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thesis entitled

PROCESS ANALYSIS OF A MULTISTAGE
CONCURRENT RICE DRYER

presented by

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has been accepted towards fulfillment
of the requirements for

Ph. D. degree in Agricultural Engineering

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Date Nov. 8, 1978

PROCESS ANALYSIS OF A MULTISTAGE CONCURRENT RICE DRYER

By

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A DISSERTATION

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

DOCTOR OF PHILOSOPHY

Agricultural Engineering Department

1978

ABSTRACT

PROCESS ANALYSIS OF A MULTISTAGE CONCURRENT RICE DRYER

By

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Rice, like most cereal grains is usually harvested at a moisture content too high for safe storage. This generates a need for artificial drying. The drying process is complicated by the susceptibility of rice to checking and breaking during drying and subsequent milling.

The current multipass procedure of drying and tempering rice in bins for 4 to 24 hours requires a large number of bins for wet storage and a substantial amount of material handling. From a logistical point of view, it is advantageous to complete the drying process in one operation, thus reducing the number of bins needed for wet storage, decreasing the handling of the rice, and improving the energy efficiency of the entire drying process.

The purpose of this investigation was to evaluate the physical feasibility of drying rice in a multistage concurrent flow dryer to determine the operating characteristics of such a dryer. This objective was achieved by conducting a series of pilot scale experiments with a one-stage concurrent flow dryer and by developing computer models to simulate a multi-stage concurrent flow dryer.

The results show that: (1) rice can be dried in a one-stage concurrent flow dryer at temperatures as high as 121°C without any significant decrease in head yield, provided that the grain flow is 0.17 m^3/hr and the air flow 2.27 m^3/min; (2) under constant drying conditions higher initial moisture content results in a higher moisture removal rate and energy efficiency, and a lower grain temperature; (3) an increase in the initial grain temperature under constant drying conditions results in an increase in the moisture removal rate, higher grain temperatures, and higher energy efficiencies; (4) under constant drying conditions, an increase in the drying air temperature results in an increase in the moisture removal rate and maximum grain temperature, and a reduction in energy required to remove a pound of water if there is not a corresponding increase in grain flow; (5) both air flow and grain flow can be used to control grain temperatures and moisture gradients; (6) an increase in the bed depth results in an increase in the moisture removed, a lowering of head yield, and a more uniform final moisture distribution; (7) tempering does not significantly improve the drying rate of rice in a concurrent flow dryer because rice dried in a concurrent flow dryer has a fairly uniform final moisture distribution; (8) drying rice in a concurrent flow dryer generally results in acceptable head yield, because of the uniform moisture distribution.

To Tina

ACKNOWLEDGEMENTS

It has been a great privilege to work under the guidance of Dr. Fred W. Bakker-Arkema. Through his example I have become aware of my social and professional responsibilities. His friendship, counsel, and understanding will always be remembered.

I would like to thank Dr. James V. Beck, Dr. Larry J. Connors, and Dr. Bill A. Stout for serving on my guidance committee. Their advice and encouragement were very helpful.

I would also like to thank Dr. James B. Hamilton, Dr. Gerald L. Parks, Mr. Roland Lartigue, and Dr. Lloyd E. Lerew for their encouragement and moral support.

Special thanks goes to Mr. Dave Calderwood of ARS-USDA, Beaumont, Texas, for his technical assistance, and Westelaken Agricultural Engineering, St. Marys, Ontario, Canada, for their financial support.

I offer my gratitude to my parents, Joe and Christine Fowlkes, and my grandmother, Mrs. Empheus Jeffery. Their love, encouragement, and moral support helped me through some of the difficult moments.

Finally, I would like to thank my wife, Tina, for her love and understanding during these last difficult months. Her warm smile made the task a little easier.

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LIST OF SYMBOLS

Symbols

a	Specific product surface area, m^2/m^3
C_a	Specific heat of air, KJ/Kg
C_p	Specific heat of dry grain, KJ/Kg
C_v	Specific heat of water vapor, KJ/Kg
C_w	Specific heat of water, KJ/Kg
D	Diffusion coefficient, cm^2/hr
D_p	Product diameter, m
G_a	Air flow rate, Kg/hr m^2
G_p	Grain flow rate, Kg/hr m^2
h_c	Convective heat transfer coefficient KJ/m^2
h_D	Convective mass transfer coefficient, cm/hr
h_{fg}	Heat or evaporation, KJ/Kg
H	Humidity ratio, Kg/Kg
j	Phenomenological coefficient
K	Phenomenological coefficient
L	Length, m
$\bar{M}$	Average moisture content, % w.b.
M	Local moisture content, decimal d.b.
M_e	Equilibrium moisture content, decimal d.b.
M_i	Initial moisture content, % w.b.

Symbol

$\bar{M}_o$	Final moisture content, % w.b.
M_s	Surface moisture content, decimal d.b.
M_R	Moisture removed, % w.b.
P_v	Vapor pressure, Kgf/cm^2
P_{sv}	Saturated vapor pressure, Kgf/cm^2
R	Radius of rice, cm
r	Radius, cm
S	Surface area of grain, m^2
T	Air temperature, °C
T_e	Entering air temperature, °C
$T_{\bar{w}}$	Wetbulb temperature, °C
T_{abs}	Absolute air temperature, °K
t	Time, hours
V	Volume, m^3
V_G	Grain velocity, m/hr
y	Phenomenlogical coefficient
α'	Phenomenlogical coefficient
α^*	Phenomenlogical coefficient
β_1	Phenomenlogical coefficient
χ	Non-dimensional time
x	Variable bed depth, m
$\underline{\bar{X}}$	Bed depth, m

I. INTRODUCTION

1-1 General remarks

Mankind's potential to evaluate and solve complex scientific and engineering problems expanded tremendously with the birth of the computer era. Operation research and system analysis are some of the problem solving methodologies that developed with the advent of the computer. Although these methodologies differ in some respect and have different meanings for different disciplines they all have the following objectives: (1) exact specification of the problem, (2) detailed analysis, and (3) development of a viable solution.

Operation research, system and process analysis differ from classical analysis in that they focus on the interaction or interdependencies of components and not just the components themselves. They are based on the premise that the "whole is more than the sum".

Both, the terms system science and process analysis are used by engineers to refer to the scientific methodology described above. Process analysis seems to be the most appropriate for this rice drying investigation because the term process denotes an actual series of operations or treatments of material in contrast to the more abstract term system.

The rice drying process is a complex interaction between the grain and air. Like most processing problems, the analysis of rice drying entails: (1) mathematical specification of the problem for a given physical situation, (2) detailed analysis to obtain mathematical models, (3) synthesis of discrepancies between theoretical and experimental results, and (4) development of procedures for obtaining viable solutions.

Dryer manufacturers and design engineers are depending more and more on computer models to evaluate preliminary designs and to gain better insights for making improvements in their current equipment. This is particularly important in light of the increased interest in grain quality and energy efficiency.

Often the design parameters and operating characteristics of a process can be obtained from field experimentation. However, this approach is costly in time and money. Mathematical modeling and simulation are an economical means of experimentation. In addition, it provides a means to explore extreme ranges of operation which may seem impractical or be impossible to obtain in the field. Also, a set of alternative designs and operating policies can easily be generated when new factors or elements are introduced into the system.

1-2 History of U. S. rice market

The birth of the U. S. rice industry can be traced back to 1685. From a bag of rice given to Dr. Henry Woodward, the Carolina Gold Variety was established (Pratt, 1960). Rice was primarily grown in the south-central states until 1890. The four Atlantic Coast states produced 96 percent of the domestic rice supply by 1856. This was reduced to 77 percent by 1879 and to 27 percent by 1899. Currently, less than 6 percent is grown in that region.

From 1884 to 1886 trial plantings of rice were made in the prairie section of southwest Louisiana (Adair, 1972). The plantings revealed that the crop was well adopted to this area. Production increased rapidly in southwest Louisiana and southeast Texas. Rice production in Arkansas did not become an important industry until 1904. Rice was grown on an experimental basis in California in 1909 and rapidly became established as a commercial crop by 1912. Table 1-1 indicates the rice growing area of the U. S. in 1977.

Commercial varieties of rice grown in the U. S. are classified and marketed under three market classes, long grain, medium grain, and short grain. At present, long-grain rice is grown primarily in the southern states and practically all short-grain rice is produced in California. Medium-grain rice is grown in all U. S. rice production areas (Adair, 1972).

The average annual U. S. production for the five years ending in 1899 was 154,200 metric tons (Adair, 1972). The average for the five-year period ending in 1949 was over 1,600,000 metric tons. By 1969 the 5-year average was 4,071,000 metric tons, better than double that of 1949. Production in 1976 was approximately 5,610,000 metric tons (USDA, 1976).

The domestic rice consumption can be divided into four main areas: (1) direct food use, (2) food processing use, (3) industrial use, and (4) feed and seed use. Currently 69 percent of the domestic rice consumption is used for food, 23 percent for industrial use and 8 percent for seed (USDA, 1976). Domestic use for 1976/1977 is expected to be about 1.94 million metric tons (USDA, 1976). The U. S. is the number one rice exporter in the world.

Table 1-1. Rough rice crop acreage, yield and production, by states, 1977.

State	Area ha	Yield kg/ha	Production million metric tons
Arkansas	322,541	5,267	1.699
California	138,406	6,051	0.8377
Louisiana	193,444	4,147	0.8022
Mississippi	42,088	4,875	0.2052
Missouri	5,261	5,896	0.0259
Texas	189,397	4,931	0.9765
United States	891,137	5,101	4.467

Source: USDA (1977)

1-3 Traditional method of rice drying

Rice is usually harvested at a moisture content too high for safe storage (Schmidt and Jebe, 1959). This generates a need for artificial drying prior to storage. Rice drying is complicated by the product's susceptibility to checking and breaking during drying and subsequent milling. Because rice is eaten whole its market value decreases as the proportion of broken grains in a sample increases.

To prevent checking and breaking of the kernel, rice has traditionally been dried in three to five stages or passes. In each stage the rice passes through the dryer and then is allowed to temper in a bin from 4 to 24 hours, to allow time for the moisture in the kernel to redistribute. Most of the rice crop in the U. S. is dried at commercial drying installations or rice mills in continuous-flow dryers by this multipass or multistage method (Wasserman and Calderwood, 1972).

There are a variety of grain dryer designs on the market. Basically, the designs fall into four categories: (1) the fixed bed dryer, (2) the crossflow dryer, (3) the concurrent flow dryer, and (4) the cascade type (Bakker-Arkema et al., 1974). Of the four designs, the concurrent flow dryer seems to have the best operating characteristics for rice drying. It can be operated at a higher temperature than fixed beds, crossflow and cascade dryers resulting in a higher thermal efficiency without excessive grain damage. Uniform drying is also achieved in a concurrent flow dryer because there is no moisture gradient across the bed perpendicular to the direction of flow, as is the case for crossflow dryers (Brooker et al., 1974). Thus, each kernel receives the same treatment in a concurrent flow dryer.

The current multipass procedure of drying the rice and tempering in bins for 4 to 24 hours requires a large number of bins for wet storage and a substantial amount of material handling. From a logistical point of view, it would be desirable to complete the drying and tempering process in one operation, thus, reducing the number of bins needed for wet storage, decrease the handling of the rice and improve the energy efficiency of the entire operation. This objective can be achieved with a multistage-concurrent flow dryer.

Figure 1-1 is a schematic of a multistage-concurrent flow dryer. Each drying stage with the exception of the last one is followed by a tempering section. The final stage is followed by a counterflow cooler.

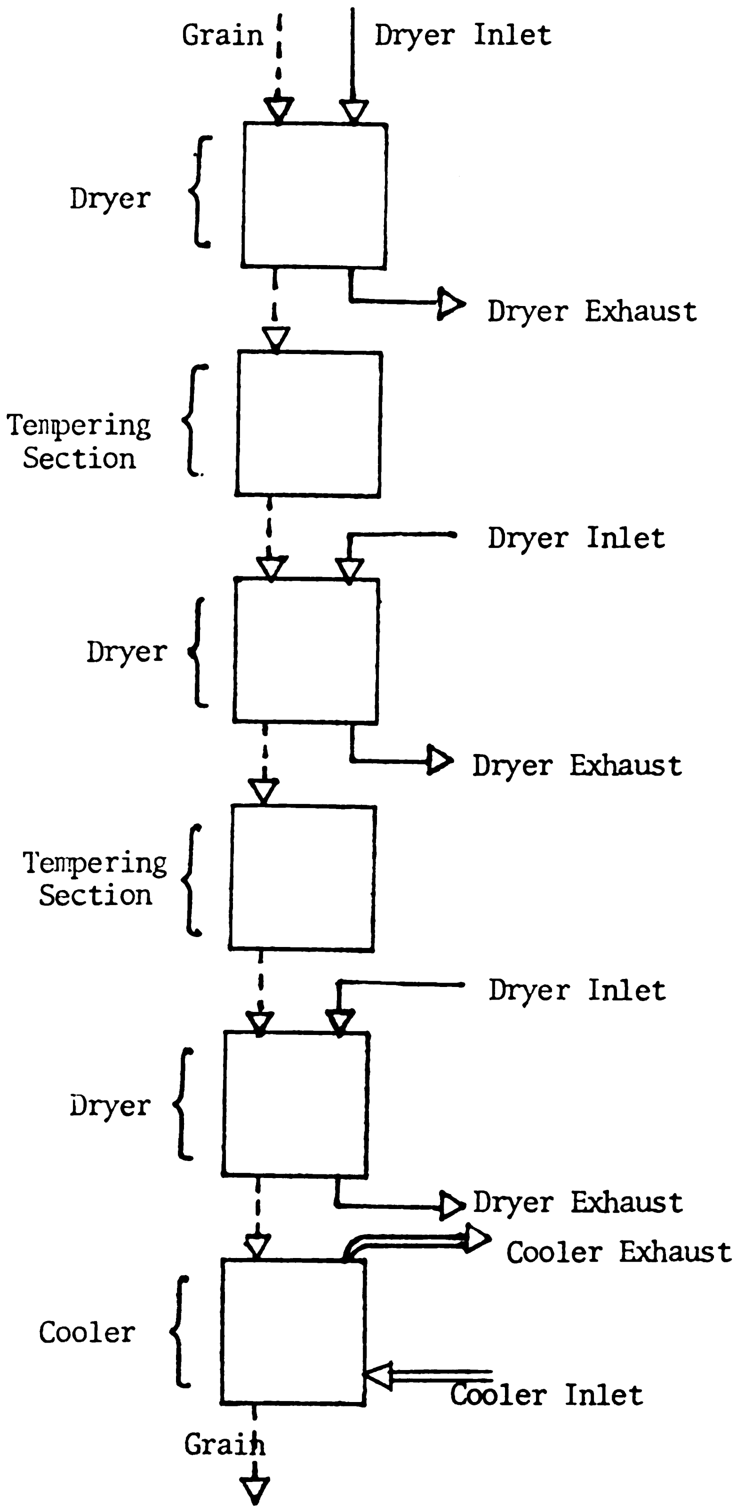


Figure 1-1. Schematic of multistage concurrent flow dryer.

The concurrent flow dryer was selected for this study because of the characteristic noted earlier. The purpose of this study is to evaluate the feasibility and operating characteristics of a multi-stage-concurrent flow dryer.

II. LITERATURE REVIEW

In view of the enormous amount of literature on dryers and the drying process, it is not possible to completely cover the topic. Instead, the principal models and theories which have been advanced to describe the single layer and deep bed drying and the tempering processes will be examined. An understanding of these processes is essential for the mathematical specification of the rice drying problem and for assessing the impact of these two processes on the energy efficiency of the dryer and the checking or cracking of the rice.

2-1 Constant vs. falling rate drying

In some biological products the moisture content is high enough to maintain a free water surface. The drying process under this condition is governed by heat and mass transfer between the water surface and the drying medium and is independent of the material (Allen, 1960). Drying under these conditions proceeds at a constant rate until the surface moisture is removed.

The constant rate drying period is followed by a falling rate period. During the falling rate period moisture transfer at the surface of the kernel is greater than the moisture movement through the interior of the kernel. This results in a decreasing rate of moisture removal. Rice and other cereal grains usually dry solely during the falling rate period (Brooker et al., 1974).

2-2 Drying equation

Essential to any dryer simulation is a single kernel or thin-layer drying equation that predicts moisture removal rates as a function of the drying variables. A substantial portion of the grain drying literature is devoted to the development of thin-layer or single kernel drying equations.

Empirical thin-layer equations are derived from experimental data of continuous drying. They constitute a lumped parameter representation of the drying process, and ignore the contributions of spatial variation in the kernel. Empirical equations are accurate and dependable as long as the analysis is conducted within the range of the experimental observations.

Several purely empirical drying equations have been developed for cereal grains. Henderson and Perry (1955) conducted a series of studies on the drying of agricultural products and observed that the drying rate during the falling rate period is approximately proportional to the difference between the moisture content of the product and the product equilibrium moisture content:

$$\frac{\partial M}{\partial t} = \alpha'(M - M_e) \tag{2-1}$$

The solution of equation (2-1) results in:

$$\frac{M - M_e}{M_o - M_e} = e^{-\alpha' t} \tag{2-2}$$

The constant α' is determined by the physical characteristics of the product. Equation (2-1) is the basis for many thin-layer drying equations. It is simple to evaluate and lends itself well to digital computaion.

Allen (1960) developed an equation similar to equation (2-2) for corn and rice:

$$t = \frac{1}{\alpha*} \log \left(\frac{M_o - M_e}{M - M_e}\right)$$

The value of $\alpha*$ for rice is 0.067.

Chancellor (1968) in his investigation of conduction-heat drying obtained the following empirical thin-layer equation for rice:

$$\frac{M - M_e}{M_o - M_e} = 0.0735 \left(e^{-Gt} + \frac{1}{4} e^{-4Gt} + \frac{1}{9} e^{-9Gt}\right) \qquad (2\text{-}4)$$

where

$$G = 8.860 \, e^{-6147.0/\Theta_{abs}}$$

Chancellor's equation is a good prediction of conduction drying but has not been verified for convective drying systems.

Ramaro and Wratten (1969) developed a mathematical expression relating moisture removal for rice to the drying parameters in the drying process. A series of experiments on rice drying was conducted in which the drying variables were formed into dimensionless parameters. The following equation was obtained:

$$M_R = (73.109 - 59.819\ T_e/T_w)\ (37.167 - 0.068\ T_e/\Theta) \left[\frac{(M_i - M_e)\ (T_e - T_w)}{T_w}\right] \left[1 - \mathrm{Exp}(-7.963\ (\frac{Vt}{X})^{1.45}\ (Re)^{-0.438}\ (\frac{\Theta}{T_w})^{-1.108}\right] \quad (2\text{-}5)$$

where

T_e = inlet air temperature, °C

T_w = wet bulb temperature, °C

Θ = grain temperature, °C

Equation (2-5) has not been verified for air temperature to grain temperature, (T_e/Θ) other than 1.0.

Agrawal and Singh (1977) conducted a thin-layer drying experiment on short grain rice. From their analysis of the experimental data the following thin-layer equation was obtained:

$$\frac{M - M_e}{M_o - M_e} = \mathrm{Exp}(-\chi t^y) \quad (2\text{-}6)$$

where

$\chi = 0.02958 - 0.44565\ rh + 0.01215\ T$

$y = 0.13365 + 1.93653\ rh + 1.77431\ rh^2 + 0.009468\ T$

Equation (2-6) was obtained from a limited number of initial moisture content from one initial moisture content, 24% w.b.

Wang and Singh (1978) conducted a series of thin-layer drying experiments with medium grain rough rice. Four different empirical models were selected and fitted to the experimental observations. They concluded that all four models with several regression constants could be used as a thin-layer equation. They recommend that the following quadiatic equation be employed because it required less computational time in a computer simulation:

$$\frac{M - M_e}{M_i - M_e} = 1 + At + Bt^2$$

where

t = time, min

$A = -0.001308 \times \Theta^{0.4687} \times rh^{-0.3187}$

and

$B = 0.00006625 \times \Theta^{0.03408} \times rh^{-0.3187}$

Appendix I contains a comparison of the equation of Wang (1978) and Husain (1973).

All of the empirical thin-layer equations examined so far require very little computational time to evaluate drying rates. The primary disadvantage of the empirical thin-layer equations is that they are lumped parameter representations of the drying process, and thus ignore spatial variation in the moisture content of the kernel. This results in a model that predicts the same drying rate regardless of tempering time or kernel moisture distribution. A more realistic model would be based on the physical mechanisms of moisture movement in a single rice kernel.

A number of physical mechanisms have been proposed to describe mass transfer in capillary porous products. It is generally agreed that moisture movement within a grain kernel takes place by diffusion (Brooker et al., 1974).

Kumar (1973) has studied moisture movement into a kernel of corn. It seems clear that moisture movement into a corn kernel occurs primarily through the base end of the tip cap. Still several researchers have successfully employed radial diffusion models in their approximation of single kernel drying.

Becker (1959) solved the spherical diffusion equation and compared it with the experimental results of some wheat drying tests. The diffusion equation in spherical coordinates is, assuming a constant D:

$$\frac{\partial M}{\partial t} = D \left[\frac{\partial^2 M}{\partial r^2} + \frac{2}{r} \frac{\partial M}{\partial r}\right] \tag{2-7}$$

Becker concluded that the spherical diffusion equation representation yields an acceptable approximation to the drying of wheat.

