Airflow in dryer sec., cfm/bu (m3/min-ton)	55.0 (57.2)	35.0 (36.4)
Airflow in cooler sec., cfm/bu (m3/min-ton)	50.0 (52.0)	30.0 (31.2)
Grainflow rate, bu/hr-ft2 (ton/hr-m2)	48.0 (14.1)	46.0 (13.5)
MCin, perc. wb	12.7	12.3
MCout Stage 4, percent wb	11.6	11.4
MCout Cooler, percent wb	10.4	10.3
Spec.energy consumption, BTU/lb (kJ/kg)	1,554 (3,615)	1,201 (2,794)
Actual spec. energy cons., BTU/lb (kJ/kg)	2,082 (4,844)	1,609 (3,744)

TABLE 34: Concurrentflow soybean drying results at the higher and lower limit conditions, using the concurrentflow proposed design No. 3 - Table 31.

DRYING PARAMETER VALUES	UPPER LIMITS	LOWER LIMITS
FIRST STAGE		
Drying air temperature, deg. F (deg. C)	251.5 (121.9)	248.5 (120.3)
Airflow rate cfm/ft2 (m3/min-m2)	70.0 (21.3)	50.0 (15.2)
MCin, percent wb	12.7	12.3
MCout, perc. wb	12.1	11.8
SECOND STAGE		
Drying air temperature, deg. F (deg. C)	201.5 (94.2)	198.5 (92.5)
Airflow rate cfm/ft2 (m3/min-m2)	70.0 (21.3)	50.0 (15.2)
MCout, perc. wb	11.1	10.9
COOLER		
Airflow rate, cfm/ft2 (m3/min-m2)	55.0 (16.7)	35.0 (10.7)
MCout, perc. wb	10.6	10.5
Grainflow rate, bu/hr-ft2 (ton/hr-m2)	9.0 (2.6)	7.0 (2.1)
Theoretical specific energy consumption,	1,828 (4,253)	1,951 (4,539)

6.4 Fixed-Bed Drying Results

A fixed-bed computer model has been developed and checked against soybean drying data from the literature. The literature data were difficult to duplicate because it was not specified if the test was run continuously or if the fan was shut off at night. Also, hourly weather data for the original drying site in Illinois was not available. Instead, East Lansing weather data for the first 14 days of September, 1974 was used. Hourly data were not available so average ambient air temperature and relative humidity values for those days were employed. The average values were 68.8 F (20.3 C) and 60 percent for the ambient air temperature and relative humidity, respectively.

The experimental and simulated results are presented in Table 35. The results are for a drying bed of 6.0-foot (1.8-m) deep initially at 20.7 percent wet basis and an airflow rate of 1.0 cubic foot per minute per bushel (1.0 m3/min-ton). Although the ambient conditions were approximate, the computer model satisfactorily predicted the experimental soybean moisture content.

The model required 1.88 seconds of computer time to simulate 156-hour drying. The time value is low enough to make the fixed-bed computer model feasible for low-temperature soybean drying simulation.

TABLE 35: Experimental and simulated results for a 6.0-foot soybean fixed-bed drying system.

LAYER No.	EXPERIMENTAL	SIMULATED
1	9.5	10.0
2	10.0	10.7
3	11.0	11.9
4	13.7	13.3
5	18.0	14.9
6	19.0	16.4
7	19.3	17.8
8	19.4	18.9
9	19.4	19.7
10	19.7	20.2
11	19.9	20.3
AVERAGE	16.2	15.8

The Fixed-Bed computer model was used to speculate on the feasibility of low-temperature drying in Brazil. Monthly weather data for 1978 for the State of Parana (a major soybean producing State) was employed. The average temperature during the harvest season was 60.6 F (15.9 C) and the ambient relative humidity, 77 percent.