Several researchers (Chu and Hustrulid, 1968; Hamdy and Barre, 1969; and Ingram, 1976) have successfully simulated single kernel drying of corn. Chu and Hustrulid (1968) obtained the following equation for the diffusion coefficient of a spherical corn kernel:

$$D(M) = 1.5134 \text{ Exp } [(0.00045\ \Theta_{abs} - 0.05485)M - \frac{2513.0}{\Theta_{abs}}] \tag{2-8}$$

Husain, Chen and Clayton (1973) developed a mathematical model for rice drying based on simultaneous heat and mass transfer. The model is based on the assumption that radial mass diffusion is the predominant mechanism of moisture movement in rice. The authors solved the following system of equation:

$$\frac{\partial M}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} (Dr \frac{\partial M}{\partial r}) \tag{2-9}$$

$$\frac{\partial \Theta}{\partial t} = \frac{a}{r} \frac{\partial}{\partial r} (r \frac{\partial \Theta}{\partial r}) + k \frac{\partial M}{\partial t} \tag{2-10}$$

where

a = thermal diffusivity, cm^2/h

k = thermal conductivity, Kcal/h m °C

The diffusion coefficient for rice was found to be:

$$D(\bar{M}) = g(\Theta) \exp \{f(\Theta)\bar{M}\} \tag{2-11}$$

where

$$g(\Theta) = 94.8787 \exp [-13914.9/\Theta_{abs}]$$

and

$$f(\Theta) = 4.90722 \times 10^{-4}\ \Theta_{abs} - 0.3788$$

They concluded that the thermal gradients in the kernel could be neglected.

Table 2-1 is a comparison of the diffusion coefficient for rice and corn. Figure 2-1 is a comparison of drying curves for long grain and short grain rice using the equations of Agrawal and Singh (1977) (equation (2-6)) and Husain, Chen and Clayton (1973) (equation (2-9)).

Nishiyama (1975) solved the spherical diffusion equation (equation 2-6) for rice assuming a constant surface moisture content. He obtained the following solution:

$$\frac{M - M_e}{M_o - M_e} = \frac{6}{\Pi^2} \sum_{h=1}^{\infty} \frac{1}{n^2} e^{-n^2 \chi} \qquad (2\text{-}12)$$

where

$\chi = kt + \chi_o$ = dimensionless time

χ_o = correction term

The correction term was chosen to correct for the discrepancies between the experimental and theoretical drying curves due to the assumption of a constant surface moisture content.

Nishiyama's (1975) approach has some of the same drawbacks that are encountered with empirical thin-layer equations. The primary disadvantage is that the moisture distribution inside of the kernel is not evaluated. Radial diffusion equations (equations 2-9 and 2-10) provide considerable insight into the effects of spatial moisture variation on drying, tempering and cracking of rice. The major drawback in using these equations is the large amount of computational time needed to evaluate the drying rates.

Table 2-1. Comparison of rough rice[a] (r = 0.0975 cm) and shelled corn[b] (r = 0.296 cm) diffusion coefficients at different moisture and temperatures using equation (2-8) and equation (2-9), respecively.

Temperature	Diffusion Coefficients - cm^2/hr							
	Moisture Contents - % w.b.							
	M = 10.0		M = 15.0		M = 20.0		M = 25.0	
°C	Rice	Corn	Rice	Corn	Rice	Corn	Rice	Corn
37.78	0.00031	0.00109	0.00055	0.00167	0.00097	0.00255	0.00174	0.00390
48.89	0.00059	0.00151	0.00114	0.00238	0.00223	0.00373	0.00435	0.00584
60.00	0.00109	0.00207	0.00232	0.00332	0.00495	0.00534	0.01054	0.00859
71.11	0.00197	0.00277	0.00459	0.00457	0.01068	0.00753	0.02485	0.01242
82.22	0.00348	0.00366	0.00884	0.00619	0.02245	0.01046	0.05705	0.01768

Source: [a]Husain, Chen, and Clayton (1973)

[b]Chu and Hustrulid (1968)

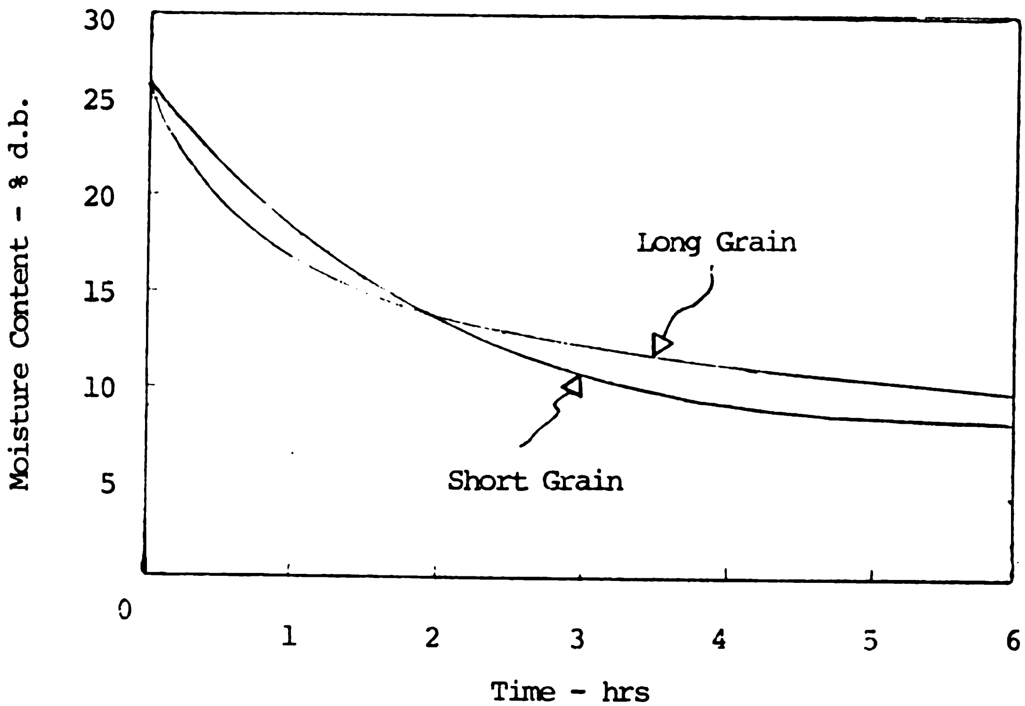


Figure 2-1. Comparison of drying curves for long and short grain rice using equation (2-9) and equation (2-6) computed at a drying temperature of 50°C and a relative humidity of 25%.

2-3 Moisture equilibrium content

The concept of the equilibrium moisture content is important in the analysis of the drying process. It serves as a boundary condition in several drying equations. Also, it is the minimum moisture content to which a grain can be dried under a given set of environmental conditions.

The equilibrium moisture content (EMC) is dependent upon the humidity and temperature of the surrounding air as well as on the species, variety, and maturity of the grain (Brooker et al., 1974).

A number of equilibrium moisture content (EMC) models have been proposed. Henderson (1952) used Gibb's adsorption equation to derive the following semi-theoretical equation for the moisture equilibrium of biological products:

$$1 - (P_v/P_{vs}) = \mathrm{Exp}\,(-h\ T_{abs}\ M_e) \qquad (2\text{-}12)$$

The Henderson equation has been found to be inadequate for cereal grains (Brooker et al., 1974 and Thompson, 1967).

Day and Nelson (1965) developed the following modified version of the Henderson equation for wheat:

$$1 - (P_v/P_{vs}) = \mathrm{Exp}\,(-j\ M_e^{k'}) \qquad (2\text{-}13)$$

where the parameters j and k' are temperature dependent. This model has proven adequate for wheat.

Henderson (1970) proposed the following EMC model for rice:

$$1 - rh = \mathrm{Exp}\,(-a\, M_e^{\,n}) \qquad (2\text{-}14)$$

where equation (2-14) was evaluated at room temperature and therefore is not appropriate for predicting the equilibrium moisture content in dryers using temperatures significantly above ambient.

Kachru and Matthes (1976) conducted a series of desorption experiments on a long grain variety called Starbonnett over a wide range of relative humidities (5-90%) and temperatures (526 °R - 560 °R). From these experiments the following empirical model was developed for predicting the equilibrium (dry basis):

$$M_e = 4.510 + 0.069\, rh + 8.837\, rh^{0.5} - 0.015\, rh^{0.5}\, T_{abs} \qquad (2\text{-}15)$$

Equation (2-6) fits the data very well over the range of humidities and temperatures quoted earlier. In addition, there are no stability problems when condensation occurs. Tabulated in Table 2-2 are some of the values of the equilibrium moisture content of rice at different temperatures and relative humidities.

2-4 Deep bed dryer models

In the previous section several thin-layer and single kernel drying models were examined. In this section model design to simulate the complete drying process will be examined.

Table 2-2. Equilibrium moisture contents of rice at different temperatures and relative humidities.

Temperature		Equilibrium Moisture Content - % d.b.				
°K	°R	rh=40%	rh=50%	rh=60%	rh=70%	rh=80%
280.0	504.0	15.35	16.99	18.54	20.02	21.45
300.0	540.0	11.93	13.17	14.36	15.51	16.62
320.0	576.0	8.52	9.35	10.18	10.99	11.79
340.0	612.0	5.10	5.53	5.99	6.47	6.96
360.0	648.0	1.69	1.72	1.81	1.95	2.13

Source: Kachru and Matthes (1976)

Computer simulation of deep bed grain drying is a recent development. Although sophisticated mathematical models based on heat and mass transfer were developed as early as 1955 (Van Arsdell, 1955), it was not until the late 60's that deep bed computer solutions were obtained.

Thompson (1967, 1968) developed a series of semi-empirical models of concurrent-cross- and counter-flow corn dryers. Thompson's models require a thin-layer equation and therefore have the same disadvantage mentioned earlier.

Bakker-Arkema et al. (1970, 1971, 1974) developed a series of theoretical fixed bed, concurrent, crossflow and counter-current dryer models. The models were developed by evaluating enthalpy and mass balances on a differential volume with the following assumptions:

1. no appreciable volume shrinkage occurs during the drying process;

2. no temperature gradient exists within each grain particle;
3. particle to particle conduction is negligible;
4. the airflow and grain flow are plug-type;
5. $\partial T/\partial t$ and $\partial H/\partial t$ are negligible compared to $\partial T/\partial x$ and $\partial H/\partial x$;
6. the bin walls are adiabatic, with negligible heat capacity;
7. the heat capacities of moist air and grain are constant during short periods of time;
8. an accurate thin-layer drying equation and moisture equilibrium isotherm are known.

The assumptions and balances result in the following system of equations for a concurrent-flow model:

$$\frac{\partial T}{\partial x} = \frac{-h_c a}{G_a C_a + G_a C_w H} (T - \Theta) \qquad (2\text{-}16)$$

$$\frac{\partial \Theta}{\partial x} = \frac{h'a}{G_p C_p + G_p C_w M} (T - \Theta) - \frac{h_{fg} + C_v(T - \Theta)}{G_p C_p + G_p C_w M} G_a \frac{\partial H}{\partial x} \qquad (2\text{-}17)$$

$$\frac{\partial H}{\partial x} = \frac{-G_p}{G_a} \frac{\partial M}{\partial x} \qquad (2\text{-}18)$$

$\frac{\partial M}{\partial t}$ = an appropriate thin-layer or single rice kernel drying equation.

The MSU models (Bakker-Arkema et al., 1974) are based on heat and mass transfer and are general enough to be used for different products, provided that the physical properties of the products are known.

Chan (1976) used the MSU fixed bed model to simulate the drying of rice in a bin. Several researchers (Evans et al., 1970; Lerew et al., 1972; Brook, 1977) have simulated drying of other agricultural products with the aid of other models developed by Bakker-Arkema et al. (1974).

Spencer (1969) developed a model similar to Bakker-Arkema et al. (1969). Spencer (1969) obtained the following system of equations:

$$\frac{\partial T}{\partial x} = \frac{h(\Theta - T)}{G_o C_a} \tag{2-19}$$

$$\frac{\partial P_v}{\partial x} = P_G \frac{(1 - \varepsilon)}{V_a} \frac{\partial M}{\partial t} \tag{2-20}$$

$$\frac{\partial \Theta}{\partial t} = \frac{\{- h(\Theta - T) + h_{fg} \frac{\partial M}{\partial t} P_G (1 - \varepsilon)\}}{\{P_G (1 - \varepsilon) (C_G + C_m M\}} \tag{2-21}$$

$$\frac{\partial M}{\partial t} = f(\Theta, M, M_s, t) \tag{2-23}$$

Since these equations are non-linear a numerical means of solving the problem is needed.

Spencer's (1969) model of wheat drying predicts drying rates well at both high and low moisture contents. However, the theoretical temperature curve deviates considerably from the experimental curve in the early period of the drying process.

Baughman, Hamdy and Barre (1973) and Ingran (1976) developed deep bed dryer models for wheat and corn similar to Bakker-Arkema et al. (1969). Both models were based on intra-particle diffusion. Only one of the dryer models mentioned so far have been applied to rice drying (Chan, 1976). None of the continuous flow dryer models has been applied to rice drying.

2-5 Tempering

During the falling rate drying period an internal moisture gradient develops in the rice kernel. This moisture gradient causes cracking (Prasad et al., 1965; Schmidt and Jebe, 1959; Kunze and Choudhury, 1972). In the tempering process the moisture content in the kernel equalizes.

Very little theoretical work has been done on the rice tempering process. However, it is generally accepted that moisture diffusion is the primary mechanism of tempering (Wasserman et al., 1964).

Several researchers have conducted experiments on tempering. Wasserman et al. (1964) found that tempering shortens the total in-dryer time and helps prevent breakage of the rice during subsequent milling (see Figures 2-2 and 2-3). From their experimental observations it was concluded that the rate of moisture migration increases with temperature.

Sabbah et al. (1972) studied the effect of tempering on cooling shelled corn. He concluded that change in average grain temperature and moisture content due to tempering was negligible and that the only change during tempering is in the moisture distribution in the kernel. Sabbah et al. (1972) also concluded that tempering had a limited effect on moisture removal during cooling.

Calderwood and Webb (1971) conducted a series of tests in a L.S.U. mixing type rice dryer (Figure 2-4). They concluded that tempering rice for periods up to 12 hours at high temperature following the dryer pass did not significantly change the amount of moisture removed during subsequent cooling cycles. In addition, they concluded that tempering duration had no significant effect on the milling yield (Table 2-3).

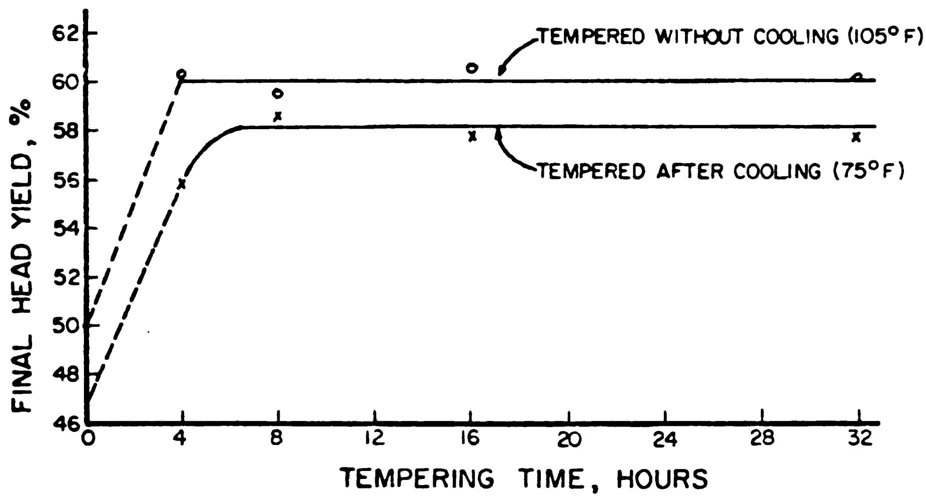


Figure 2-2. Effect of tempering time and temperature on total head yield.

Source: Wasserman and Ferrel (1964).

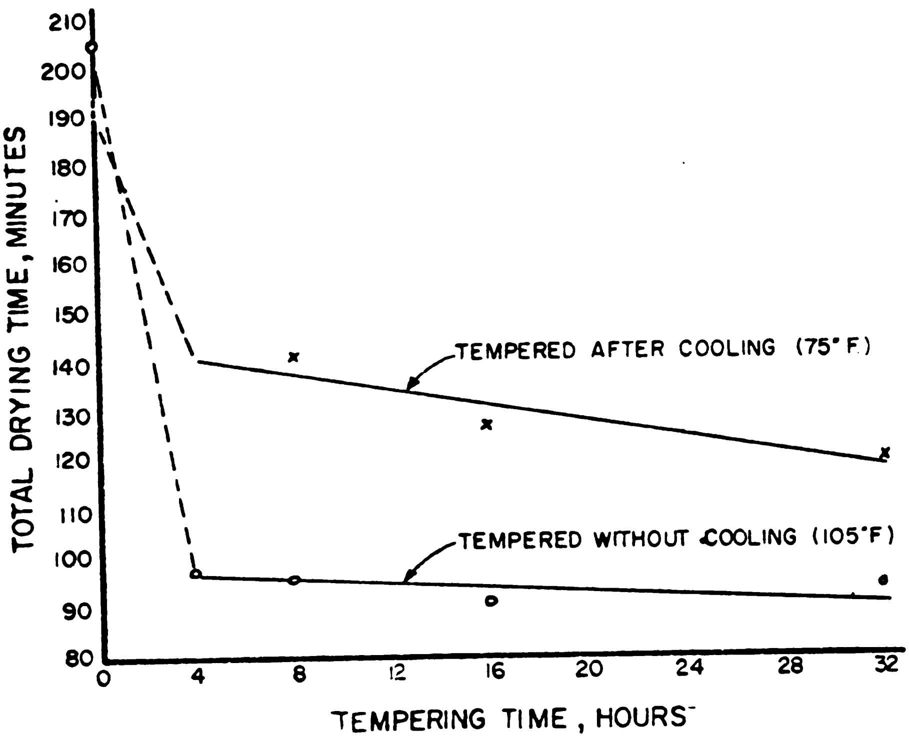


Figure 2-3. Effect of tempering time and temperature on total drying time.

Source: Wasserman and Ferrel (1964).

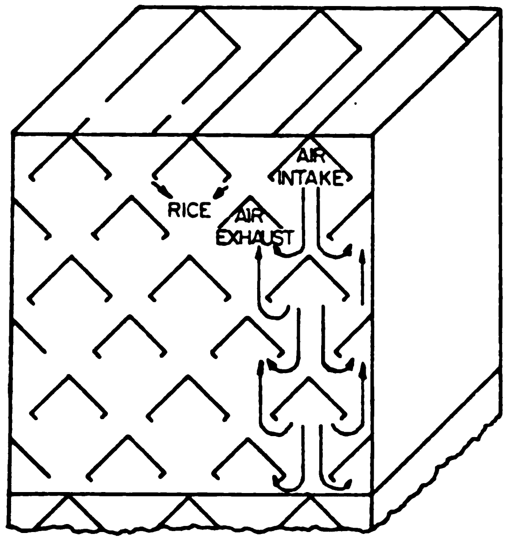


Figure 2-4. Air and rice flow patterns in L. S. U. mixing-type dryer.

Source: Calderwood (1972)

Variety	Tempering time	Rice temperature leaving dryer average	max.	Moisture removed, avg. per cooling period*	Milling yield† head rice control	treated	change
	Hours	°F	°F	Percent	Percent	Percent	Percent
Belle	0	111	112	1.0	52.6	48.7	-3.9
Patna	0	114	119	1.2	50.6	48.9	-1.7
	6	111	112	1.1	51.5	47.3	-4.2
	6	115	117	0.5	49.4	49.2	-0.2
	12	111	112	1.3	48.5	48.2	-0.3
	12	114	117	0.8	49.7	46.0	-3.7
Nato	0	113	114	1.0	66.4	67.1	+0.7
	0	111	113	1.4	66.4	64.0	-0.9
	6	111	115	1.2	65.4	64.0	-1.4
	6	111	113	0.8	67.2	64.6	-2.6
	12	111	112	1.4	65.3	64.0	-1.3
TP 49	0	113	113	1.0	65.0	61.9	-3.1
	0	106	111	1.4	65.3	64.0	-1.3
	6	112	115	1.3	64.3	62.0	-2.3
	6	106	110	1.2	62.5	64.5	+2.0
	12	112	114	1.0	64.1	60.2	-3.9
	12	108	111	1.1	63.0	63.2	+0.2
Avg. all lots not tempered,				1.2			-2.0
Avg. all lots tempered 6 hours,				1.0			-2.3
Avg. all lots tempered 12 hours,				1.0			-1.8

* Moisture removed, percent (dry basis)
† Milling yields were obtained by project personnel.

Table 2-3. Effect of tempering rice, and subsequent cooling by aeration in bins following dryer passes, upon the amount of moisture removed during the cooling period and the milling yield of the rice.

Source: Calderwood and Webb (1971).

Beeny and Ngin (1970) concluded that milling head yields increase with prolongation of tempering durations but only slightly after 5 hours. He also noted that the fuel consumption was reduced as tempering duration was increased. Beeny and Ngin's (1970) conclusion about the effect of tempering duration on head yields contradicts the observation of Calderwood and Webb (1971) and confirms the observation of Wasserman et al. (1964).

Brook (1977) concluded that tempering times beyond 1.25 hours had a negligible effect on the final moisture content and temperature of corn in a concurrent flow dryer. He attributes this to the uniformities of the average moisture content and temperature between kernels after drying in a concurrent flow dryer. Brook (1977) also noted that higher inlet temperatures resulted in a decrease in tempering time.