Drying of a 12.0-foot (3.7-m) deep bed of soybeans was simulated using an airflow rate of 1.0 cubic foot per minute per bushel (1.0 m3/min-ton). The ambient air was increased to 65.0 F (18.3 C). After 14 days (336 hours) of drying at 65.0 F and after 2 days (48 hours) of natural air drying the average bed moisture content was predicted to be 12.0 percent and the top bean layer 15.5 percent wet basis. A similar soybean drying test was simulated using 68.0 F (20.0 C) as the drying air temperature. After 12 days (288 hours) of 68.0 F drying and 2 days (48 hours) of natural air drying the average bed moisture content was 10.1 percent and the top bean layer was at 13.7 percent wet basis. A combination of the two previous runs was then simulated. During the first 4 days (96 hours) the drying air temperature was increased to 68.0 F (20.0 C). In the next 6 days (144 hours) 65.0 F (18.3 C) was used. After these 10 days of drying, natural air was employed for 2 days (48 hours). The airflow rate was increased to 1.5 cubic feet per minute per bushel (1.6 m3/min-ton) in this test. The final average moisture content of the soybean bed was 9.8 percent and the top soybean layer was at 12.0 percent moisture content. The results for these three tests are summarized in Table 36.

TABLE 36: Predicted soybean moisture content in a 12-foot bed, initially at 20.0 percent wet basis.

LAYER No.	TEST No.1	TEST No.2	TEST No.3
1	11.2	9.9	9.4
2	10.7	9.0	8.9
3	10.7	8.9	9.0
4	10.7	8.9	9.1
5	11.0	9.0	9.2
6	11.4	9.4	9.5
7	12.1	9.9	9.9
8	13.0	10.7	10.4
9	14.0	11.8	11.0
10	15.0	13.0	11.7
11	15.5	13.7	12.0
MCaverage, perc	12.0	10.1	9.8
Drying time, hours	384.0	336.0	288.0
Drying time, days	16.0	14.0	12.0
Drying temperature, deg. F	65.0	68.0	65.0/68.0

CHAPTER 7

C O N C L U S I O N S

Soybean drying in continuous-flow dryers and fixed-bed systems has been investigated. The conclusions drawn from this study follow.

7.1 Crossflow Drying

1. The ideal airflow rate for crossflow soybean drying is on the order of 40.0 to 50.0 cubic feet per minute per bushel (41.6 to 52.0 m3/min-ton). These values are much lower than those presently used in the tested commercial dryers.

2. Increasing the airflow rate in the cooling stages to a value similar to that in the drying sections increases the amount of water removed during cooling, thus increasing the dryer thermal efficiency.

3. Tempering (steeping) is highly desirable in crossflow soybean drying. Tempering allows moisture redistribution inside the soybean kernels and consequently

easies the removal of moisture in subsequent drying.

4. By converting the fifth and third sections from drying stages into tempering stages in the FR-3000, savings of 39.8 percent in specific energy consumption are predicted when soybean drying from 12.1 to 10.5 percent wet basis was simulated.

5. If the FR-3000 airflow rate is reduced from 83. to 45. cubic feet per minute per bushel (86.4-46.8 m3/min-ton) in the drying stages and increased from 23. to 45. cubic feet per minute per bushel (23.9-46.8 m3/min-ton) in the cooling stages and, if the cooler height is increased from 15.7 to 23.5 feet (4.8-7.2 m), the amount of fuel consumed in the soybean drying process (from 12.1 to 10.5 percent wet basis) is expected to be reduced by 35.7 percent.

6. The implementation of the two previous saving features in the FR-3000 is expected to result in energy savings of 67.9 percent.

7. If efficient soybean crossflow dryers are made available to the American soybean processing industry it will be possible to save over $30 million dollars per year with drying at 1981 fuel prices.

7.2 Concurrentflow Drying

1. The ideal airflow rate for concurrentflow soybean drying at low initial moisture contents (around 12.5 percent wet basis) is on the order of 45. to 60. cubic feet per minute per square foot (13.7-18.3 m3/min-m2). These values are much lower than those presently used in concurrentflow corn dryers.

2. Tempering (steeping) is highly desirable in concurrentflow soybean drying. It is recommended that the use of a 10-foot (3.1-m) tempering zone after each drying section in concurrentflow soybean dryers is considered.

3. Soybeans may be dried at temperatures as high as 400 F (204.4 C) in a three-stage concurrentflow dryer without a significant reduction in the product quality (germination, cracks, and splits).

4. The combination of drying air temperature and product flow rate are the factors affecting the soybean quality in concurrentflow drying.

5. The total airflow rate requirements for concurrentflow soybean drying is lower than for crossflow soybean drying and lower than for concurrentflow corn drying.

6. Although the best germination percentage experimentally obtained (71 percent) is low if the soybeans are to be used as seed, soybeans may be dried for seed in a multi-stage concurrentflow dryer if fine tunning is accomplished in the drying air temperature and soybean flow rate relationship.

7.3 Fixed-Bed Drying

1. The new version of the MSU Fixed-bed Drying Model is highly efficient in terms of computer time requirement. 1.88 computer seconds were required to simulate 156 hours of soybean drying on a CYBER 750 computer.

2. The new version of the MSU Fixed-Bed Drying Model is suitable for use in the optimization of on-farm stationary drying systems.

3. Low-temperature drying of soybeans is feasible in Brazil if the ambient air temperature is raised by 5.0 to 8.0 F (2.8-4.4 C) and the airflow rate is increased to 1.5 cubic feet per minute per bushel (1.6 m3/min-ton).

CHAPTER 8

SUGGESTIONS FOR FURTHER STUDIES

1. The inclusion of optimization subroutines in the computer simulation programs must be considered. These built-in optimization capabilities will greatly increase the flexibility of the computer programs for design purposes.

2. Soybean dryer prototypes designed through similitude will permit faster experimental tests of the designs proposed by simulation than on-site tests usually possible only during the crop harvesting season.

3. On-farm soybean drying tests are necessary to more accurately determine the drying parameters necessary in design and simulation.

REFERENCES

REFERENCES

Ahmadnia, A. 1977. The quality of soft wheat dried in a concurrent-countercurrent dryer. Special Report. Michigan State University: East Lansing, Michigan.

Alam, A. 1972. Drying simulation of soybeans. Unpublished Ph.D. thesis. University of Illinois: Urbana, Illinois.

Alam, A. and Shove, G. 1973. Hygroscopicity and thermal properties of soybeans. Transactions of the ASAE 16(4):707-709 .

Bakker-Arkema, F. W., Brook, R. C., and Brooker, D. B. 1978. Energy and capacity performance evaluation of grain dryers. ASAE Paper No. 78-3523 . Am. Soc. Agr. Eng.: St. Joseph, Michigan.

Bakker-Arkema, F. W., Brook, R. C., and Lerew, L. E. 1978. Cereal grain drying. In: Advances in Cereal Science and Technology, ed. by Y. Pomeranz, pp 1-90. American Association of Cereal Chemists, Inc.: St. Paul, minnesota.

Bakker-Arkema, F. W., Brooker, D. B., and Hall, C. W. 1972. Comparison evaluation of crossflow and concurrentflow grain dryers. ASAE Paper No. 72-849 . Am. Soc. Agr. Eng.: St. Joseph, Michigan.

Bakker-Arkema, F. W., Brooker, D. B., and Roth, M. G. 1977. Feasibility study of in-bin corn drying in Missouri using solar energy. USDA Special Report.

Bakker-Arkema, F. W., Dalpasquale, V. A., Stevenson, B. C., and Naylor, J. L. 1980. Commercial Drying of soybeans for processing. ASAE Paper No. 80-3555 . Am. Soc. Agr. Eng.: St. Joseph, Michigan.

Bakker-Arkema, F. W., Fosdick, S., and Naylor, J. L. 1979. Testing of commercial crossflow grain dryers. ASAE Paper No. 79-3521 . Am. Soc. Agr. Eng.: St. Joseph, Michigan.

Bakker-Arkema, F. W. and Hall, C. W. 1965. Static versus dynamic moisture equilibria in the drying of biological products. Journal of the Agr. Eng. Res. 10(2):308-311 .