Steffe, Singh, and Bakski (1978) investigated the effect of tempering time on moisture removal and milling yields in the drying of high moisture medium grain rice. The dryer was constructed so that three rice samples could be dried simultaneously. The rice was dried in three identical bins (23.5 cm^2 base, 18 cm deep) at 38°C and 50°C for periods of 20 and 35 minutes. Tempering time varied from 0 to 24 hours. They concluded that tempering high moisture rice between drying resulted in an increase in moisture removed without a reduction in head yield. They also concluded tempering times of 3 hours are satisfactory and shorter times were adequate for maintaining grain quality.

2-6 Cracking or checking of rice

There have been many investigations of checking or cracking of rice and other cereal grains. Schmidt and Jebe (1959) found that approximately 57 percent of the total variability found in head rice losses could be attributed to variations in the saturation deficit of the drying air and 30 percent to the drying temperature. The saturation deficit is the difference between the saturated water vapor pressures at the dew point and the dry-bulb temperature of the drying air. It is interpreted as a measure of the drying rate. Caution must be used in applying Schmidt and Jebe's (1959) results to dryer configurations other than a fixed bed thin-layer dryer.

Kunze and Hall (1965. 1967) observed that brown rice fissured readily from moisture adsorption effects without the presence of a temperature gradient. They determined that a temperature difference of 16.67°C between the rice and air did not produce fissures as long as the rice was maintained at a constant moisture content. They also observed that high moisture rice kernels fissured faster than low moisture kernels when exposed to the same vapor-pressure difference at a particular temperature.

Kunze and Choudhury (1972) investigated the relation between moisture adsorption and tensile strength of rice. They observed that the rate of moisture adsorption and its penetration into the kernel depends on the initial condition of the kernel and the environment to which the kernel is subjected. For slow adsorption the rheological properties of a kernel are such that no fissuring occurs. At fast rates fissures occur rapidly.

Arora, Henderson and Burkhardt (1973) found the same temperature dependency on the fissuring of rice that Kunze (1972) had observed. They reported that a temperature larger than 43°C between the air and the rice kernel results in serious cracking. They recommended that the temperature of the drying air be kept below 53°C to avoid thermal stress that may cause cracking.

Prasad, Mannapperuma and Wratten (1975) investigated the thermal and hydroscopic expansion of brown rice. They concluded that stresses due to moisture gradient are a major cause of cracking or checking whereas thermal stress constitutes a minimal source of damage. Kuntz (1977) observed that rice fissuring occurs after drying. He concluded that the fissuring was caused by: (1) the grain surface readsorbing moisture from the environment; (2) the grain surface adsorbing moisture from center of the kernel; (3) the grain surface moisture from both environment and center of the kernel.

One of the most comprehensive studies on multipass drying of rice was conducted by Beeny and Ngin (1970). From a series of shallow bed drying tests they were able to assess the effects of the number of passes, number of hours of tempering, and airflow rate through the grain on milling head yield, drying rate and fuel consumption. The results of their study can be summarized as follows:

1. The head yield increases with an increase in the number of passes through the dryer.
2. The drying time is greatly reduced as the number of passes is increased.

3. The head yield increases with prolongation of tempering period but only slightly after 5 hours;
4. The fuel consumption is reduced as the length of tempering is increased.
5. The dryer capacity increases with increased airflow.
6. The head yields are lowered with increased airflow.

III. MATHEMATICAL MODELS

3-1 Dryer model

Each of the concurrent flow grain dryer models (Thompson, 1967; Bakker-Arkema *et al.*, 1969; and Ingram, 1976) examined in the literature is based on a system of four equations and four unknowns:

$$\frac{\partial T}{\partial x} = f_1(T,M,H,\Theta) \qquad (3\text{-}1)$$

$$\frac{\partial H}{\partial x} = f_2(T,M,H,\Theta) \qquad (3\text{-}2)$$

$$\frac{\partial \Theta}{\partial x} = f_3(T,M,H,\Theta) \qquad (3\text{-}3)$$

$$\frac{\partial \bar{M}}{\partial x} = f_4(T,M,H,\Theta) \qquad (3\text{-}4)$$

where

T = drying air temperature, °C

M = moisture content, $Kg_{H_2O}/Kg_{Dry\ Matter}$

H = humidity ratio, $Kg_{H_2O}/Kg_{Dry\ air}$

Θ = grain temperature, °C

Thompson's model (Thompson, 1967) is partly empirical and can be generalized for crops other than corn if the proper thin-layer equation and EMC is provided. The Bakker-Arkema et al. (1969) model is based on heat and mass transfer and is general enough to be used for different products, provided the transfer properties are known. Spencer (1969), Hamdy et al. (1969) models are extensions of the work of Bakker-Arkema et al. (1969).

In all of the models an appropriate equation for predicating moisture removal from a product (equation 3-4) is needed. Empirical thin-layer equations are accurate and dependable as long as the analysis is conducted within the range of the experimental data. Because empirical thin-layer equations are lumped parameter representations of the drying process the influence of moisture distribution in the kernel is masked. A single kernel diffusion model that takes into account the effects of spatial variation in a grain kernel is a more appropriate model.

In this investigation the moisture distribution and the rate of moisture removal is assumed to be governed by the following radial diffusion equation:

$$\frac{\partial \bar{M}}{\partial t} = \frac{1}{r} \frac{\partial}{\partial} (Dr \frac{\partial M}{\partial r}) \qquad (3\text{-}5)$$

where $\bar{M}$ is the local moisture content. To complete the concurrent-flow dryer model the following equations developed by Bakker-Arkema et al. (1969) will be used:

$$\frac{\partial T}{\partial x} = \frac{-\,ha}{G_a C_a + G_a C_v H} (T - \Theta) \qquad (3\text{-}6)$$

$$\frac{\partial \Theta}{\partial x} = \frac{ha}{G_a C_a + G_a C_v H} (T - \Theta) - \frac{h_{fg} + C_v (T - \Theta)}{G_p C_p + G_p C_w \bar{M}} G_a \frac{\partial H}{\partial x} \quad (3\text{-}7)$$

$$\frac{\partial H}{\partial x} = - \frac{G_p}{G_a} \frac{\partial \bar{M}}{\partial x} \quad (3\text{-}8)$$

Equally as important as the formulating of the differential equation (equation 3-5, 3-6, 3-7 and 3-8) is the selection of the appropriate boundary conditions and initial conditions. Several researchers (Young and Whitaker, 1971; Chu and Hustrulid, 1968; and Brook, 1977) assumed that the grain surface moisture content instantaneously reach the equilibrium moisture content:

$$M(t, r = R) = M_e \quad (3\text{-}9)$$

This boundary condition is based on the assumption that h_D approaches infinity. The other alternative would be to solve the diffusion equation with a convective boundary condition:

$$-D \left. \frac{\partial M}{\partial r} \right|_s = h_D (M_s - M_e) \quad (3\text{-}10)$$

In this section a model for each of these two boundary conditions will be tested. In a later chapter these two models will be compared to determine which one yields the best approximation.

The boundary conditions are

$$T(x = 0) = T(\text{inlet}) \quad (3\text{-}11)$$

$$\Theta(x = 0) = \Theta(\text{inlet}) \tag{3-12}$$

$$H(x = 0) = H(\text{inlet}) \tag{3-13}$$

$$M(x = 0, r) = \overline{M}(\text{initial}) \tag{3-14}$$

$$\frac{\partial M}{\partial r}(x = 0, r) = 0 \tag{3-15}$$

Equations (3-5 to 3-15) define the concurrent drying process. The next step is to develop a technique to solve this system of equations.

Equations (3-6), (3-7), and (3-8) are first order-coupled-nonlinear ordinary differential equations. Equation (3-5) is a second order partial differential equation. An analytical solution does not exist for this system of equations. Thus, numerical techniques must be employed to solve the system of equations.

Numerical techniques for solving first order ordinary differential equations are well established (Henrici, 1964 and Hamming, 1971). Therefore, it is desirable to express equation (3-5) as a first order ordinary differential equation. This can be achieved by approximating the spatial derivative by a set of finite difference equation (Carver, 1976).

Consider a cylindrical representation of a rice kernel with its radius divided into n equal increment as shown in Figure 3-1. The moisture content gradient can be obtained from the following forward and backward difference equations:

$$M_{i+1} = M_i + \frac{\partial M}{\partial r}\Big|_i \Delta r + \frac{1}{2}\frac{\partial^2 M}{\partial r^2}\Big|_i \Delta r^2 + \text{error term} \tag{3-16}$$

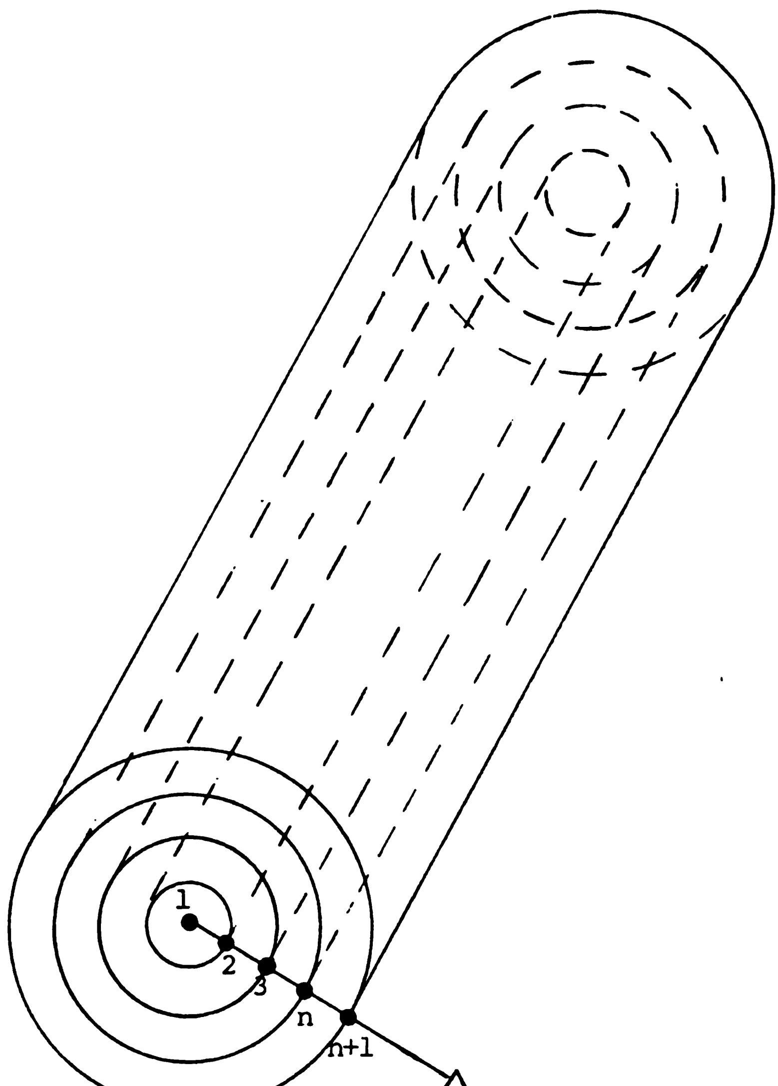


Figure 3-1. Cylindrical representation of a rice kernel with mass diffusion in radial direction only.

$$M_{i-1} = M_i - \frac{\partial M}{\partial r}\Big|_i \Delta r + \frac{1}{2}\frac{\partial^2 M}{\partial r^2}\Big|_i \Delta r^2 \qquad (3\text{-}17)$$

for $i \neq 0$.

From equations (3-16) and (3-17) the following solutions are obtained:

$$\frac{\partial^2 M_i}{\partial r^2} = \frac{M_{i+1} + M_{i-1} - 2M_i}{\Delta r^2} \qquad (3\text{-}18)$$

$$\frac{\partial M_i}{\partial r} = \frac{M_{i+1} + M_{i-1}}{2\Delta r} \qquad (3\text{-}19)$$

Substituting equation (3-17), (3-18) and

$$r = i\Delta r \qquad (3\text{-}20)$$

into equation (3-5) yields:

$$\frac{\partial M_i}{\partial t} = D\left[\frac{(2i + 1)\, M_{i+1} + (2i - 1)\, M_{i-1} - 4iM_i}{2i\Delta r^2}\right] \qquad (3\text{-}21)$$

Crank (1957) derived the following equation for the center node:

$$\frac{\partial M_o}{\partial t} = \frac{4}{\Delta r^2}\ (M_i - M_o) \qquad (3\text{-}22)$$

The moisture gradient at the surface of the kernel assuming a convective boundary condition (Type 3) can be obtained by substituting equation (3-10) into the following backward difference equation:

$$M_{s-1} = M_s - \frac{\partial M}{\partial r}\Big|_s \Delta r + \frac{1}{2}\frac{\partial^2 M}{\partial r^2}\Big|_s (\Delta r)^2 + \ldots$$

This yields, neglecting third and higher order terms:

$$M_{s-1} = M_s + \frac{h_D}{D}(M_s - M_e)\,\Delta r + \frac{1}{2}\left.\frac{\partial^2 M}{\partial r^2}\right|_s \Delta r^2$$

or

$$\frac{\partial^2 M}{\partial r^2} = \frac{2(M_{s-1} - M_s)}{\Delta r^2} - \frac{2h_D}{D}\frac{(M_s - M_e)}{\Delta r} \tag{3-23}$$

Substituting equations (3-23), (3-10) and (3-20) into equation (3-5) yields:

$$\left.\frac{\partial M}{\partial t}\right|_s = \frac{2D}{\Delta r^2}(M_{s-1} - M_s) - h_D\left(\frac{1}{R} + \frac{2}{\Delta r}\right)(M_s - M_e) \tag{3-24}$$

If the assumption that the surface moisture content equals the equilibrium moisture content (equation 3-9) then the moisture gradient at the surface is:

$$\left.\frac{\partial M}{\partial t}\right|_s = D\left[\frac{(2I + 1)\,M_e + (2i - 1)\,M_{s-1} - 4i\,M_s}{2i\Delta r^2}\right] \tag{3-25}$$

To make equations (3-21), (3-22), (3-24) and (3-25) compatible with equations (3-6), (3-7) and (3-8) they should be expressed as derivatives with respect to bed depth, x. This can be achieved by using the chain rule

$$\frac{\partial M}{\partial x} = \frac{\partial M}{\partial t}\,\frac{\partial t}{\partial x} = \frac{1}{V_G}\,\frac{\partial M}{\partial t} \tag{3-26}$$

where V_G = grain velocity, m/hr

which yields the following results:

$$\frac{\partial M_o}{\partial x} = \frac{4}{\Delta r^2 V_G} (M_i - M_o), \text{ for } i = 0 \quad (3\text{-}27)$$

$$\frac{\partial M_i}{\partial x} = \frac{D}{V_G} \left[\frac{(2i + 1) M_{i+1} + (2i - 1) M_{i-1} - 4i M_i}{2i \Delta r^2}\right] \quad (3\text{-}28)$$

$$\left.\frac{\partial M}{\partial x}\right|_s = \frac{2D}{V_G \Delta r^2} (M_{s-1} - M_s) - \frac{h_D}{V_G} \left(\frac{1}{R} + \frac{2}{\Delta r^2}\right) (M_s - M_e) \text{ (Type 3 B.C)} \quad (3\text{-}29)$$

or

$$\left.\frac{\partial M}{\partial x}\right|_s = \frac{D}{V_G} \left[\frac{(2i + 1) M_e + (2i - 1) M_{s-1} - 4i M_s}{2i \Delta r^2}\right] \text{ (Type 1 B.C)} \quad (3\text{-}30)$$

for i = 1, 2 ..., n

It is important to remember that the moisture contents and gradients obtained from equations (3-27), (3-28), (3-29) and (3-30) are local or point values. They represent the values of the concentration at a point and are functions of the kernel radius, r. Because the entire model is a plug flow model (sometimes called maximum gradient) a cross sectional averaged value for the average moisture content and its derivatives is needed (Himmelblau and Bischoff, 1968).

The average moisture content and the average rate of change of the moisture content with respect to time are defined by the following equations:

$$\frac{\partial \overline{M}}{\partial x}(x) = \frac{1}{\Pi R^2} \int_o^R \frac{\partial M}{\partial x} (r,x)\, 2\Pi r \partial r \quad (3\text{-}31)$$

and

$$\overline{M}\ (x) = \frac{1}{\pi R^2} \int_0^R M\ (r,x)\ 2\pi r \partial r \qquad (3\text{-}32)$$

There are several ways of evaluating equations (3-31) and (3-32). One way is to approximate the local moisture content and its derivative as Lagrangian interpolation polynomials:

$$\frac{\partial M}{\partial x}\ (r,x) = \sum_{i=o}^{n} \left.\frac{\partial M}{\partial x}\right|_i L_i\ (r) \qquad (3\text{-}33)$$

$$M\ (r,x) = \sum_{i=o}^{n} M_i L_i\ (r) \qquad (3\text{-}34)$$

where

$$L_i\ (r) = \prod_{\substack{m=1 \\ m \neq i}} \frac{r - r_m}{r_i - r_o} \qquad (3\text{-}35)$$

Equations (3-33) and (3-24) can now be substituted into equations (3-31) and (3-32) and integrated numerically. The disadvantage of this approach is that is requires excessive computer time to evaluate the integral.

An alternative technique involves the use of the moisture content and its derivative with respect to x at each node to define the following functions:

$$F_i = \frac{1}{\pi R^2} \frac{\partial M_i}{\partial x}\ (r,x)\ 2\pi r = \frac{2}{N^2 \Delta r^2}\ \frac{\partial M_i}{\partial x}\ n\Delta r \qquad (3\text{-}36)$$

and

$$G_i = \frac{1}{\Pi R^2} M(r,x)\, 2\Pi r = \frac{2}{N^2 \Delta R^2} M_n(r,t)\, n\Delta r \qquad (3\text{-}37)$$

Equations (3-36) and (3-37) can be integrated using the trapesodial rule:

$$\frac{\partial \bar{M}}{\partial x}(r,x) = \sum_{n=o}^{n} (F_{n+1} + F_n) \frac{\Delta r}{2}$$

$$= \sum_{n=0}^{n} \frac{1}{N^2} \left((n+1 \frac{\partial M_{n+1}}{\partial x} + \frac{n \partial M_n}{\partial x}\right) \qquad (3\text{-}38)$$

$$\bar{M}(r,x) = \sum_{n=0}^{n} (G_{n+1} + G_n) \frac{\Delta r}{2}$$

$$= \sum_{n=0}^{n} \frac{1}{N^2} ((n+1) M_{n+1} + n M_n \qquad (3\text{-}39)$$

Thus, equations (3-38) and (3-39) complete the mathematical definition of the system. Table 3-1 is a summary of the equations which define the drying process. In the next section some of the parameters which enter into the model will be examined.

3-2 Drying parameters

The evaluation of the physical and thermal properties of rice and the drying air is crucial for the successful simulation of a dryer. Specific heats, convective mass and heat transfer coefficient and latent heats of evaporation must be obtained. Table 3-2 contains a list of all

Table 3-1. Summary of the concurrent flow dryer model equations.

$$\frac{\partial T}{\partial x} = \frac{-ha}{G_a C_p + G_p C_v H} (T - \Theta) \qquad (3\text{-}6)$$

$$\frac{\partial \Theta}{\partial x} = \frac{ha}{G_p C_p + G_p C_w \overline{M}} (T - \Theta) - \frac{h_{fg} + C_{V(T-\Theta)}}{G_p C_p + G_p C_w \overline{M}} G_a \frac{\partial H}{\partial x} \qquad (3\text{-}7)$$

$$\frac{\partial H}{\partial x} = - \frac{G_p}{G_a} \frac{\partial \overline{M}}{\partial x} \qquad (3\text{-}8)$$

$$\frac{\partial M_o}{\partial x} = \frac{4}{\Delta r^2 V_G} (M_1 - M_0), \quad \text{for i-0} \qquad (3\text{-}27)$$

$$\frac{\partial M_i}{\partial x} = \frac{D}{V_G} \left[\frac{(2i + 1) M_{i+1} + (2i - 1) M_{i-1} - 4i M_i}{2i\Delta r^2}\right] \qquad (3\text{-}28)$$

$$\left.\frac{\partial M}{\partial x}\right|_s = \frac{2D}{V_G \Delta r^2} (M_{s-1} - M_s) - \frac{h_D}{V_G} \left(\frac{1}{R} + \frac{2}{\Delta r}\right) (M_s - M_e) \quad \text{Type 3 B C} \qquad (3\text{-}29)$$

or

$$\left.\frac{\partial M}{\partial x}\right|_s = \frac{D}{V_G} \frac{(2i + 1) M_e + (2i - 1) M_{s-1} - 4i M_s}{2i\Delta r^2} \quad \text{Type 1 B C} \qquad (3\text{-}30)$$

$$\frac{\partial \overline{M}}{\partial x} (x) = \sum_{n=0}^{N} \frac{1}{N^2} \left((n + 1) \frac{\partial M_{n+1}}{\partial x} + \frac{n \partial M_n}{\partial x}\right) \qquad (3\text{-}38)$$

$$\overline{M} (x) = \sum_{n}^{N} \frac{1}{N^2} ((n + 1) M_{n+1} + n M_n) \qquad (3\text{-}39)$$

Table 3-2. Physical and thermal properties of rice and the drying air needed to simulate rice drying.