Bakker-Arkema, F. W., Lerew, L. E., DeBoer, S. F., and Roth, M. G. 1974. Grain Dryer Simulation. Research Report 224. Agr. Exp. Sta., Michigan State University: East Lansing, Michigan.

Bakker-Arkema, F. W., Sokhansanj, A. A., and Green, R. 1977. High temperature wheat drying. ASAE Paper No. 77-3527 . Am. Soc. Agr. Eng.: St. Joseph, Michigan.

Barre, H. J. 1976. Storage and grain quality control of soybeans on the farm. World Soybean Research, ed. by L. D. Hill. The Interstate Printers and Publishers, Inc.: Danville, Illinois.

Bauer, W. W., Walker, L. P., and Bakker-Arkema, F. W. 1977. Testing of a commercial sized conventional crossflow and modified crossflow grain dryers. ASAE Paper No. 77-3014 . Am. Soc. Agr. Eng.: St. Joseph, Michigan.

Bloome, P. D. 1969. Drying shelled corn with ambient air - a computational model. Unpublisehd Ph.D. thesis, University of Illinois: Urbana, Illinois.

Blount Agribussines. 1981. Commercial brochure.

Brook, R. C. 1977. Design of multistage grain dryers. Unpublished Ph.D. thesis, Michigan State University: East Lansing, Michigan.

Brook, R. C. and Bakker-Arkema, F. W. 1977. Design of multi-stage grain dryers using computer optimization. ASAE Paper No. 77-3529 . Am. Soc. Agr. Eng.: St. Joseph, Michigan.

Brook, R. C. and Bakker-Arkema, F. W. 1980. Design of multi-stage corn dryers using computer optimization. Transactions of the ASAE 23(1):200-203 .

Brooker, D. B., Bakker-Arkema, F. W., and Hall, C. W. 1974. Drying Cereal Grains. AVI: Westport, Connecticut.

Brooker, D. B., McKenzie,B. A., and Johnson, H. K. 1978. Thr present status of on-farm grain drying. ASAE Paper No. 78-3007 . Am. Soc. Agr. Eng.: St. Joseph, Michigan.

Byg, D. M. and Johnson, W. H. 1970. Reducing soybean harvest losses. Ohio Report 35(1):17-18.

Chanchai, R., White, G. M., Loewer, O. J., and Engli, D. B. 1976. Influence of heated air drying on soybean impact. Transactions of the ASAE 19(2):372-377 .

Carrano, J.F. 1970. High temperature continuous flow grain drying with concurrent drying and countercurrent cooling. Unpublished M.S. thesis, Michigan State University: East Lansing, Michigan.

Carver, M. B. 1976. The choice of algorithms in automated method of lines solution of partial differential equations. In: Numerical Methods for Differential Systems, ed. by L. Lapidus and W. E. Sciesser. Academic Press, New York, NY.

Converse, J. O. 1972. A commercial cross-flow grain dryer: The Hart-Carter dryer. ASAE Paper No. 72-828 . Am. Soc. Agr. Eng.: St. Joseph, Michigan.

Crank, J. 1979. The Mathematics of Diffusion. 2nd ed., Clarendon Press: Oxford, England.

Dalpasquale, V. A. 1979. Continuous-flow drying of soybeans. Unpublished M.S. thesis, Michigan State University: East Lansing, Michigan.

Delouche, J. C. 1975. Seed quality and storage of soybeans. Soybean Production, Protection, and Utilization, ed. by D. K. Whingham. University of Illinois: Urbana, Illinois.

Family, A., Huber, S. G., Holmer, R. G., and Herum, F. L. 1980. Effect of compression strain on soybean seed quality. ASAE Paper No. 80-3540 . Am. Soc. Agr. Eng.: St. Joseph, Michigan.

Farmer, D. M., Bakker-Arkema, F. W., DeBoer, S. F., and Roth, M. G. 1972. Simulation and optimum design of a commercial concurrent-counterflow grain dryer - the Anderson model. ASAE Paper No. 72-847 . Am. Soc. Agr. Eng.: St. Joseph, Michigan.

Gustafson, R. J. and Morey, R. V. 1980. Moisture and quality variations across the column of a crossflow grain dryer. ASAE Paper No. 80-3513 . Am. Soc. Agr. Eng.: St. Joseph, Michigan.

Gygax, R. A., Diaz, A., and Bakker-Arkema, F. W. 1974.

Comparison of commercial crossflow and concurrent flow dryers with respect to grain damage. ASAE Paper No. 74-3021 . Am. Soc. Agr. Eng.: St. Joseph, Michigan.

Haghighi, K. and Segerlind, L. J. 1978. Computer simulation of the stress cracking of soybeans. ASAE Paper No. 78-3560 . Am. Soc. Agr. Eng.: St. Joseph, Michigan.

Hall, G. E. 1974. Damage during handling of corn and soybeans. Transactions of the ASAE 17(2):335-338 .

Hamdy, M. Y. and Barre, H. J. 1970. Analysis of hybrid simulation of deep-bed drying of grain. Transactions of the ASAE 13(4):752-757 .

Hawk, A. L., Noyes, R. T., Westelaken, C. M., Foster, G. H., and Bakker-Arkema, F. W. 1978. The present status of commercial grain drying. ASAE Paper No. 78-3008 . Am. Soc. Agr. Eng.: St. Joseph, Michigan.

Herderson, S. M. 1952. A basic concept of equilibrium moisture. Agr. Eng 33(1):29-31.

Holman, J. P. 1976. Heat Transfer. 4th ed., McGraw-Hill, New York, New York.

Holmer, L. E. and Carter, D. G. 1952. Soybean storage in farm-type bins. Illinois Agr. Exp. Sta., Bulletin 553.

Hukill, W. V. 1947. Basic principles in drying corn and grain sorghum. Agricultural Engineering 28(8):335-338.

Jornal da Armazenagem. 1980. Centreinar 1(4):1-12.

Kalchik, S. V. 1977. Drying soybeans in a pilot scale concurrent flow dryer. Unpublished M.S. thesis, Michigan State University: East Lansing, Michigan.

Kalchik, S. V., Silva, J. S., Bakker-Arkema, F. W., and Miller, B. S. 1979. An engineering-economic comparison of five drying techniques for shelled corn on Michigan farms. ASAE Paper No. 79-3518 . Am. Soc. Agr. Eng.: St. Joseph, Michigan.

Keener, H. M. ang Glenn, T. L. 1978. Measuring performance of grain drying systems. ASAE Paper No. 78-3521 . Am. Soc. Agr. Eng.: St. Joseph, Michigan.

Kline, D. P. 1977. Design of a pilot-scale concurrent flow grain dryer. Unpublished M. S. thesis, Michigan State University: East Lansing, Michigan.

Lerew, L. E. 1972. A FORTRAN psychrometric model. Unpublished M. S.. thesis, Michigan State University: East Lansing, Michigan.

Lerew, L. E., Bakker-Arkema, F. W., and Brook, R. C. 1972. Simulation of a commercial crossflow dryer - The Hart-Carter model. ASAE Paper No. 72-829 . Am. Soc. Agr. Eng.: St. Joseph, Michigan.

Madison, M. 1980. Personal communication.

Matthes, R. K. and Welch, G. B. 1974. Heated air drying of soybean seed. ASAE Paper No. 74-3001 . Am. Soc. Agr. Eng.: St. Joseph, Michigan.

Mensah, J. K., Nelson, G. L., Hamdy, M. Y., and Richard, T. G. 1980. A mathematical model for predicting seedcoat cracking during drying. ASAE Paper No. 80-3060 . Am. Soc. Agr. Eng.: St. Joseph, Michigan.

McAdams, W. H. 1954. Heat Transmission. McGraw-Hill,New York, New York.

Miller, B. S., Hughes, J. W., and Pomeranz, Y. 1979. Measuring breakage susceptibility of soybeans. ASAE Paper No. 79-3560 . Am. Soc. Agr. Eng.: St. Joseph, Michigan.

Milner, M. and Geddes, W. F. 1946. The relation between moisture content, mold growth and respiration of soybeans. Cereal Chemistry 23:225-245.