Parameter	Symbol	Units
Diffusion Coefficient	D	cm^2/hr
Heat of Evaporation	h_{fg}	kJ/kg
Convective Heat Transfer Coefficient	h	kJ/m^2 °C
Convective Mass Transfer	h_D	cm/hr
Specific Heat of Water Vapor	C_V	kJ/kg°C
Specific Heat of Liquid Water	C_w	kJ/kg°C
Specific Heat of Dry Grain	C_p	kJ/kg°C
Specific Heat of Air	C_a	kJ/kg°C
Equilbrium Moisture Content	M_e	decimal - w.b.

the physical and thermal properties of rice and dry air needed to simulate the drying process. Appendix II contain a table with the rice property used, EMC equation, and drying rate equation. The specific heat of water and air can be obtained from any heat transfer book (Holman, 1976; Perry and Chilton, 1973; Threlkeld, 1970).

Wratten et al. (1969) evaluated some of the physical and thermal properties of rough rice. Tabulated in Table 3-3 are some of the individual grain and bulk physical properties for medium and long grain rough rice. Table 3-4 is a tabulation of the thermal properties of rough rice.

3-2.1 Latent heat of vaporization

The latent heat of water in rice is the energy needed to evaporate water from the grain. There are no specific values or functions for the latent heat of water in rice. However, Gallaher (1951) derived a general expression for predicating the latent heat of water in cereal grains:

$$h_{fg} = (1.0 + 23.0\ \text{Exp}\ (-40.0\ \overline{M})\ h_v \qquad (3\text{-}40)$$

3-2.2 Diffusion coefficient

In the development of the radial diffusion model it is assumed that the diffusion coefficient is not a constant but a function of temperature and moisture content. This assumption is verified by the observation that higher temperature results in a more rapid moisture redistribution (Wasserman et al., 1964). Also Kunze and Hall's (1965,

Table 3-3. Physical properties of rough rice.

	Individual Grain Properties							Bulk Properties		
Moisture Content %	Length cm	Width cm	Thickness cm	Volume cu. cm x 1000	Density (true) kg/m^3	Specific Gravity	Area sq. cm	Density kg/cu.m	Porosity %	Specific Gravity (apparent)
				Medium grain (Saturn)						
12	0.796	0.312	0.196	16.059	1324.24	1.374	0.402	598.29	58.5	0.599
14	0.792	0.312	0.196	16.715	1337.06	1.355		618.00	56.5	0.618
16	0.795	0.312	0.198	17.206	1354.04	1.350		633.69	55.0	0.630
18	0.798	0.318	0.201	19.173	1371.82	1.325	0.425	648.59	53.1	0.653
				Long grain (Bluebonnet-50)						
12	0.968	0.259	0.191	18.354	1362.37	1.384		585.64	56.6	0.586
14	0.975	0.262	0.191	18.517	1371.02	1.378		588.20	59.3	0.586
16	0.986	0.264	0.193	19.173	1377.58	1.372		605.11	57.9	0.606
18	1.003	0.269	0.198	19.664	1383.04	1.358		615.11	56.9	0.615

Source: Wratten et al. (1969).

Table 3-4. Thermal properties of medium grain rough rice.

Moisture Content %	Specific Heat kJ/kg-°C	Conductivity W/m °C	Diffusivity m^2/hr x 10^{-4}
12	1.599	0.102	3.7904
14	1.696	0.105	3.5953
16	1.796	0.108	3.4188
18	1.892	0.111	3.2516
20	1.993	0.112	3.0844

Source: Wratten <u>et</u> <u>al</u>.(1969).

1967) observation that high moisture rice fissures faster than low moisture rice. Assuming a constant diffusion coefficient over a significant moisture range will lead to serious error. The effect of the kernel moisture content and temperature on the diffusion coefficient, D, has been determined for rice by Husain, Chen and Clayton (1973) in the 37 to 100°C temperature range and the 5 to 50% d.b. moisture content range. The following empirical relation for the diffusion coefficient was developed:

$$D(\bar{M}) = g(\bar{\Theta}) \text{ Exp } (f(\bar{\Theta})\bar{M}) \tag{2-11}$$

The function $g(\bar{\Theta})$ and $f(\bar{\Theta})$ are defined in the literature review.

3-2.3 Convective heat transfer coefficient

The convective heat transfer coefficient between a flowing fluid and particle in a packed bed has been examined by several researchers. Gamson et al. (1943) and Wilke and Hougen (1945) developed the following equations for the convective heat transfer coefficient in a packed bed for turbulent and laminar flow:

$$h_c = 1.064\ C_p G \left[\frac{D_p G}{\mu}\right]^{-0.41} \left[\frac{C_p \mu}{k}\right]^{-2/3}, \qquad Re \geq 450 \tag{3-41}$$

$$h_c = 1.95\ C_p G \left[\frac{D_p G}{\mu}\right]^{-0.41} \left[\frac{C_p \mu}{k}\right]^{-2/3}, \qquad Re < 40 \tag{3-42}$$

where

$$D_p = \sqrt{D_c H_c + \frac{D_c}{2}}$$

The cylinder diameter, D_c for rice was determined from the relation:

$$\left(\frac{V}{S}\right)_{cylinder} = \left(\frac{V}{S}\right)_{rice} \tag{3-43}$$

Clifford (1972) and Brook (1977) used equations (3-41) and (3-42) in simulation of the drying of corn in a concurrent-flow dryer; Chan (1976) used the two equations to simulate rice drying. Equations (3-41) and (3-42) will be used in this investigation.

3-2.4 Convective mass transfer

Very little work has been conducted on the convective mass transfer coefficient of packed beds of cereal grains. However, a great deal has been done on mass transfer in packed beds in general (Barker, 1965). Wilke and Hougen (1945) noted that the Colburn j-factor for mass transfer j_D and the j factor for heat transfer, j_h, were approximately equal in a packed bed. This observation was supported by McCune, Wilhelm and Barker's (1965) review.

Clifford (1972) used this approximation and derived the following equation for the convective mass transfer coefficient:

$$h_D = \beta_1 h \tag{3-44}$$

Clifford (1972) determined the value of β_1 for corn using thin-layer data.

In the next chapter a method for obtaining β_1 for rice using experimental observations will be developed. Appendix III contains a set of conversion factors to go from metric to english unit.

3-3 Tempering model

As stated earlier very little theoretical work has been done on the tempering process. However, it is generally agreed that radial diffusion is the primary mechanism. Thus equation (3-5) with the following assumption completely defines the process:

$$\left.\frac{\partial M}{\partial r}\right|_{\text{surface}} = 0 \qquad (3\text{-}45)$$

$$\frac{\partial \Theta}{\partial x} = 0 \qquad (3\text{-}46)$$

$$\frac{\partial T}{\partial x} = 0 \qquad (3\text{-}47)$$

$$\frac{\partial H}{\partial x} = 0 \qquad (3\text{-}48)$$

$$M(r,0) = M(r, \underline{\bar{X}}) \qquad (3\text{-}49)$$

where $\underline{\bar{X}}$ is the bed depth of the dryer.

The first assumption, equation (3-45) is based on the fact that no moisture is lost from the kernel during the tempering process. Equation (3-46) is based on the assumption that the product temperature changes very little over a short period (2-4 hours). Equations (3-47) and (3-48) are based on the assumption that tempering takes place in a steady state environment. Equation (3-49) is based on the assumption that the final moisture distribution out of the dryer is the initial moisture distribution for the tempering stage.

For the tempering model equation (3-5) is solved using the same numerical technique developed for the dryer model. The right side of equation (3-5) is approximated by a finite difference equation which results in the following equation for the inner nodes:

$$\frac{\partial M_o}{\partial x} = \frac{4}{\Delta r^2 V_G} (M_1 - M_0), \quad \text{for } i = 0 \tag{3-27}$$

$$\frac{\partial M_i}{\partial x} = \frac{D}{V_G} \; \frac{(2i + 1)\, M_{i+1} + (2i - 1)\, M_{i-1} - 4i\, M_i}{2i\Delta r^2} \tag{3-28}$$

for i - 1, 2 ... η

Equation (3-45) is used as a boundary condition to obtain the following equation for the surface node:

$$\left.\frac{\partial M}{\partial x}\right)_{\text{surface}} = \frac{2D}{V_G} \; \frac{(M_{s-1} - M_s)}{\Delta r^2} \tag{3-50}$$

Equations (3-27), (3-28) and (3-50) completely define the tempering process. The diffusion coefficient is the same one used in the dryer model (equation 2-9).

3-4 Numerical solution of differential equations

The mathematical formulation of many engineering problems leads to relations which cannot be evaluated analytically. Such is the case in the analysis of a multi-stage rice dryer. Both the dryer model and the cooling models are systems of first order nonlinear ordinary differential equations for which there are no explicit solutions. However, there are several powerful numerical techniques for solving these systems of equations (Henrici, 1964; Hamming, 1971). One such program contains both the Adams-Moulton and the Runge-Kutta methods. The Runge-Kutta method is used as a starting method for the Adams-Moulton method. A computer program developed by Lastman (1964) was used to solve the system of equations for the drying and tempering model. Appendix IV contains a Fortran computer code for the EMC and convective models. Appendix V contains the input and output format for the models.

IV. EXPERIMENTATION AND MODEL VALIDATION

The experimental results reported in this chapter are important for two reasons. First, the experimental results are needed to estimate parameters in the model and secondly, to establish whether or not the models are a valid representation of the concurrent-counterflow drying process.

4-1 Experimentation

In the summer of 1976 a series of rice drying experiments was conducted at the Texas A. M. Experiment Station, Beaumont, Texas. The Michigan State University experimental concurrent flow dryer was erected on a site at the Experiment Station.

The dryer was made of round steel sections bolted together. Rice was manually fed into a bucket elevator and entered into the dryer via a mechanical airlock. The rice was distributed by a mechanical grain spreader powered by a heavy motor and gear boxes. The grain flow was regulated by a perforated circular drying and cooling unloading mechanism. Both the drying and cooling unloading mechanisms and the cooler air lock were powered by the same motor. A gear box at the base of the dryer was used to match the dryer and cooler grain flow rate. The dryer bed depth was 1.52 meters and the cooler bed depth 0.60 meter. Figure 4-1 is a drawing of the Michigan State University concurrent flow dryer used in

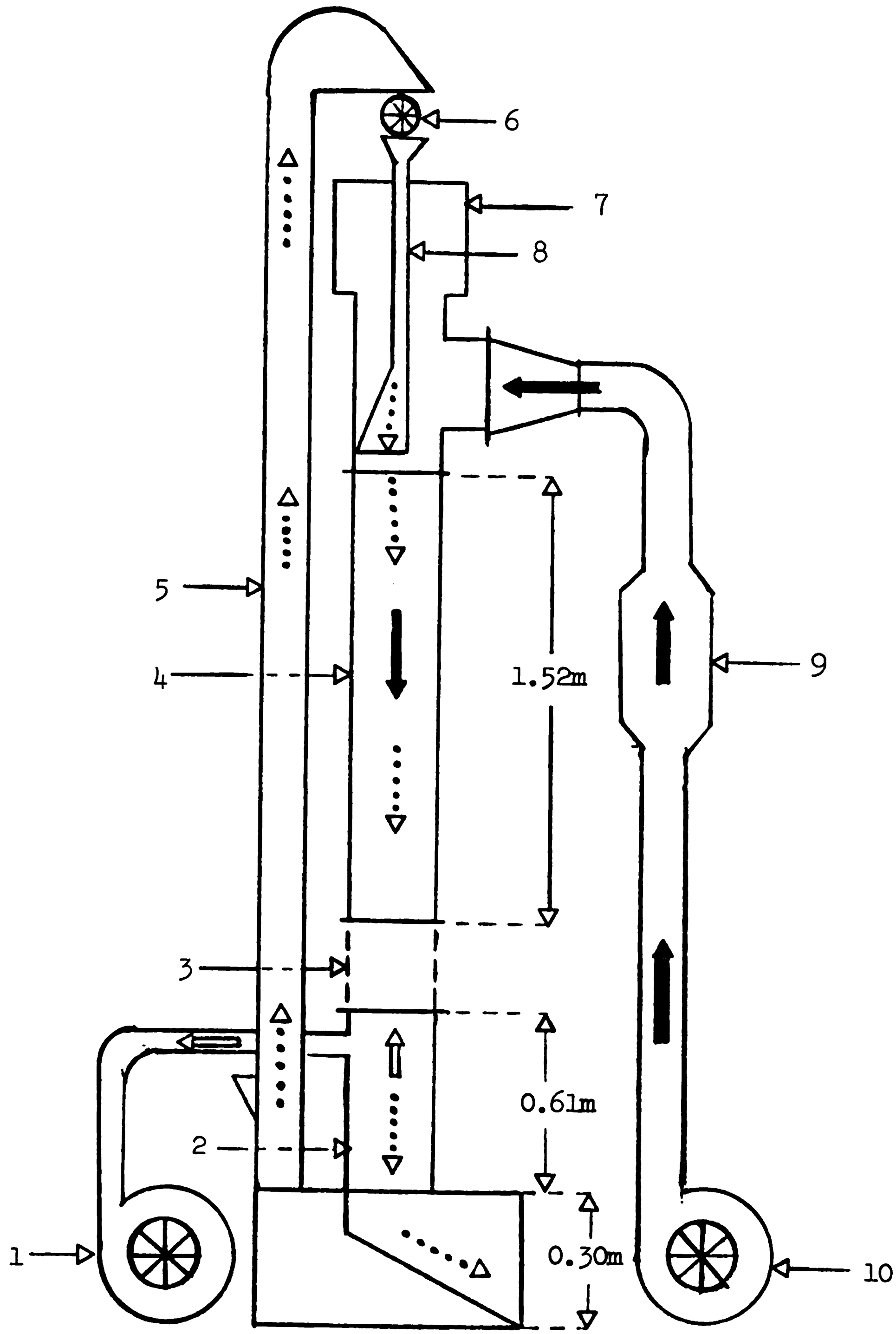
Figure 4.1 MSU dryer before modifications.

Legend:
1. Cooling fan
2. Counter-current cooling section
3. Air exhaust
4. Concurrent drying section
5. Bucket elevator
6. Mechanical air lock
7. Grain storage hopper
8. Mechanical grain spreading device
9. Burner
10. Dryer fan

◁••• Grain flow

◀▬ Drying air flow

◁═ Cooling air flow


6
7
8
5
4
1.52m
9
3
0.61m
2
0.30m
1
10

the Beaumont drying test.

The airflow was measured with a Meriam Flow Meter (Model 50 MC2-4P) and a Meriam Manometer (Model 406D10WM-6). Temperatures of the drying air and in the bed were measured with copper-constantan thermocouples and recorded on a Honeywell multi-point recorder. Moisture contents were measured with a Motomco moisture meter which was checked by using a Brown-Duvel moisture tester (Calderwood, 1972). The grain flow rate was determined by measuring the amount of grain discharged from the dryer in a given period of time. Tabulated in Table 4-1 is a summary of the monitoring equipment and their accuracy.

Several tests were conducted with the long grain rice variety, Labelle. During the tests several problems were encountered. The dryer had many air leaks which effected the accuracy of the temperature and air flow measurements. The grain flow could not be kept at a constant rate. In addition, the cooler and dryer grain flows were not matched properly, resulting in a bottle neck at the entrance to the cooler. Because of these difficulties only three of the tests were successful. Tabulated in Table 4-2 are the results from the three tests.

As a result of some of the mechanical and logistical problems encountered during the Beaumont drying tests, the M. S. U. concurrent flow dryer was modified. The modification involved the separation of the dryer and cooler, the addition of a garner bin to prevent air losses through the grain entry point and a complete redesign of the grain discharge mechanism. Figure 4-2 is a diagram of the modified concurrent flow dryer. A more complete explanation of the modifications can be found in Kline (1977).

Table 4-1. Summary of monitoring equipment.

Instruments	Description -- Accuracy
1. Manometer	Meriam Model 40GD10WM-6 Accuracy ± 0.02-inch water
2. Laminar Flow Elements	Meriam Model 50 MC2-4p. Accuracy ± 0.05 of calibration curve
3. Recorder	Honeywell twenty-four Channel Model Electronik 15 Accuracy ± 0.75 °F
4. Recorder	Texas Instrument two-channel Model P 502 W6A Accuracy ± 2 F, linearity ± 0.3 °F
5. Recorder	Esterline Angus twenty channel Model 2020 D Accuracy ± 0.5 °F
6. Moisture Tester	Steinlite Model 400G Accuracy ± 0.5% moisture content wet basis
7. Moisture Tester	Motomco Model No. 915 Accuracy ± 0.5%
8. Drying Oven	Blue M Electric Company Model OV510 Mercury in steel thermometer used Accuracy ± 2.5 °F

Table 4-2. Results of the Beaumont drying tests.

Variables	Test Number 5	6	7
Bed Depth - m	1.524	1.524	1.524
Initial Ave. M.C. - %w.b.	17.56	22.53	18.36
σ^2	0.038	0.049	0.006
Initial Grain Temp. - °C	23.3	33.8	32.7
Initial Head Yield - %	64.00	60.00	60.00
Pass 1			
Ambient Air Temp. - °C	33.0	35.19	35.33
Relative Humidity - %	52.00	41.67	45.60
Drying Air Temp. - °C	121.1	118.2	117.5
Grain Flow Rate -kg/hr	78.94	85.31	101.34
Air Flow Rate - m^3/s	0.033	0.033	0.033
Final Ave. M.C. - %w.b.	13.94	17.88	15.66
Final Grain Temp. - °C	42.2	40.0	41.6
Tempering Time - hr	2.5	1.42	--
Pass 2			
Ambient Air Temp. - °C	34.3	34.3	35.3
Relative Humidity - %	46.0	40.50	53.80
Drying Air Temp. - °C	121.12	121.12	119.45
Grain Flow Rate - kg/hr	278.63	77.20	117.19
Air Flow Rate - m^3/s	0.033	0.033	0.033
Final Ave. M.C. - %w.b.	13.12	14.78	14.00
Final Grain Temp. - °C	41.7	42.2	41.6
Tempering Time - hr	--	1.17	--
Pass 3			
Ambient Air Temp. - °C		28.70	33.12
Relative Humidity - %		66.83	57.60
Drying Air Temp. - °C		118.70	119.67
Grain Flow Rate - kg/hr		88.58	106.56
Air Flow Rate - m^3/s		0.033	0.033
Final Ave. M.C. - %w.b.		12.69	12.72
Final Grain Temp. - °C		42.23	41.67
Final Head Yield - %	66.00	51.00	58.00

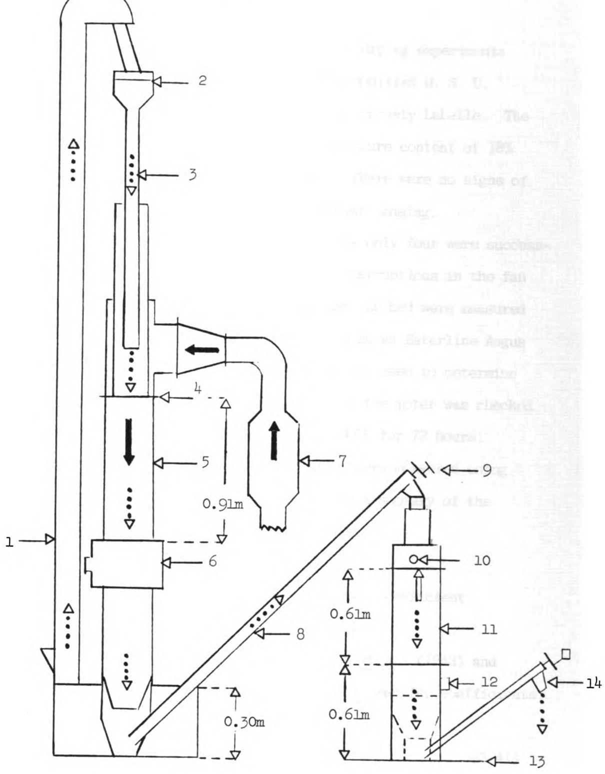
Figure 4-2. Modified MSU Concurrent Flow Grain Dryer

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. D. C. shunt wound variable speed motor
10. Cooler exhaust
11. Cooling section
12. Cooling air entrance
13. Cooler base
14. Cooling section discharge auger

◁••• Grain flow

⬅ Drying air

⇦ Cooling air


2
3
4
5
7
9
0.91m
1
6
10
11
0.61m
8
12
14
0.61m
0.30m
13

In the summer of 1977 another series of rice drying experiments were conducted at Michigan State University. The modified M. S. U. dryer was used to dry 1134 kg of long grain rice, variety Labelle. The rice was shipped from Beaumont, at an average moisture content of 18% w.b. and an average head yield of 61.8 percent. There were no signs of molding or other deterioration upon arrival in East Lansing.

Five tests were conducted. Of the five tests only four were successful. During the fifth test there were several interruptions in the fan power supply. Temperatures of the drying air and the bed were measured with copper-constantan thermocouples and recorded on an Esterline Angus multipoint recorder. A Steinlite moisture meter was used to determine the moisture content of the rice. The accuracy of the meter was checked by placing samples of rice in a drying oven at 100°C for 72 hours. Grain temperatures entering and leaving the dryer were measured using a dry-bulb thermometer. Tabulated in Table 4-3 is a summary of the results obtained from the second year drying tests.