Misra, R. N. and Young, J. H. 1978. Finite element analysis of simultaneous moisture diffusion and shrinkage of soybeans during drying. ASAE Paper No. 78-3056 . Am. Soc. Agr. Eng.: St. Joseph, Michigan.

Misra, R. N. and Young, J. H. 1980. Numerical solution of simultaneous moisture diffusion and shrinkage during soybean drying. Transactions of the ASAE 23(3):1277-1282 .

Morey, R. V. and Cloud, H. A. 1973. Simulation and evaluation of a multiple column crossflow grain dryer. Transactions of the ASAE 16(5):984-987 .

Muhlbauer, W., Kuppinger, H., and Isaacs, G. W. 1978. Design and operating conditions of single-stage concurrent flow and two-stage concurrent-counter flow grain dryers. Appendix - B2. Am. Soc. Agr. Eng.: St. Joseph, Michigan.

Muhlbauer, W., Scheuermann, A., and Blumel, K. 1971. Drying of corn in a concurrentflow dryer at high air temperatures. Grundlagen Landtechnic 21(1):1-5.

Ngoddy, P. O., Bakker-Arkema, F. W., and Bickert, W. G. 1966. Heat transfer in a deep bed of peabeans. Quart. Bull. Mich. Agr. Exp. Sta. 49:132-143.

Overhults, D. G., White, G. M., Hamilton, H. E., and Ross, I. J. 1973. Drying soybeans with heated air. Transactions of the ASAE 16(1):112-113 .

Othmer, D. F. 1940. Correlation vapor pressure and latent heat data. Ind. Eng. Chem. 32:841-846.

Pabis, S. and Henderson, S. M. 1961. Grain drying theory: II. A critical analysis of the drying curve for shelled maize. Journal of the Agr. Eng. Res. 6(3):272-277 .

Paulsen, M. R. 1978. Fracture resistance of soybeans to compressive loading. Transactions of the ASAE 21(6):1210-1216 .

Paulsen, M. R. and Thompson, T. L. 1973. Effects of reversing the airflow in a crossflow grain dryer. Transactions of the ASAE 16(3):541-545 .

Pfost, D. L. 1975. Environmental and varietal factors affecting damage to seed soybeans during drying. Unpublished Ph.D. thesis, The University of Ohio: Columbus, Ohio.

Pfost, H. B., Maurer, S. G., Chung, D. S., and Milliken, G. A. 1976. Summarizing and reporting equilibrium moisture data for grains. ASAE Paper No. 76-3520 . Am. Soc. Agr. Eng.: St. Joseph, Michigan.

Pinheiro Filho, J. B. 1976. An experimental study of the effect of intermittent drying of soybeans on quality and rate of drying. Unpublished Ph.D. thesis, Purdue University: West Lafayette, Indiana.

Ramstad,P. E. and Geddes, W. F. 1942. The respiration and storage of soybeans. Minnesota Agr. Exp. Sta., Technical Bulletin 156.

Roa, G., Fioreze, R., Rossi, S. J., and Villa, L. G. 1977. dynamic estimation of thin-layer drying parameters. ASAE Paper No. 77-3530 . Am. Soc. Agr. Eng.: St. Joseph, Michigan.

Roa, G. and Macedo, I. C. 1976. Drying of carioca dry beans with solar energy in a stationary bin. ASAE Paper No. 76-3021 . Am. Soc. Agr. Eng.: St. Joseph, Michigan.

Roberts, D. E. and Brooker, D. B. 1975. Grain drying with a recirculator. Transactions of the ASAE 18(1):181-183 .

Rodda, E. D. 1974. Soybean drying-seed, food, feed. ASAE Paper No. 74-3540 . Am. Soc. Agr. Eng.: St. Joseph, Michigan.

Rodda, E. D. and Ravalo, E. J. 1978. Soybean seed storage under constant and ambient tropical conditions. ASAE Paper No. 78-7002 . Am. Soc. Agr. Eng.: St. Joseph, Michigan.

Rodda, E. D., Ravalo, E. J., Tenne, F. D., and Sinclair, J. B. 1980. Tropical storage of US certified soybean seed. Transactions of the ASAE 23(2):398-402 .

Rodrigues-Arias, J. H. 1956. Description isotherms and drying rates of shelled corn in the temperature range of 40 to 140 F. Unpublished Ph.D. thesis, Michigan State University: East Lansing, Michigan.

Rossi, S. J. and Roa, G. 1980. Secagem e armazenamento de produtos agropecuarios com uso de energia solar e ar natural. Academia de Ciencia do Estado de Sao Paulo: Sao Paulo, Sao Paulo.

Sabbah, M. A., Meyer, G. E., Keener, H. M., and Roller, W. L. 1976. Reversed-air drying for fixed bed of soybean seed. ASAE Paper No. 76-3023 . Am. Soc.

Agr. Eng.: St. Joseph, Michigan.

Sabbah, M. A., Meyer, G. E., Keener, H. M., and Roller, W. L. 1977. Reversed-direction airflow drying for soybean seed. Transactions of the ASAE 20(3):562-566 .

Sabbah, M. A., Meyer, G. E., Keener, H. M., and Roller, W. L. 1979. Simulation studies of reversed-direction airflow drying method for soybeans. Transactions of the ASAE 22(5):1162-1166 .

Silva, J. S. and Dalpasquale, V. A. 1979. Personal communication.

Soya Bluebook, 1980. American Soybean Association, 186 p.

Ting, K. C., White, G. M., and Loewer, O. J. 1978. Seed coat damage in deep bed drying of soybeans. ASAE Paper No. 78-3006 . Am. Soc. Agr. Eng.: St. Joseph, Michigan.

Ting, K. C., White, G. M., Ross, I. J., and Loewer, O. J. 1980.. Seed coat damage in deep bed drying of soybeans. Transactions of the ASAE 23(5):1293-1296 .

Thompson, T. L. 1967. Predicted performance and optima designs of convection grain dryers. Unpublished Ph.D. thesis, Purdue University: West Lafayette, Indiana.

Thompson, T. L., Foster, G. H., and Peart, R. M. 1969. Comparison of concurrent flow, crossflow, and counter flow drying methods. USDA Mkt. Res. Rep. 841.

Walker, L.P. 1978. Process analysis of a multistage concurrent rice dryer. Unpublished Ph.D. thesis, Michigan State University: East Lansing, Michigan.

Wang, J. K. and Hall, C. W. 1961. Moisture movement in hygroscopic materials. Transactions of the ASAE 4(1):33-36 .

Watts, K. C. and Bilanski, W. K. 1970. Calorimetric determination of the specific heat of soybeans. Canadian Agricultural engineering 12(1):45-47,56.

Westelaken, C. M. and Bakker-Arkema, F. W. 1978.

Concurrent-flow grain drying. ASAE Paper No. 78-0712 . Am. Soc. Agr. Eng.: St. Joseph, Michigan.

Whitaker, T. B., Barre, H. J., and Hamdy, M. Y. 1969. Theoreticall and experimental studies of diffusion in spherical bodies with a variable diffusion coefficient. Transactions of the ASAE 12(3):668-672 .

White, G. M., Bridges, T. C., Loewer, O. J., and Ross, I. J. 1978. Seed coat damage in thin-layer drying of soybeans as affected by the drying conditions. ASAE Paper No. 78-3052 . Am. Soc. Agr. Eng.: St. Joseph, Michigan.

White, G. M., Bridges, T. C., Loewer, O. J., and Ross, I. J. 1980. Seed coat damage in thin-layer drying of soybeans. Transactions of the ASAE 23(1):224-2277 .

White, G. M., Loewer, O. J., Ross, I. J., and Egli, D. B. 1976. Storage characteristics of soybeans dried with heated air. Transactions of the ASAE 19(2):306-310 .

Young, J. H. and Whitaker, T. B. 1971. Evaluation of the diffusion equation for describing thin-layer drying of peanuts in the hull. Transactions of the ASAE 14(2):309-312 .