4-2 Estimation of convective heat and mass transfer coefficient

In Chapter 3 the following equation by Gamson et al. (1943) and Wilke and Hougen (1945) were presented for the heat transfer coefficients:

$$h_c = 1.064\, C_p G \left[\frac{C_p \mu}{k}\right]^{-2/3} \left[\frac{D_p G}{\mu}\right]^{-0.41}, \quad \frac{D_p G}{\mu} > 350 \qquad (3\text{-}41)$$

$$h_c = 1.95\, C_p G \left[\frac{C_p \mu}{k}\right]^{-2/3} \left[\frac{D_p G}{\mu}\right]^{-0.51}, \quad \frac{D_p G}{\mu} \le 350 \qquad (3\text{-}42)$$

Table 4-3. Summary of East Lansing drying tests.

Variables	Test Number 1	2	3	4
Bed Depth - m	0.9144	0.9144	0.9144	0.9144
Initial Ave. M.C. - %w.b.	17.51	16.85	16.81	17.13
σ^2	0.1387	0.4705	0.1612	0.5202
Initial Grain Temp. - °C	23.7	24.1	19.3	12.2
σ^2	0.12	0.21	1.30	3.95
Initial Head Yield - %	61.9	62.4	62.6	60.3
Pass 1				
Ambient Air Temp. - °C	25.4	26.0	29.0	25.5
Ambient Wet Bulb Temp - °C	17.2	20.0	23.3	21.1
Drying Air Temp. - °C	93.3	93.3	121.1	121.1
Grain Flow Rate - kg/hr	106.24	101.46	158.74	131.16
Air Flow Rate - m^3/s	0.0408	0.0409	0.0312	0.0298
Final Ave. M.C. - %w.b.	15.23	14.79	15.57	15.72
σ^2	0.0974	0.5641	0.2558	0.1283
Final Grain Temp. - °C	32.6	33.7	36.6	35.6
σ^2	0.41	0.14	0.38	0.79
Head Yield - %	63.1	61.6	60.00	61.0
Tempering Time - hr	—	2.0	--	2.0
Pass 2				
Ambient Air Temp. - °C	23.4	28.3	29.7	25.0
Ambient Wet Bulb Temp - °C	16.4	21.1	23.0	20.5
Drying Air Temp. - °C	93.3	93.3	121.1	121.1
Grain Flow Rate - kg/hr	108.8	110.5	158.7	135.8
Air Flow Rate - m^3/s	0.0408	0.0409	0.0312	0.0298
Final Ave. M.C. - %w.b.	13.2	13.0	14.0	13.6
σ^2	0.1913	0.1661	0.8483	0.4387
Final Grain Temp. - °C	35.4	37.8	39.8	39.1
σ^2	0.3022	0.0000	0.3810	0.8439
Head Yield - %	60.7	60.7	61.2	59.7

Table 4-3 (continued)

Cooler Bed Depth				
Ambient Air Temp. - °C	—	—	29.4	25.0
Ambient Wet Bulb - °C	—	—	22.8	20.5
Grain Flow Rate - kg/hr	—	—	158.7	135.9
Air Flow Rate - m /s	—	—	0.00834	0.00958
Final Ave. M.C. - %w.b.	—	—	13.79	13.35
σ^2	—	—	0.0935	0.2765
Final Grain Temp. - °C	—	—	34.1	31.2
σ^2	—	—	0.1921	0.2142
Final Head Yield - %	—	—	61.2	60.0

For most grain drying systems the latter equation is used. However, preliminary analysis indicated that equation (3-42) does not adequately simulate the temperature profile in a concurrent flow dryer. This can be attributed to the discrepancy between the reported and the actual surface area of rough rice. Morita and Singh (1977) reported the average surface area of short grain rice to be approximately 0.475 cm^2. Wratten et al. (1969) reported a surface area for short grain rice of 0.392 cm^2.

The discrepancy between the two can be attributed to the difference in the technique used. Wratten et al. (1969) sliced a rice grain into fifteen sections. The major and minor axes were measured by use of a pre-calibrated microscope. Once the major and axes were determined, the following formula was used to determine the perimeter (P) of each section:

$$P = \pi \quad \frac{a^2 + b^2}{2} \tag{4-1}$$

Morita and Singh (1977) used electron microscope scans to determine the surface area of rough rice. They observed that the surface of rough rice consists of many small ridges which have to be considered in the determination of the surface area. They determined the average density of the ridges per unit basic area of hull. The total surface area was calculated from the dimension of the ridges, the surface area of the ridges, the average density of the ridges, and the average total basic area of the hull.

To correct for this discrepancy, the following modification is made to equation (3-42):

$$h_C = \beta_0 \; \{1.95 \; C_p G \left[\frac{C_p \mu}{k}\right]^{-2/3} \left[\frac{D_p G}{\mu}\right]^{-0.51} \}, \quad \frac{D_p G}{\mu} < 350 \qquad (4\text{-}2)$$

where β_0 is a corrective parameter to be estimated.

In addition to estimating β_0 the convective mass transfer coefficient, h_D, must be estimated. As stated earlier, the mass transfer coefficient should be proportional to the heat transfer coefficient:

$$h_D = \beta_1 \; h \qquad (3\text{-}44)$$

where h is equal to the left hand side of equation (3-42). Both β_0 and β_1 can be estimated from the experimental results tabulated in Tables 4-2 and 4-3.

To obtain the best values of β_0 and β_1 for a concurrent flow dryer, a multivariable unconstrained search alogirthm (Kuester and Mize, 1973), developed by Nelder and Mead (1964), was used to minimize the following objective function:

$$S = 100 \quad \Sigma \; (\overline{M}_{exp} - \overline{M}_{sim})^2 + \Sigma \; (\Theta_{exp} - \Theta_{sim})^2$$

The weighting factor of 100 was used so that a 01% error in moisture content counted as much as a 1°F error in temperature. The objective function was evaluted over five runs - all four of the East Lansing drying tests (Table 4-3) and number 6 of the Beaumont drying tests (Table 4-2). Test number 6 of the Beaumont drying tests was used because it was the only test conducted at a high initial moisture content (22.5% w.b.).

The best values for β_0 and β_1 were found to be 0.07105 and 0.002065, respectively. This indicates that the value used for the surface area is too large. Substituting β_0 and β_1 into equations (4-1) and equation (3-44), respectively, yields:

$$h_C = 0.13855\ C_pG \left[\frac{C_p\mu}{k}\right]^{-2/3} \left[\frac{D_pG}{k}\right]^{-0.51}, \quad \frac{D_pG}{\mu} < 350 \qquad (4\text{-}3)$$

and

$$h_D = 0.00403\ C_pG \left[\frac{C_p\mu}{k}\right]^{-2/3} \left[\frac{D_pG}{k}\right]^{-0.51}, \quad \frac{D_pG}{\mu} \leq 350 \qquad (4\text{-}4)$$

Tabulated in Table 4-4 is a comparison of the experimental and simulated values.

Table 4-4. Comparison of experimental and simulated values for concurrent flow dryer.

Test No.	1	2	3	4	6
Grain Flow Rate, kg/hr	106.24	101.46	158.74	131.16	85.31
Air Flow Rate, m^3/min	0.0408	0.0409	0.0312	0.0298	0.0330
Inlet Conditions:					
T, °C	93.33	93.33	121.11	121.11	118.56
M, %w.b.	17.51	16.85	16.81	17.13	22.53
Θ, °C	23.73	24.12	19.39	12.22	33.89
H, Kg/Kg	0.009	0.0125	0.0150	0.0130	0.0120
Experimental Exit Conditions:					
Θ, °C	32.62	33.78	36.67	35.67	40.00
M, %w.b.	15.23	14.79	15.57	15.72	17.88
Simulated Exit Conditions:					
EMC B.C.					
Θ, °C	32.61	34.39	31.83	29.56	27.78
M, %w.b.	15.72	15.08	15.88	16.23	18.93
Convective Mass B.C.					
Θ, °C	35.11	36.89	31.83	29.44	27.78
M, %w.b.	15.87	15.23	16.04	16.35	19.15

V. RESULTS AND DISCUSSION

5-1 Effect of boundary condition

From Table 4-4 it seems that the EMC boundary condition yields the best approximation. However, the difference between the residuals of the EMC (Type 1 B. C.) and the convective (Type 3 B. C.) models is not significant enough to warrant a rejection of the convective model. The discrepancy between the values predicted by the experimental values can be attributed to the relatively large convergence parameter used. The convergence parameter had to be large to keep the computational time down to practical levels. Despite this restriction, both models predicted the moisture contents to within 0.5% w.b. of the experimental values. Also, the final grain temperatures predicted by both models are within 5% of the experimental values.

The convective and EMC models exhibit very different transient behavior. Figure 5-1 is a comparison of the drying rates $\partial M/\partial X$ as a function of bed depth, X, for the two models. Both simulations were run using the standard conditions listed in Table 5-1. The use of an EMC boundary condition results in a larger area under the curve than the convective model indicating more moisture removed as shown in Figure 5-2.

The shapes of the two drying curves in Figure 5-1 are also dissimilar. The drying rate curve of the convective model very rapidly reaches a

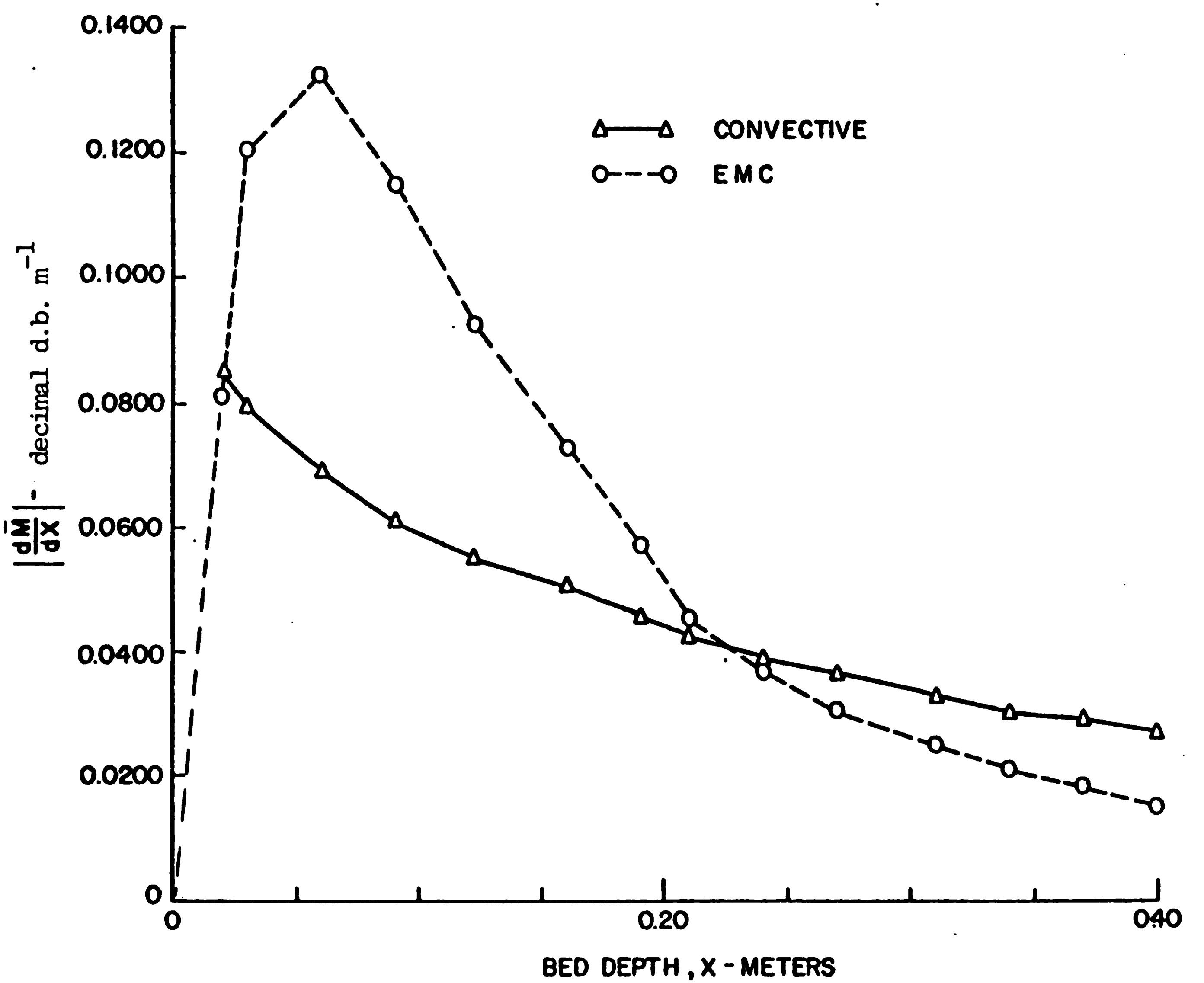


Figure 5-1. Comparison of the drying rate profiles for the convective and EMC boundary conditions. The drying variables are listed in Table 5-1.

Table 5-1. Standard operating conditions for drying simulations.

Number of Stages	2
Number of Tempering Sections	1
Environmental Conditions:	
Ambient Temperature	25.6°C
Absolute Humidity	0.009 kg/kg
Grain Status:	
Initial Moisture Content	20.0% w.b.
Initial Grain Temperature	23.9°C
Stage 1:	
Inlet Air Temperature	121.1°C
Airflow Rate	2.27 m^3/min
Grain Flow Rate	130.0 kg/hr
Bed Depth	0.91 m
Length of Tempering Section	4.6 m
Stage 2:	
Inlet Air Temperature	121.1°C
Airflow Rate	2.27 m^3/min
Bed Depth	0.91 m

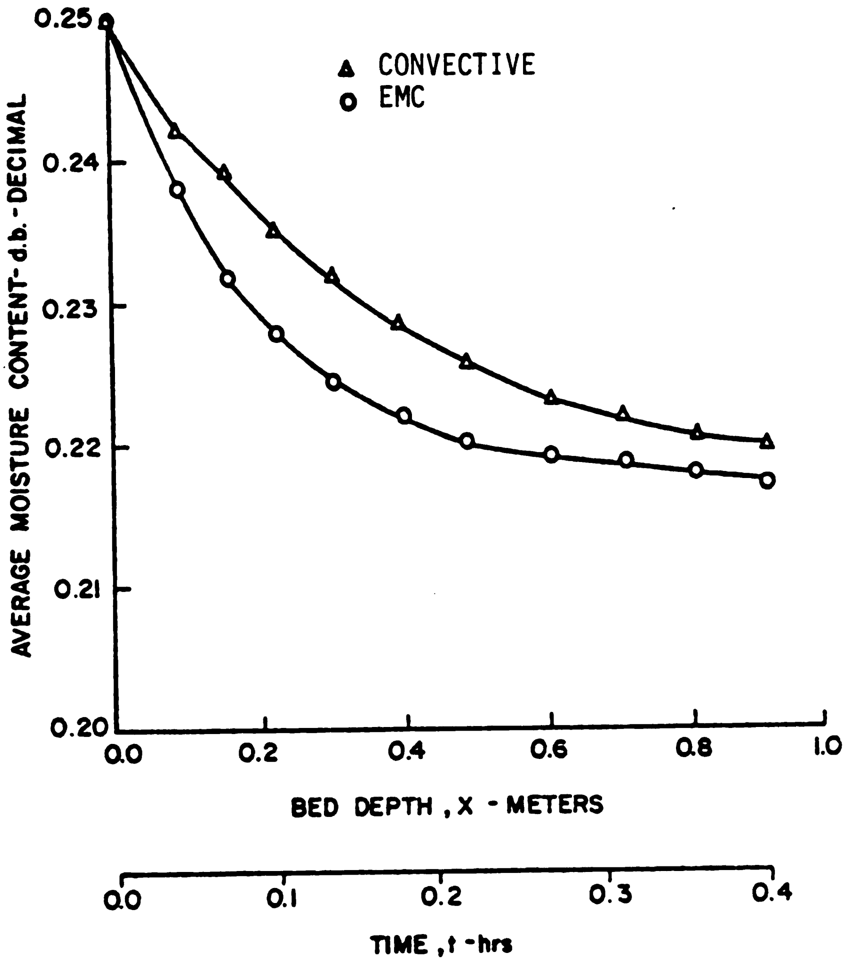


Figure 5-2. Comparison of moisture content profiles for the convective and EMC boundary conditions. The drying variables are listed in Table 5-1.

maximum and gradually decreases with bed depth (Figure 5-1). The explanation for this is that the surface moisture is very rapidly removed after which the term,

$$D \frac{\partial M}{\partial r}\bigg|_s = h_D (M_s - M_e) \qquad (3\text{-}10)$$

becomes very small, and the rate of moisture diffusion from the center to the rice surface becomes the limiting factor.

On the other hand, the EMC model reaches its maximum later than the convective model, and the magnitude of the maximum is larger. Also, the curve decreases very rapidly. The explanation for this is that during the initial drying period, the rate of the moisture migration to the surface is approximately equal to the rate of moisture removed. By the time the grain reaches about 10 cm into the bed, the rate of moisture diffusion to the surface can no longer keep pace with the rate of moisture removed at the surface. Tabulated in Table 5-2 are the values of the diffusion coefficient at different positions in the bed for the two models. Equation 2-11 was used to calculate the values in Table 5-2.

The rate of change of the absolute humidity with respect to bed depth is directly proportional to the rate of change of the grain moisture content, $\partial M/\partial x$ [Equation (3-8)]. Because the rate of change of the moisture content $\partial M/\partial x$ is larger for the EMC model, the rate of change of the absolute humidity, $\partial H/\partial X$, is larger for the EMC model than for the convective model. Figure 5-3 shows how the absolute humidity changes with bed depth for both the convective and EMC models.

Table 5-2. Comparison of moisture content, grain temperature, and diffusion coefficient at different bed depths for the convective and EMC boundary conditions. The values were calculated from equation 2-11.

	Convective B. C.			EMC B. C.		
Bed Depth M	M·C d·b dec.	Grain Temp °C	Diffusion Coeff. cm^2/hr	M·C d·b dec.	Grain Temp °C	Diffusion Coeff. cm^2/hr
0.021	0.2481	32.7	0.0011	0.2484	32.7	0.0011
0.034	0.2468	36.2	0.0015	0.2466	35.8	0.0014
0.064	0.2444	40.4	0.0020	0.2423	38.6	0.0017
0.095	0.2423	42.2	0.0023	0.2381	39.2	0.0017
0.125	0.2404	42.9	0.0024	0.2346	39.0	0.0016
0.155	0.2387	42.9	0.0023	0.2318	38.6	0.0015
0.186	0.2370	42.6	0.0022	0.2296	38.0	0.0014
0.213	0.2355	42.2	0.0021	0.2278	37.4	0.0013
0.244	0.2342	41.6	0.0020	0.2264	37.0	0.0012
0.274	0.2329	41.1	0.0019	0.2252	36.6	0.0012
0.305	0.2315	40.5	0.0017	0.2241	36.3	0.0011

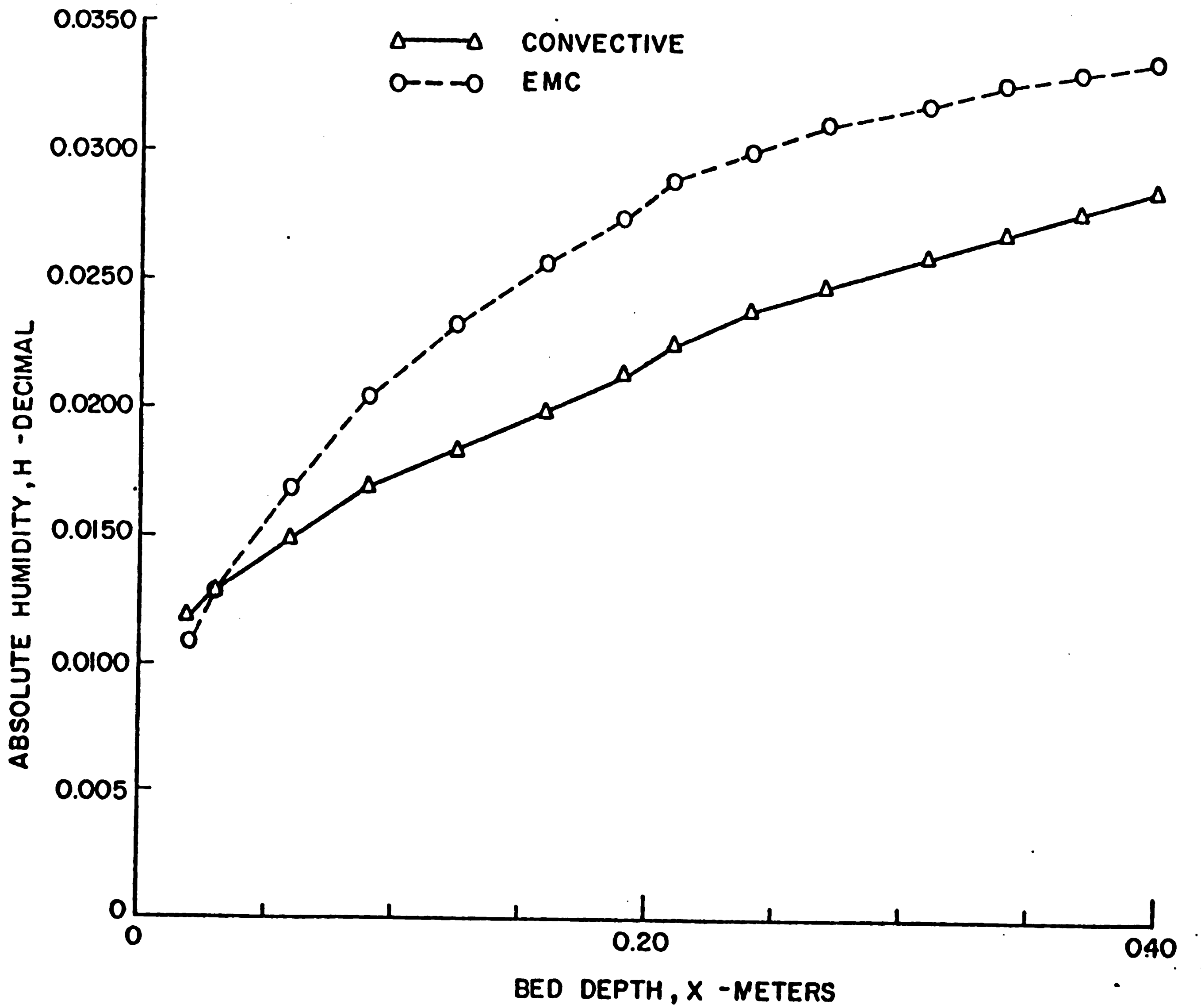


Figure 5-3. Comparison of absolute humidity profiles for the convective and EMC boundary conditions. The drying variables are listed in Table 5-1.

The grain temperature profile is also influenced by the choice of the boundary conditions. Figure 5-4 shows how the grain temperature changes with bed depth for both the convective and EMC models. The convective model predicts higher grain temperatures than the EMC model. An examination of equation (3-7) will provide some insight into the response:

$$\frac{\partial \Theta}{\partial x} = \frac{h_a (T - \Theta)}{G_a C_a + G_a C_v} - \frac{h_{fg} + C_v (T - \Theta)}{G_p C_p + G_p C_w} G_a \frac{\partial H}{\partial x} \qquad (3\text{-}7)$$

Because the EMC model predicts more moisture removed that the convective model evaporative cooling would be higher for the convective model. Therefore, lower grain temperatures are predicted by the EMC model.

Figure 5-5 shows how the air temperature changes in the bed. Both models have very similar air temperature profiles. Initially, the EMC model predicts higher air temperatures than predicted by the convective model. However, very soon the situation reverses. This also can be attributed to the higher evaporative cooling that is predicted by the EMC model.

Throughout the remainder of this chapter, the EMC model will be used to evaluate the response of the dryer to changes in the drying parameter. The EMC model was selected because it yields the best approximation of the drying process. However, this is not simply a rejection of the convective model.

Unless otherwise stated, the operating conditions listed in Table 5-1 will be used as the standard conditions. All of the simulated results presented in the following sections will be based on the standard conditions.

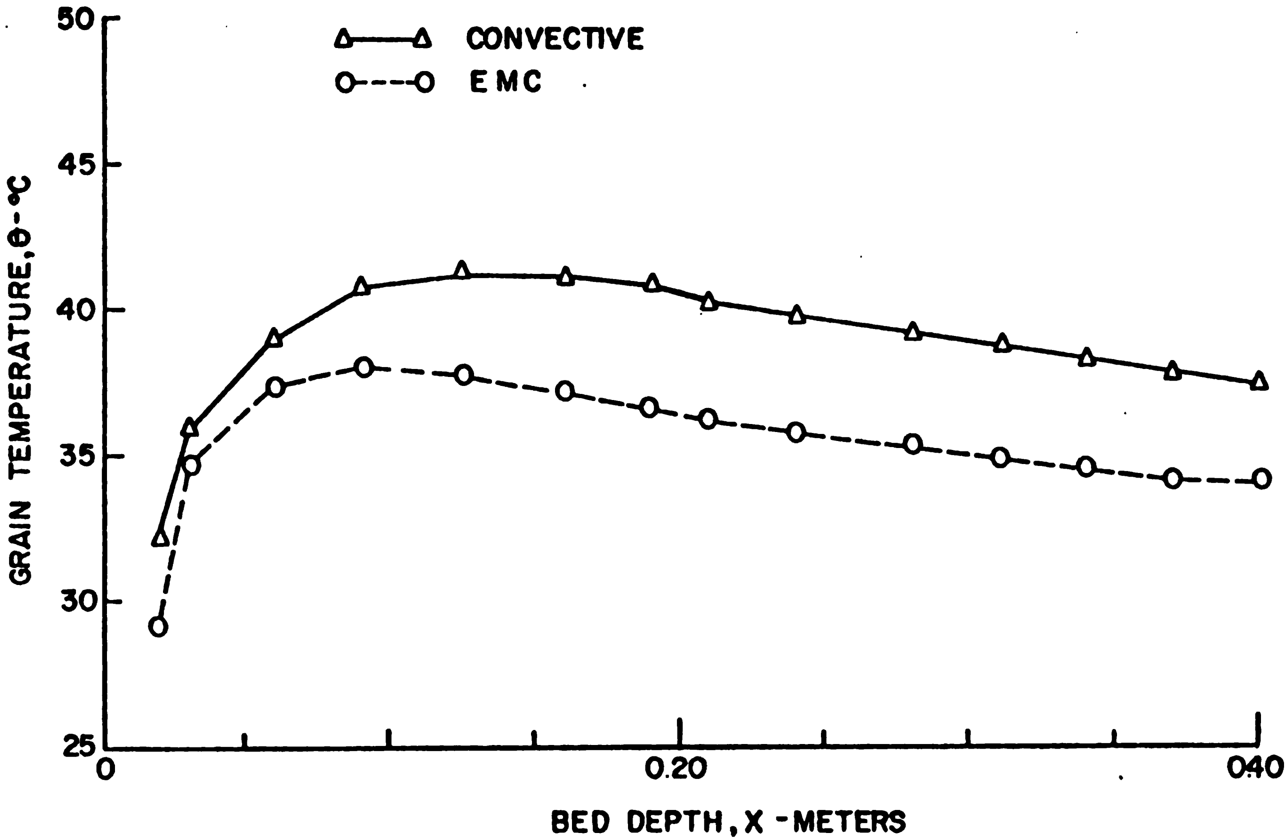


Figure 5-4. Comparison of grain temperature profiles for the convective and EMC boundary conditions. The drying variables are listed in Table 5-1.

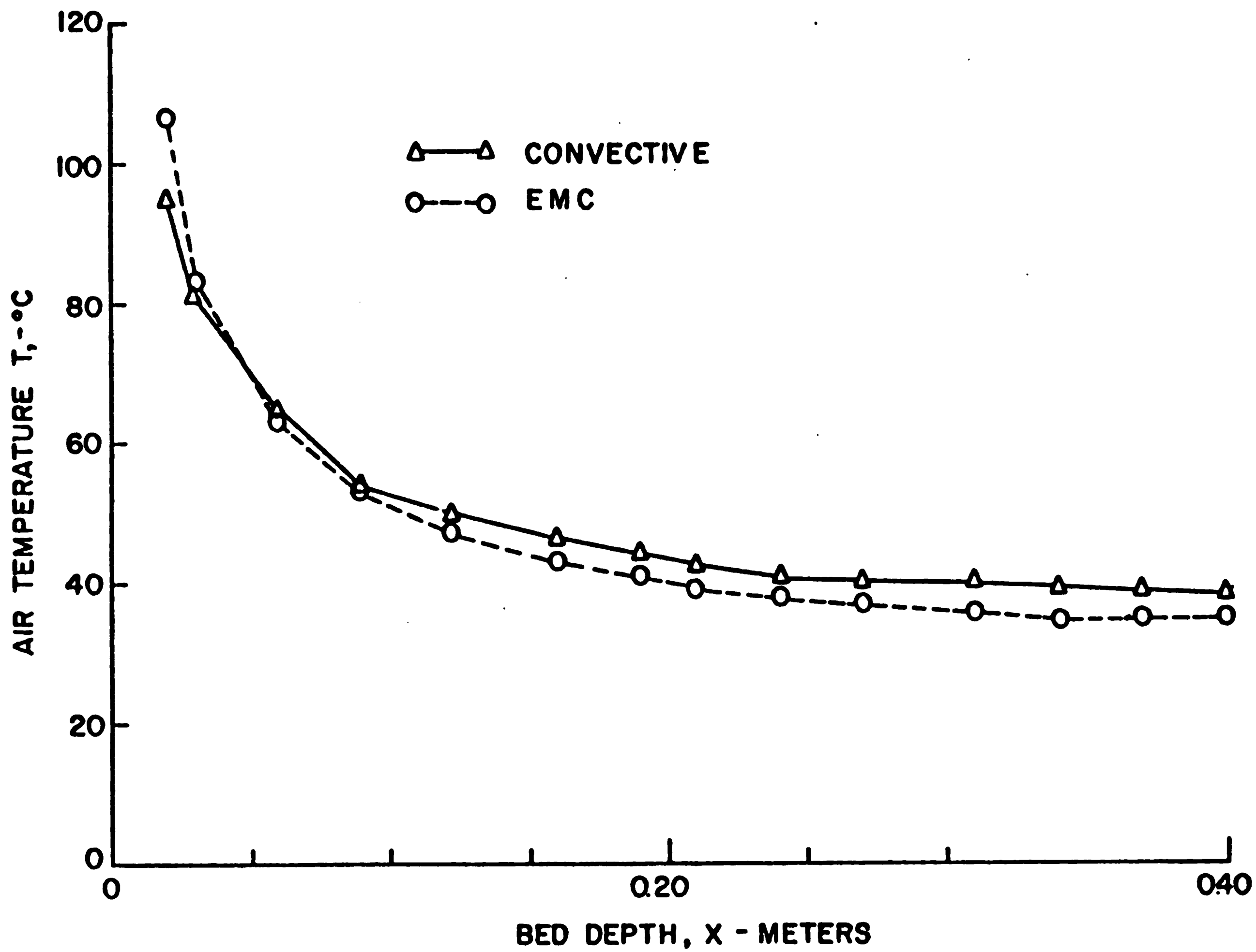


Figure 5-5. Comparison of air temperature profiles for the convective and EMC boundary conditions. The drying variables are listed in Table 5-1.

5-2 Effect of initial moisture content

Under field conditions, the moisture content of rice may vary from batch to batch. This can have a significant effect on the performance of a dryer. Figure 5-6 shows how the initial moisture content effects the drying rate, $\partial M/\partial x$. Note how the maximum drying rate increases with increasing initial moisture content. The increase in moisture removal rate results in lower moisture contents as shown in Figure 5-7.

The rapid increase in $\partial M/\partial x$ with increasing initial moisture content is due to an increase in the diffusion coefficient. Equation 2-11 shows that the diffusion coefficient increases exponentially with moisture content. Tabulated in Table 5-3 are the values for the diffusion coefficients at the different bed positions for three initial moisture content values.

In addition to increasing points removed, increasing the initial moisture content results in a reduction in the maximum and final grain temperatures (Table 5-4). One explanation for this is that more energy is utilized to vaporize the additional easily diffused moisture, and therefore, the amount of energy available for heating the grain is reduced. Eventually, the lower grain temperature begins to effect the rate of moisture diffusion and the rate of drying as can be observed in Figure 5-6. Because more moisture is removed at a higher initial moisture content for the same amount of energy, the energy efficiency is higher at the higher initial moisture contents (Table 5-3). Thus, an increase in the initial moisture content will lead to lower grain temperatures, higher energy efficiency and more moisture removed. In a later section, the effect of initial moisture content on head yield will be discussed.

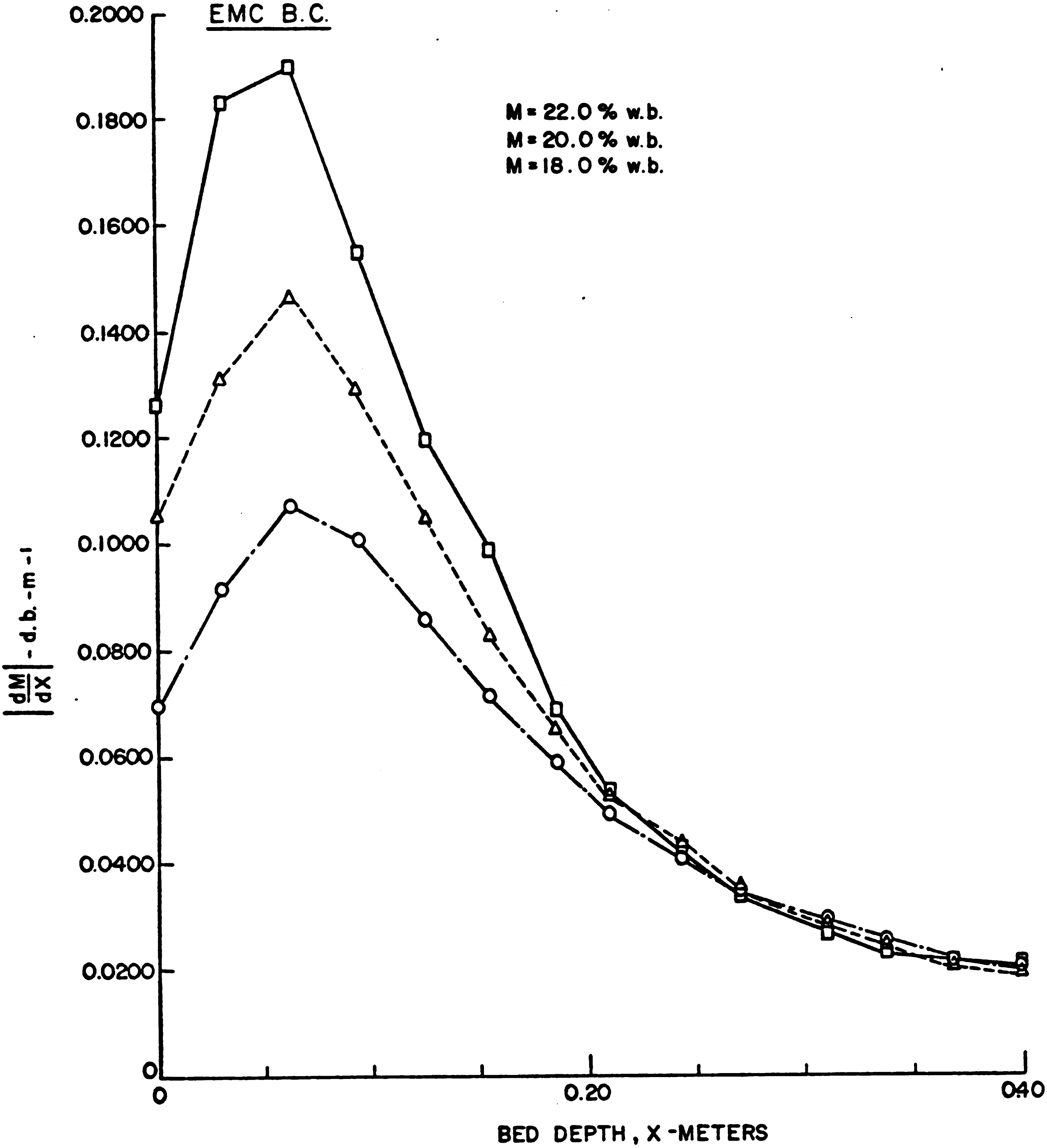


Figure 5-6. Effect of initial moisture content on the drying rate profiles. The drying variables are listed in Table 5-1.

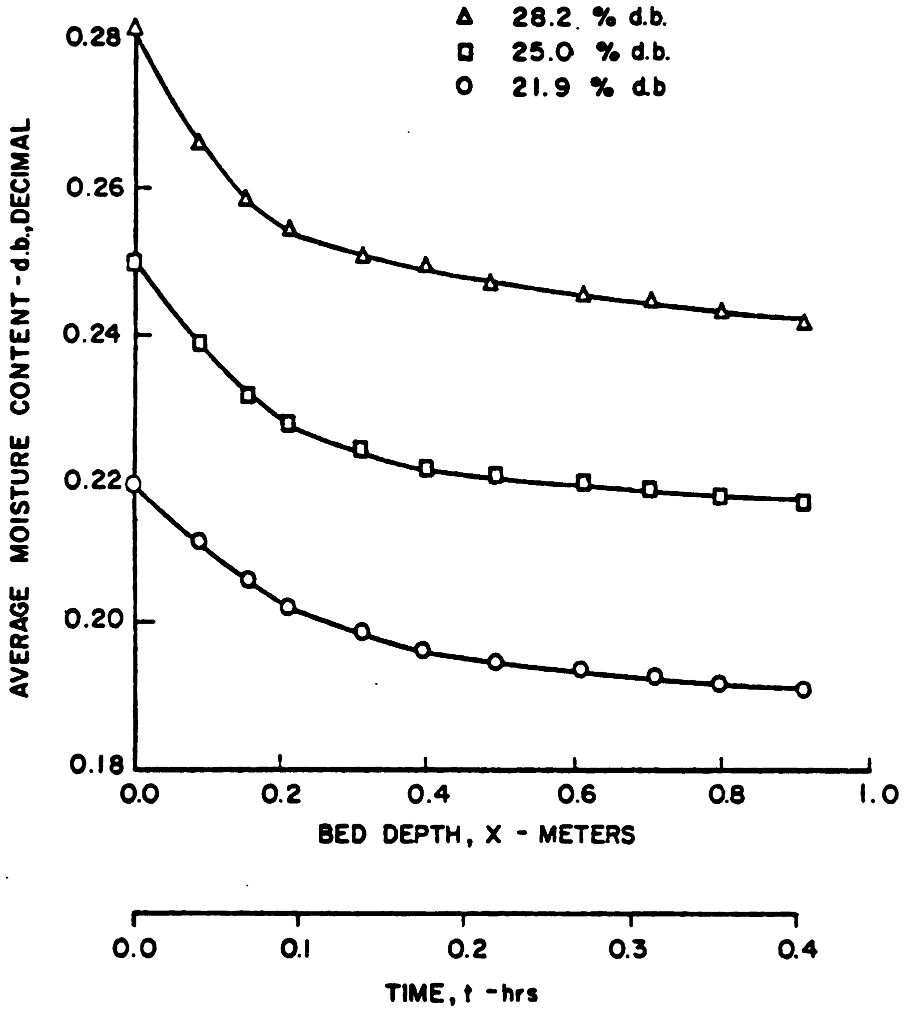


Figure 5-7. Effect of initial moisture content on the moisture content profiles. The drying variables are listed in Table 5-1.

Table 5-3. Comparison of the effect of initial moisture content on the diffusion coefficient at different bed depths. The values were calculated from Equation 2-11.

Bed Depth meter	Diffusion Coefficient cm^2/hr 18% w.b.	20% w.b.	22% w.b.
0.000	0.0004	0.0005	0.0007
0.095	0.0015	0.0017	0.0019
0.155	0.0014	0.0015	0.0016
0.311	0.0011	0.0011	0.0012
0.491	0.0009	0.0010	0.0010
0.616	0.0008	0.0009	0.0009
0.765	0.0008	0.0008	0.0008
0.914	0.0007	0.0008	0.0007

Table 5-4. Summary of the results from three simulations with different initial moisture contents. Drying variables are listed in Table 5-1.

	Stage 1					Stage 2				
Initial MC % wb	Θ_{max} °C	Θ_f °C	Final MC % wb	Points Removed % wb	Energy Efficiency Kcal/Kg H_2O	Θ_{max} °C	Θ_f °C	Mf % wb	Points Removed % wb	Energy Efficiency Kcal/Kg H_2O
22.0	36.5	28.9	19.5	2.5	718	41.5	34.7	17.2	2.3	851
20.0	39.2	32.7	17.8	2.2	875	45.5	38.1	15.5	2.3	875
18.0	41.9	35.4	16.1	1.9	1029	49.3	41.4	13.9	2.2	954

5-3 Effect of initial grain temperature

The effect of initial grain temperature on the moisture content distribution within the bed is shown in Figure 5-8. An increase in the initial grain temperature results in an increase in the amount of moisture removed and higher grain temperatures as shown in Table 5-3. The increase in the moisture removed can be attributed to an increase in the grain temperature. Increasing the grain temperature results in higher values for the diffusion coefficient (Table 5-6) and more moisture migration to the surface.

In addition to increasing moisture removal rate and grain temperature, increasing the initial grain temperature results in higher energy efficiency as shown in Table 5-5. The explanation for this is that more moisture is removed due to higher grain temperatures, while the energy used to heat the air remains constant. Thus, the overall effects of increasing the initial grain temperature are an increase in moisture removed, higher grain temperature, and higher energy efficiency.

5-4 Effect of drying air temperature

Increasing the drying air temperature significantly increases the amount of moisture removed as shown in Figure 5-9. There seems to be two factors responsible for this. First, part of the additional energy goes to increasing the temperature of the product, as shown in Table 5-7. As the product temperature increases, so does the diffusion coefficient and the rate of moisture migration to the surface. In addition, at higher temperatures, less energy is needed to remove the moisture from the surface of the grain.

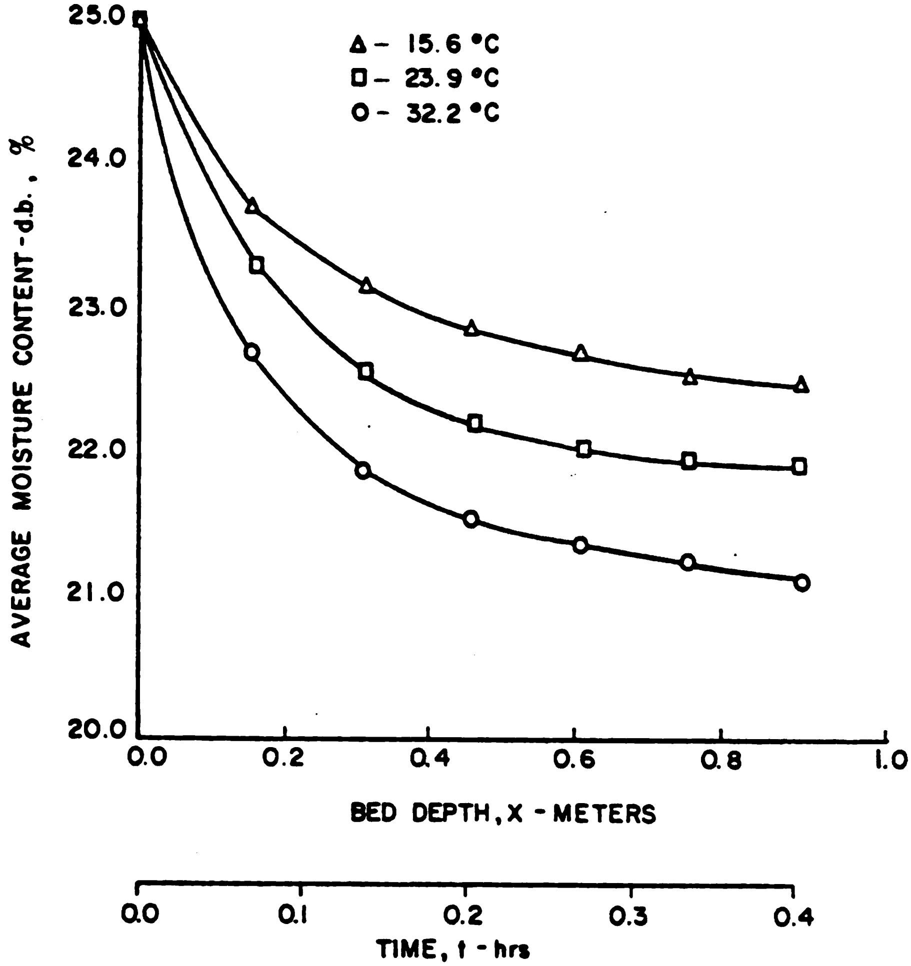


Figure 5-8. Effect of initial grain temperature on the moisture content profile. The drying variable are listed in Table 5-1.

Table 5-5. Summary of the results obtained from three drying simulations using the standard operating conditions listed in Table 5-1 for a single stage dryer. The initial moisture content was varied as shown below.

Initial Moisture Content % wb	Initial Grain Temp °C	Maximum Grain Temp °C	Final Grain Temp °C	Final Moisture Content % wb	Points Removed % wb	H_2O Kg	Energy Efficiency Kcal/Kg H_2O
18.0	18.3	35.9	30.8	18.2	1.8	3.6	1070
20.0	26.7	39.8	33.0	17.7	2.3	4.4	859
22.0	32.2	42.2	34.8	17.4	2.6	5.7	757

Table 5-6. Comparison of the effect of initial grain temperature on the diffusion coefficient at different bed depths. The values were calculated from Equation 2-11.

Bed Depth Meter	Diffusion Coefficient cm^2/hr 18.3°C	26.7°C	32.2°C
0.000	0.0003	0.0007	0.0011
0.159	0.0012	0.0015	0.0017
0.308	0.0010	0.0011	0.0013
0.463	0.0008	0.0010	0.0011
0.613	0.0008	0.0009	0.0010
0.765	0.0007	0.0008	0.0009
0.917	0.0007	0.0008	0.0009

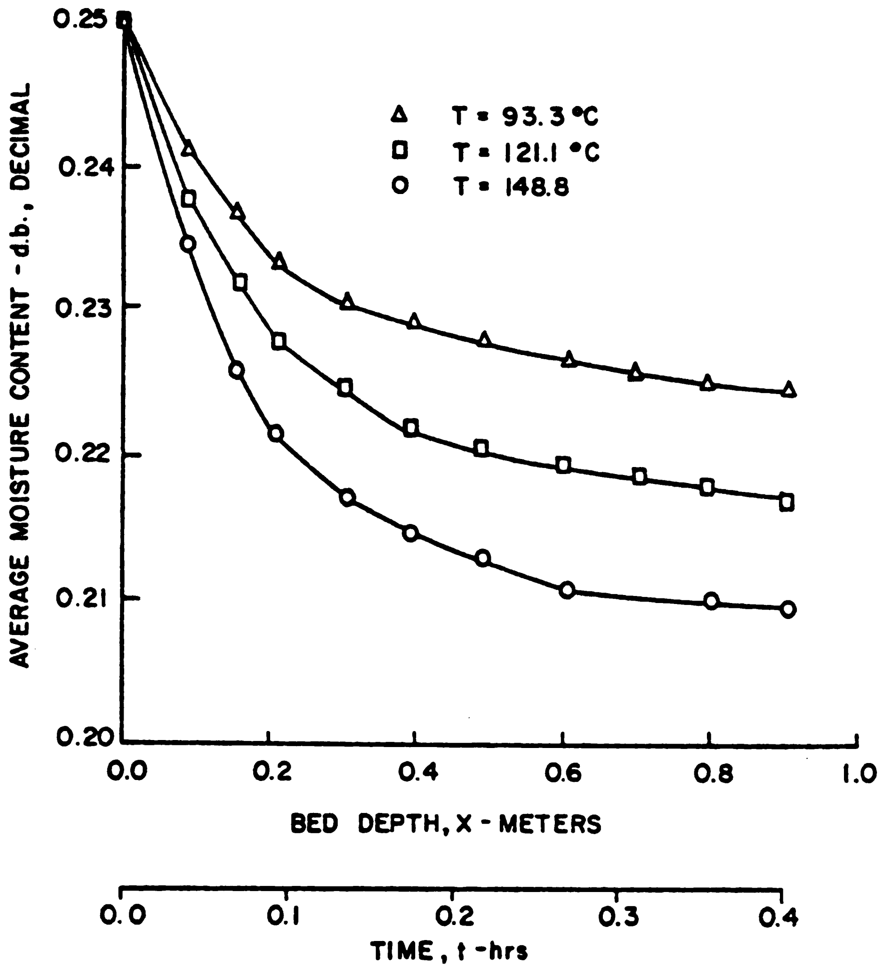


Figure 5-9. Effect of drying air temperature on the moisture content profile. The drying variables are listed in Table 5-1.

Table 5-7. Summary of the results from three simulations with different inlet air temperatures. The drying variables are listed in Table 5-1.

	Stage 1					Stage 2				
Hot Air Temp °C	Θ_{max} °C	Θ_f °C	Final MC % wb	Points Removed % wb	Energy Efficiency Kcal/Kg H_2O	Θ_{max} °C	Θ_f °C	M_f % wb	Points Removed % wb	Energy Efficiency Kcal/Kg H_2O
93.3	35.1	29.5	18.3	1.7	807	38.9	33.1	16.7	1.6	843
121.1	39.2	32.7	17.8	2.2	875	45.5	38.1	15.5	2.3	876
148.9	43.1	35.7	17.3	2.7	911	51.9	42.9	14.4	2.9	895

The effect of drying air temperature on the energy efficiency of the dryer is tabulated in Table 5-5. According to the simulated results, the energy efficiency of the dryer decreases with increasing hot air temperature, and keeping the other drying variable fixed. The reason for this is that as the air temperature is increased, more energy is exhausted and the relative humidity of the air is lower; therefore, the full drying potential of the air is not used. The results indicate that operating at higher air temperature and lower airflow or higher grain flow rates would result in better efficiencies.

In assessing the impact of the drying air temperature on the cracking of rice, factors such as air and grain flow and initial moisture content must be considered along with the drying rate and maximum grain temperature. From the field work conducted during this investigation, it can be concluded that rice can be safely dried at a drying air temperature of 121°C and airflow of 0.17 m^3/hr. A more complete discussion on the effect of air temperature on cracking will be presented in a later chapter.

Besides increasing the moisture removed and maximum grain temperature in the first stage, increasing the drying air temperature does significantly increases the maximum grain temperature even more in the succeeding drying stage, as shown in Table 5-7. This will result in additional moisture removal and an increase in the risk of cracking.

5-5 Effect of air flow

Airflow has a significant effect on the drying of rice as shown in Figures 5-10 and 5-11. This can be attributed to a significant increase in the total energy supplied. The increase in the total energy supplied

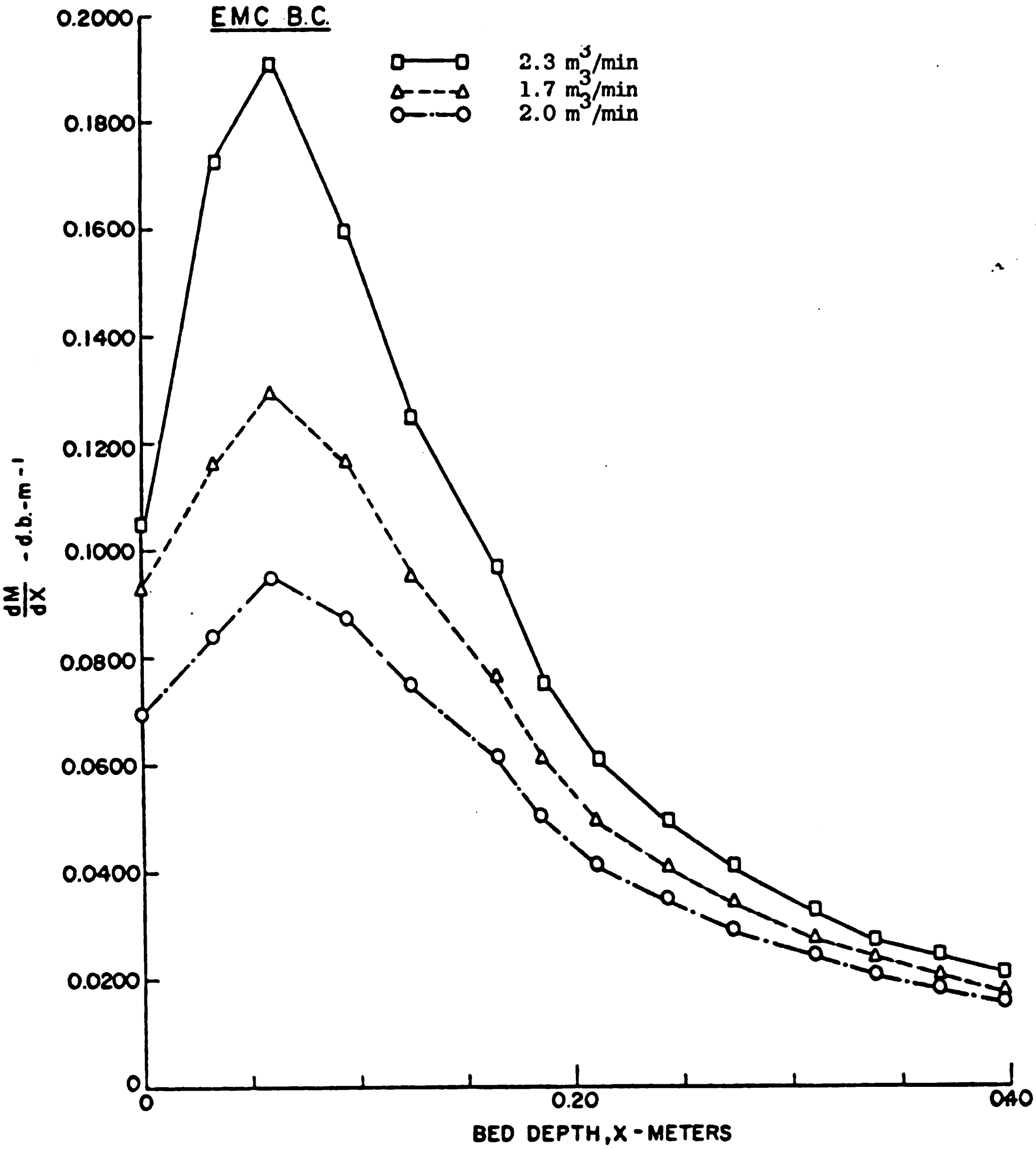


Figure 5-10. Effect of airflow on the drying rate profile. The drying variables are listed in Table 5-1.

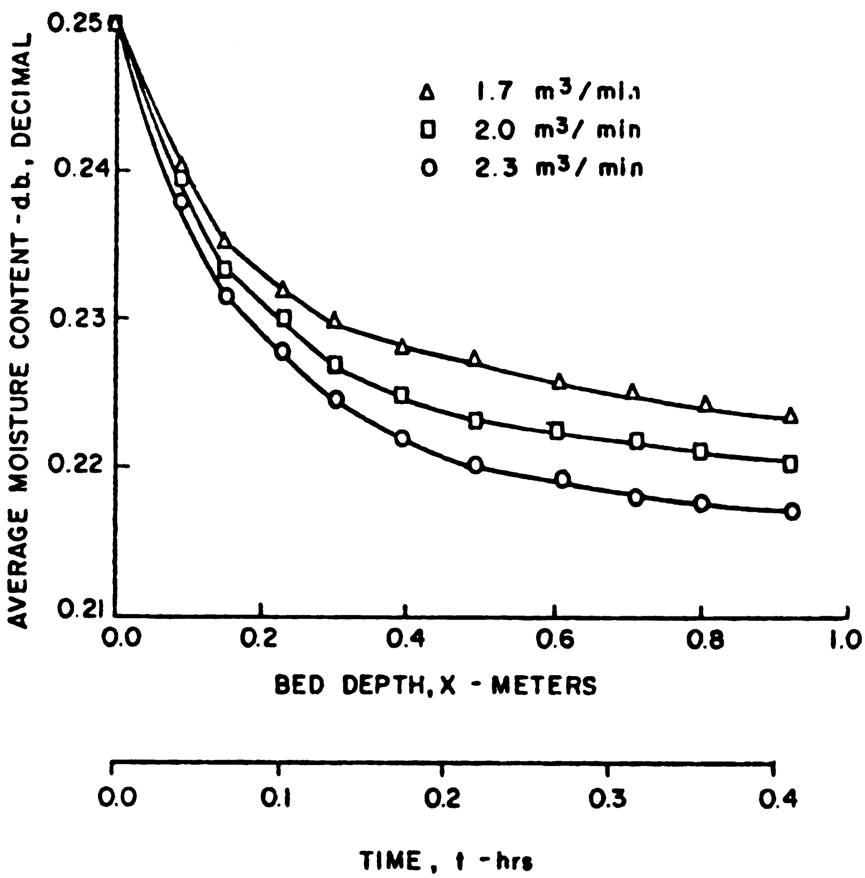


Figure 5-11. Effect of airflow on the moisture content profile. The drying variables are listed in Table 5-1.

results in an increase in the grain temperature (Table 5-8) and therefore, an increase in the diffusion of moisture. In addition, energy efficiency of the dryer decreases with an increase in airflow. This can be attributed to the fact that more energy is exhausted without a significant increase in the humidity; thus, the full drying potential of the air is not used.

The simulated results tabulated in Table 5-8 indicate that increasing the air flow rate does not cause a large enough increase in the grain temperature or points removed to cause a significant reduction in head yield. However, it cannot be stated conclusively that higher airflows coupled with higher drying temperatures and lower grain flows will not cause significant cracking. Airflow, along with grain flow and drying air temperatures, can be used to control grain temperatures and moisture gradients.

5-6 Effect of grainflow

Grainflow strongly effects the rate of moisture removed as shown in Figures 5-12 and 5-13. The reason for this is that as the grain velocity is increased, the retention time of the product in the dryer is shortened and the temperature of the product is decreased, as shown in Table 5-9. This can be attributed to the fact that as the grain flow is increased, more grain has to be dried with the same amount of energy resulting in a reduction in grain temperatures and the amount of moisture removed.

It was stated earlier that grain flow and airflow could be used to control grain temperature and moisture gradients. From a logistical point of view, it is easier to use grain flow. It is much simpler to change the speed of a discharge auger than to change the pully on a fan

Table 5-8. Summary of the results from three simulations with different airflows. The other drying variables are listed in Table 5-1.

	Stage 1					Stage 2				
Air flow m^2/min	Θ_{max} °C	Θ_f °C	Final M % wb	Points Removed % wb	Energy Efficiency Kal/Kg H_2O	Θ_{max} °C	Θ_f °C	Final MC % wb	Points Removed % wb	Energy Efficiency Kcal /Kg H_2O
1.69	36.5	30.3	18.3	1.7	807	41.1	34.9	16.6	1.7	832
1.98	37.9	31.6	18.0	2.0	845	43.4	36.6	16.0	2.0	862
2.26	39.2	32.7	17.8	2.2	875	45.5	38.1	15.5	2.3	875

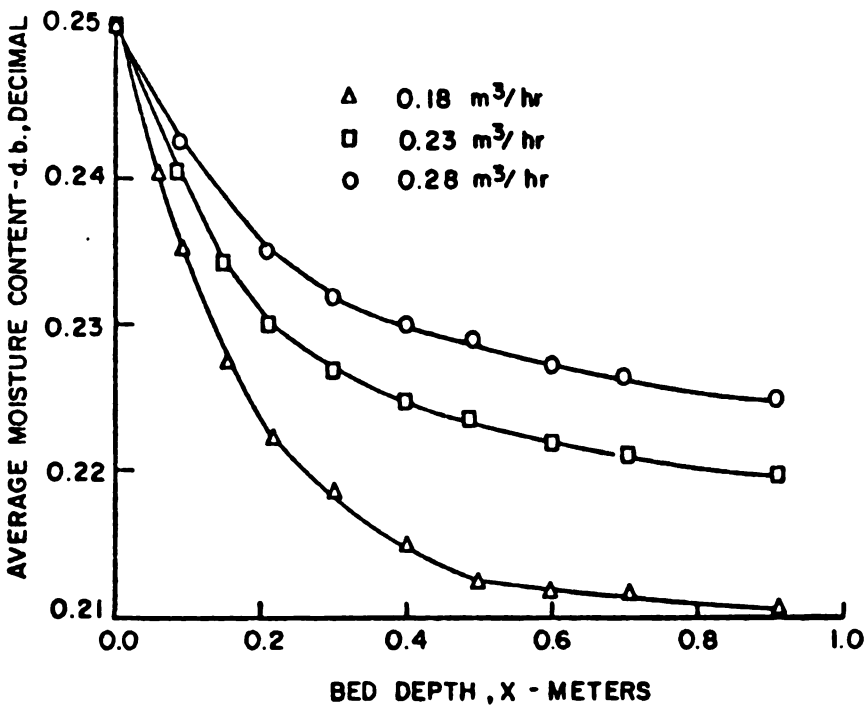


Figure 5-12. Effect of grain flow on the moisture content profile. The drying variables are listed in Table 5-1.

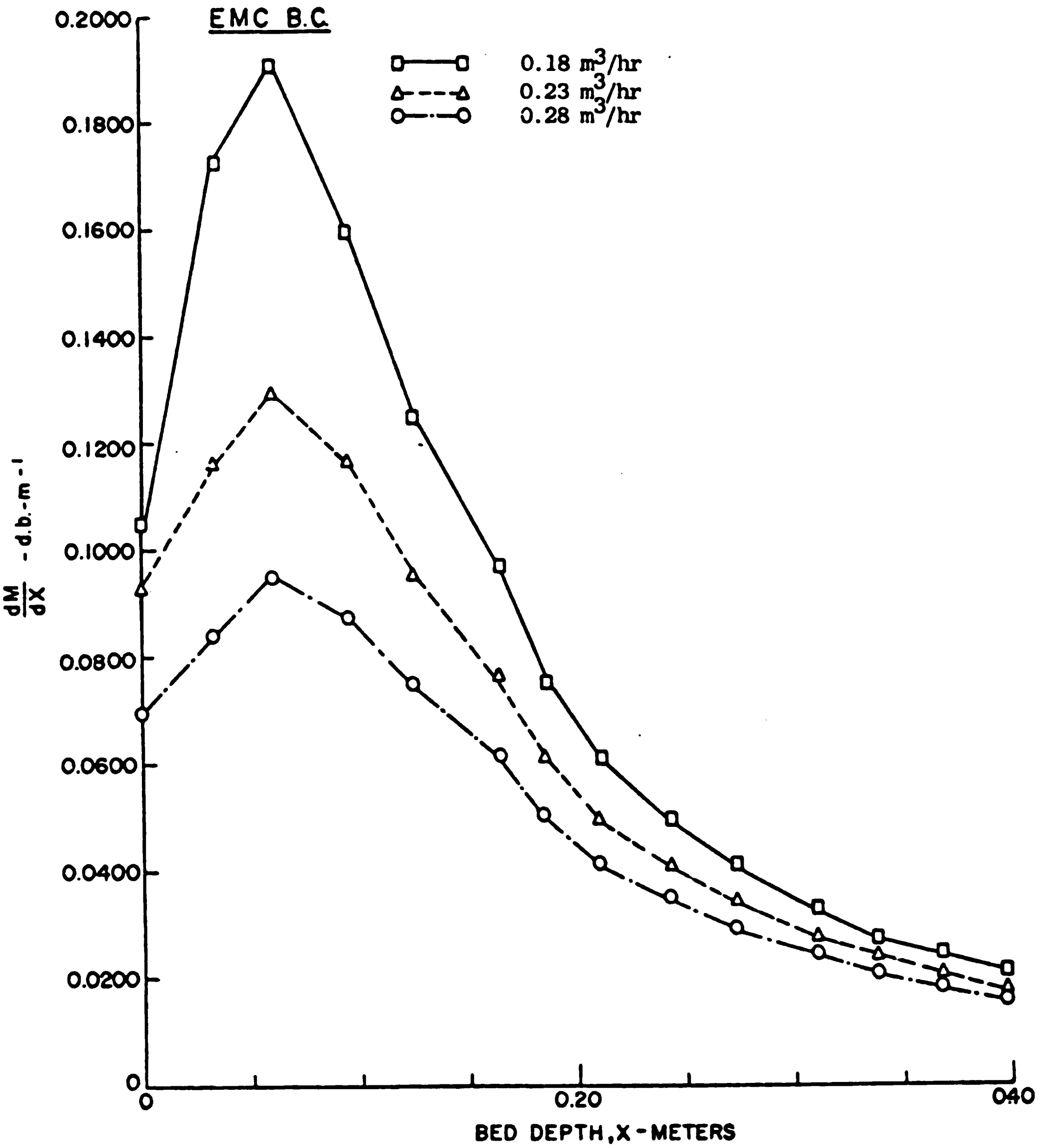


Figure 5-13. Effect of grain flow on the drying rate profile. The drying variables are listed in Table 5-1.

Table 5-9. Summary of the results from three simulations with different grain flow rates. The drying variables are listed in Table 5-1.

	Stage 1					Stage 2				
Grain flow m^3/hr	Θ_{max} °C	Θ_f °C	Final MC % wb	Points Removed % wb	Energy Efficiency Kcal/Kg H_2O	Θ_{max} °C	Θ_f °C	Final MC % wb	Points Removed % wb	Energy Efficiency Kcal/Kg H_2O
0.18	40.7	33.8	17.4	2.6	878	48.1	39.9	14.6	2.4	891
0.23	38.7	32.3	18.0	2.0	874	44.5	37.4	15.9	2.1	872
0.28	37.1	31.3	18.4	1.6	874	42.0	35.6	16.7	1.7	868

and thus, the horsepower requirement of a fan. In addition, the response of the drying rate ($\frac{dM}{dX}$) to changes in grain flow is greater than that to changes in airflow.

5.7 Effect of bed depth

Increasing the length of a concurrent flow dryer results in a lower final grain temperature and moisture content as shown in Table 5-10. However, it has no effect on the maximum grain temperature. Because more moisture is removed as the length is increased, the energy efficiency will increase to a limited degree. Eventually, a point will be reached were the energy required to move the air will negate any additional energy saving from increasing length.

In addition to lowering the final grain temperature and moisture content, increasing the bed depth results in a more uniform moisture distribution. The explanation for this is that during the latter portion of the drying process, the rate of moisture removed from the surface is smaller than the rate of diffusion from the center of the kernel to the surface of the kernel. This results in tempering of the rice.

5-8 Effect of ambient air temperature and humidity

Ambient air temperature and humidity have a marginal effect on high temperature drying of rice as shown in Table 5-11. The reason for this is that during the drying process, the rice kernel will approach equilibrium. The equilibrium moisture content is a function of the air temperature and humidity, as given by (Equation (2-15). When the

Table 5-10. Effect of dryer length on the drying performance of a single stage concurrent flow dryer. The drying variables are listed in Table 5-1.

Bed Depth Meters	Maximum Grain Temp °C	Final Grain Temp °C	Final Moisture Content % wb	Points Removed % wb	H_2O Removed Kg	Energy Efficiency Kcal/Kg H_2O
0.91	38.5	32.1	17.9	2.1	4.16	911
1.22	38.5	31.2	17.8	2.2	4.41	870
1.52	38.5	29.7	17.6	2.4	4.76	8.19

Table 5-11. Effect of ambient air condition on the drying performance of a concurrent flow dryer. The other drying variables are listed in Table 5--1.

Ambient Air Temp °C	Relative Humidity %	Absolute Humidity lb/lb	Final Grain Temp °C	Final Moisture Content % wb	Energy Efficiency Kcal/Kg H_2O
12.8	95.0	0.009	33.1	17.7	995
23.9	50.0	0.009	32.8	17.8	889
35.0	25.0	0.009	32.4	17.9	785
23.9	60.0	0.012	32.3	17.9	938
29.0	50.0	0.012	32.7	17.9	882
35.0	40.0	0.012	32.0	18.0	827
23.9	80.0	0.015	32.5	17.9	945
35.0	50.0	0.015	32.1	18.0	834

air is heated to high temperatures (93.3°C or higher), the relative humidity becomes very small and the EMC approaches zero regardless of the initial relative humidity of the air, hence, the drying rate is essentially constant regardless of the ambient humidity.

5-9 Effect of tempering

The moisture distribution in a rice kernel is shown in Figure 5-14 for different tempering periods. As the tempering time is increased, the moisture distribution becomes more uniform. The tempering time required to obtain a uniform distribution is a function of the grain temperature and moisture content as shown in Table 5-12. At high grain temperatures and moisture contents, moisture diffusion through the kernel occurs rapidly. Therefore, rice at high temperatures and moisture content tempers faster than rice at lower temperature and moisture content.

Tabulated in Tables 5-13, 5-14, and 5-15 is a summary of the results from a series of simulations. The results indicate that tempering had very little effect on the maximum and final grain temperature, and on the moisture removed in the second stage. In addition, tempering had only a marginal effect on the energy efficiency of the dryer. This can be attributed to the uniform moisture distribution in the kernel after drying in a concurrent flow dryer as shown in Table 5-12. Even at a drying temperature of 176.7°C and no tempering the surface moisture content, M_s is within 82% of the average moisture content of the kernel.

Brook (1977) obtained similar results in his investigation of concurrent flow corn drying; he attributed this to the uniformity of the moisture content and temperature profile within the kernel after drying in

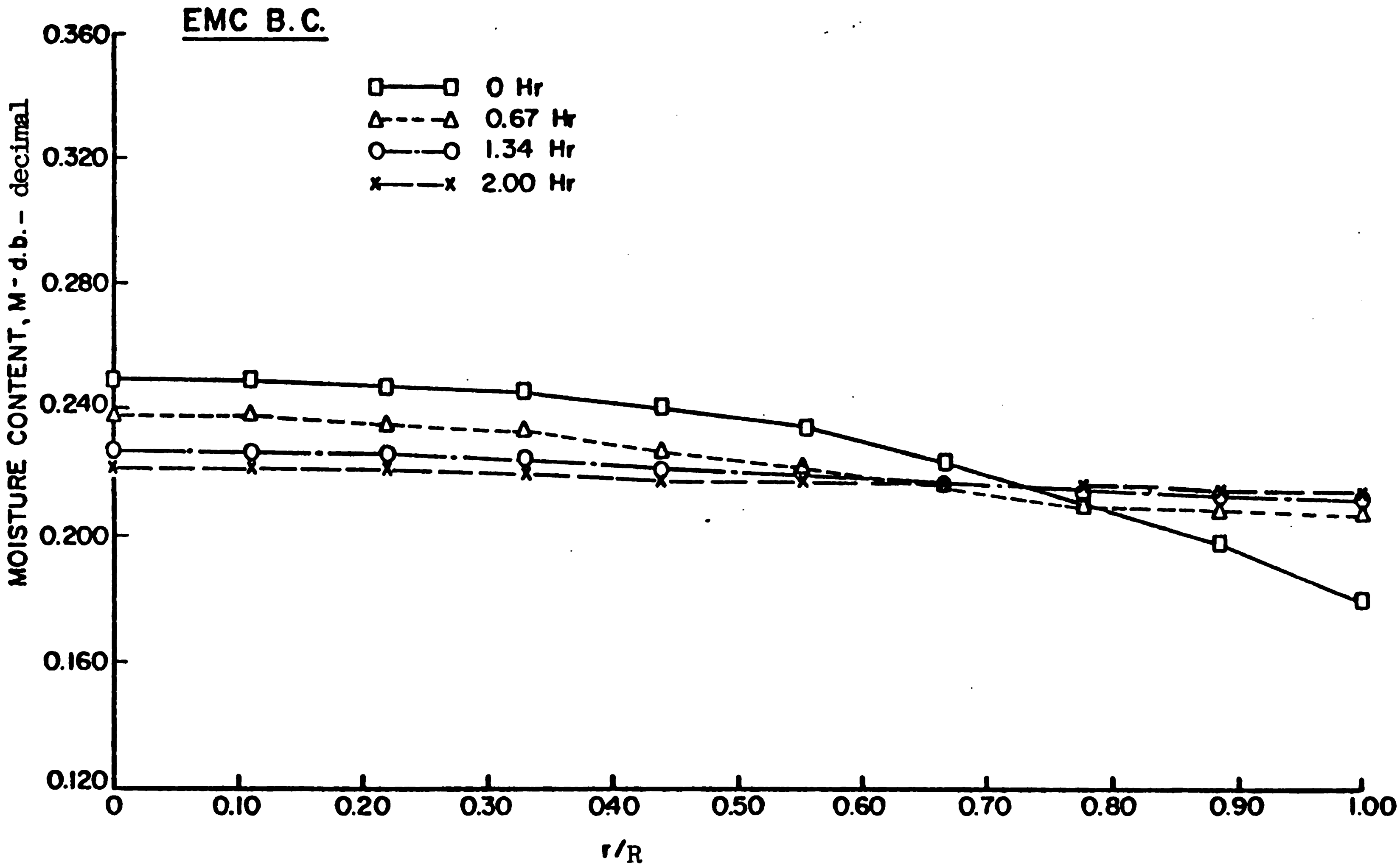


Figure 5-14. Comparison of moisture distribution in a rice kernel after different tempering periods. The drying variables are listed in Table 5-1.

Table 5-12. Effect of drying temperature and initial moisture content, and time on the ratio of surface moisture content to average moisture content.

Tempering Time	$M_S/\bar{M}$								
	M = 18.0% w.b.			M = 20.0% w.b.			M = 22.0% w.b.		
	T, °C			T, °C			T, °C		
hr	65.5	121.1	176.1	65.5	121.1	176.7	65.5	121.1	176.7
0.00	0.860	0.817	0.785	0.876	0.835	0.806	0.839	0.811	0.816
0.50	0.954	0.942	0.937	0.951	0.945	0.945	0.944	0.938	0.945
1.00	0.968	0.968	0.971	0.973	0.973	0.974	0.963	0.971	0.979
1.50	0.983	0.983	0.988	0.981	0.986	0.989	0.978	0.084	0.989
2.00	0.988	0.989	0.994	0.990	0.991	0.994	0.986	0.992	0.994
2.50	0.993	0.994	0.999	0.994	0.995	0.999	0.990	0.996	0.999
3.00	0.998	0.999	0.999	0.994	0.999	0.999	0.990	0.996	1.000
3.50	0.998	0.999	0.999	0.999	0.999	0.999	0.998	0.100	1.000
4.00	0.998	0.999	0.999	0.999	0.999	0.999	0.999	0.100	1.000

Table 5.13. Summary of four simulations of the second stage with four different tempering times. The temperature of the drying air is 65.6°C. All other drying variables are listed in Table 5-1.

Tempering Time hr	Maximum Grain Temp °C	Final Grain Temp °C	Final Moisture Content % w.b.	Points Removed % w.b.	Energy Efficiency Kcal/Kg H_2O
0.00	31.8	27.8	17.83	1.0	823
0.67	31.6	27.4	17.80	1.1	796
1.34	31.5	27.3	17.79	1.1	785
2.00	31.5	27.3	17.78	1.1	779

Table 5-14. Summary of four simulations of the second stage with four different tempering times. The drying variables are listed in Table 5-1.

Tempering Time hr	Maximum Grain Temp °C	Final Grain Temp °C	Final Moisture Content % w.b.	Points Removed % w.b.	Energy Efficiency Kcal/Kg
0.00	46.2	38.8	15.6	2.2	912
0.67	45.7	38.3	15.6	2.2	888
1.34	45.6	38.2	15.5	2.3	880
2.00	45.5	38.1	15.5	2.3	875

Table 5-15. Summary of four simulations of the second stage with four different tempering times. The temperature of the drying air is 176.6°C and the air flow is 2.83 m^3/min. The other drying variables are listed in Table 5-1.

Tempering Time hr	Maximum Grain Temp °C	Final Grain Temp °C	Final Moisture Content % w.b.	Points Removed % w.b.	Energy Efficiency Kcal/Kg
0.00	60.1	49.0	13.4	4.3	950
0.67	59.1	48.4	13.3	4.4	933
1.34	58.8	48.2	13.3	4.4	928
2.00	57.8	47.3	13.2	4.5	911

a concurrent flow dryer. The results obtained by Calderwood and Webb (1971) and the results from the author drying test support the simulated results.

Although tempering does not significantly improve the drying performance of a concurrent flow dryer, it does reduce the moisture gradient in the kernel as shown in Figure 5-14. This reduction in the moisture gradient should result in an improvement in the head yield. In a later section, the problem of predicting the impact of tempering on head yield will be discussed.

5-10 Number of stages

Throughout most of this investigation the primary emphasis has been on one- and two-stage dryers with the standard operating conditions listed in Table 5-1. The main reason for this is that most of the rice used in the experiments was in the moisture content range of 17 to 20.0% w.b. The dryer settings in Table 5-1 are quite adequate for this initial moisture content. However, for very moist rice in the initial moisture content range between 20-24% w.b., a different set of dryer settings or dryer design is needed.

On alternative is to raise the drying air temperature to 150°C or higher. This may result in a final moisture content of approximately 14.0-14.5%. Increasing the air temperature to 150°C or higher might cause significant cracking at the low grain flow rates. The drying experiments have proven that rice can be dried safely at 121.1°C. However, at that temperature, the head yield is very sensitive to the grain flow and the sensitivity would increase with an increase in the drying air temperature.

The best alternative is to choose a three-stage dryer, using for example, the dryer settings listed in Table 5-16. A three-stage dryer has greater flexibility. If the moisture content of the rice being harvested is around 22% w.b. the operator can use the dryer settings in Table 5-16 for a three-stage dryer. This will insure him that the final moisture content is low enough for safe storage. If the rice harvested is lower in moisture content, around 18 or 20% w.b., an operator has the option of using a three- or two-stage dryer as shown in Table 5-16. In summary, a three-stage dryer provides the operator with more flexibility in selecting drying air temperature and better quality control than one- and two-stage dryers.

5-11 Grain quality

It is very difficult to predict the amount of cracking that occurs during the drying of rice. Arora et al. (1973) conducted a series of experiments on rice and observed a strong correlation between the drying air temperature and head loss (Figure 5-15). If the same correlation is used for the concurrent flow dryer the values predicted (40% broken kernels by weight at 121°C) far exceed the maximum value obtained from the field (10% broken kernels by total weight at 121°C). Part of this may be attributed to the difference in drying technique. In the study conducted by Arora, rice was dried in a thin layer at a constant temperature from 22 to 13% w.b. in which the grain temperature equals the air temperature. In the concurrent dryer, the grain is constantly passing by the hot inlet air entrance without reaching the inlet air temperature. Also, the residence time at the maximum temperature is very short, on the order of a couple minutes.

Table 5-16. Possible dryer settings for a multistage concurrent flow dryer.

Initial Moisture Content % wb	Stage No.	Inlet Air Temp °C	Grain Flow m^3/hr	Airflow Rate m^3/min	Length M	Final Moisture Content % w.b.	Maximum Grain Temp °C	Final Grain Temp °C	Energy Efficiency Kcal/Kg H_2O
22.0	1	121.1		2.41	1.5	19.1	36.4	26.7	700
	2	107.2	0.21	2.41	1.5	17.0	39.5	32.0	857
	3	93.3		2.41	1.5	15.1	42.1	34.6	848
	1	121.1		2.41	1.5	18.9	37.0	27.2	717
	2	107.2	0.19	2.41	1.5	16.6	40.6	32.9	866
	3	93.3		2.41	1.5	4.5	43.6	35.7	864
20.0	1	107.2		2.27	1.5	18.2	36.5	28.9	814
	2	93.3	0.21	2.27	1.5	17.9	39.1	32.3	846
	3	79.4		2.27	1.5	14.7	40.0	33.6	840
	1	107.2	0.19	2.41	1.5	17.5	39.3	30.9	846
	2	93.2		2.41	1.5	15.2	43.6	35.4	867
18.0	1	107.2	0.21	2.27	1.5	16.2	38.7	32.1	1002
	2	93.3		2.27	1.5	14.5	42.5	35.3	892

A similar problem is encountered if the correlation of Schmidt and Jebe (1959) (Figure 5-16) is used. They observed a correlation between the saturated deficit of the drying air and head yield. If this correlation is used for the concurrent flow dryer the predicted value (35% at 121°C) also far exceeds the value obtained in the field (10% at 121°C). The saturated deficit is only a measure of the drying potential of the air and therefore, cannot be used to assess the effect of the initial moisture content, maximum grain temperature and moisture gradient.

Figure 5-14 is a plot of the moisture distribution in a rice kernel after tempering for different time periods. The distribution serves as the initial condition for the second stage. As stated earlier, there is no significant difference in the grain temperature and final moisture content leaving the second stage as shown in Table 5-14. But there is a significant difference in the moisture distribution and gradients within the kernels, because the initial distribution entering the second stage is different. A similiar problem is encountered if a head yield-temperature correlation is used to assess the effect of initial moisture content on head yield.

The results in Table 5-4 indicate that the maximum and final grain temperatures decrease with an increase in the initial moisture content. The Arora et al. correlation predictes a decrease in head yield loss for an increase in moisture content. However, this contradicts the observation of Kunze and Hall (1965, 1967) and Mannapperuma and Wratten (1975). Therefore, any model that does not consider the moisture gradient inside the kernel cannot be used to predict the effect of drying temperature, initial moisture content, and tempering on head yield.

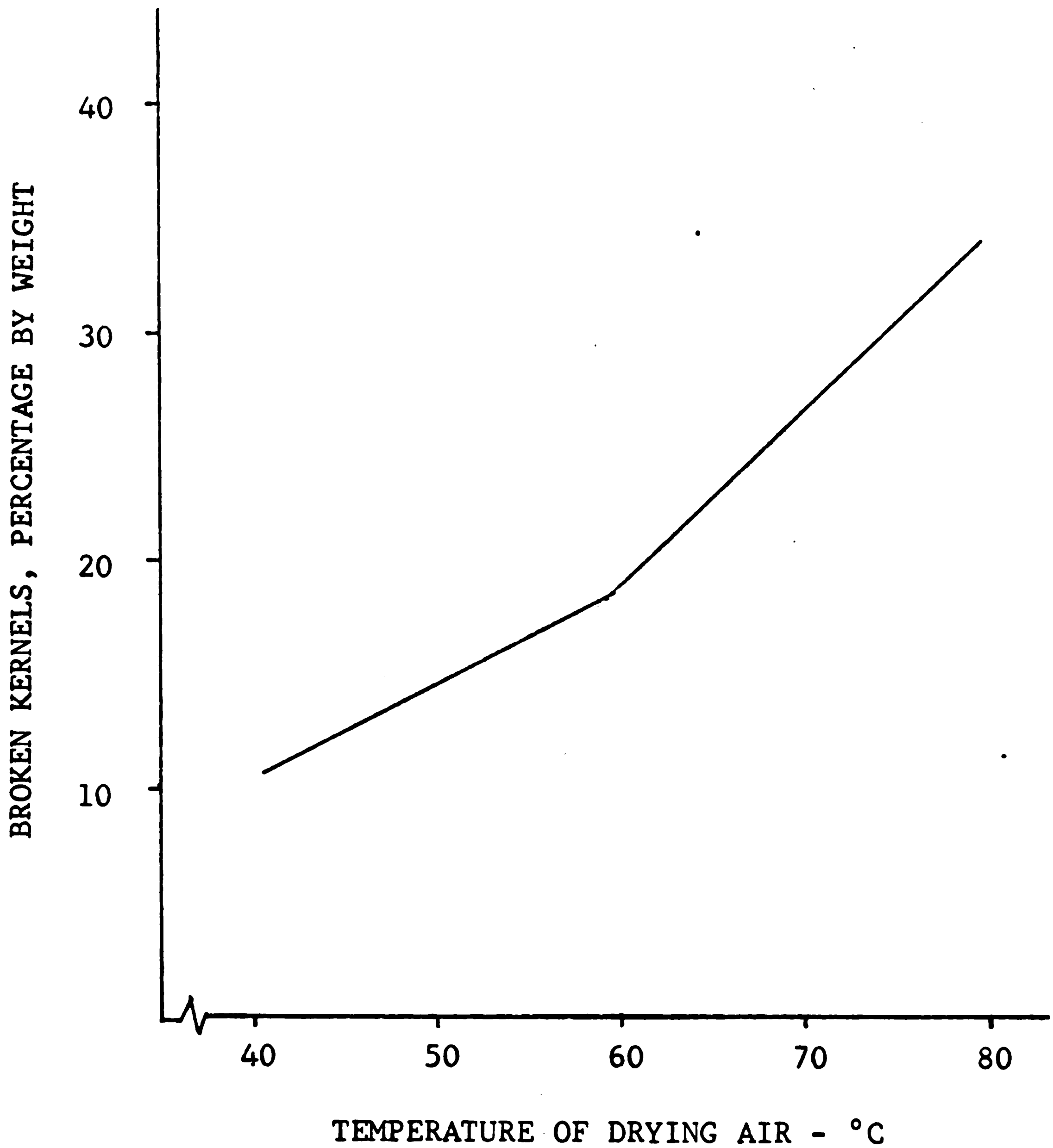


Figure 5-15. Broken kernels versus air temperature.

Source: Arora, Henderson and Burkhardt (1973)

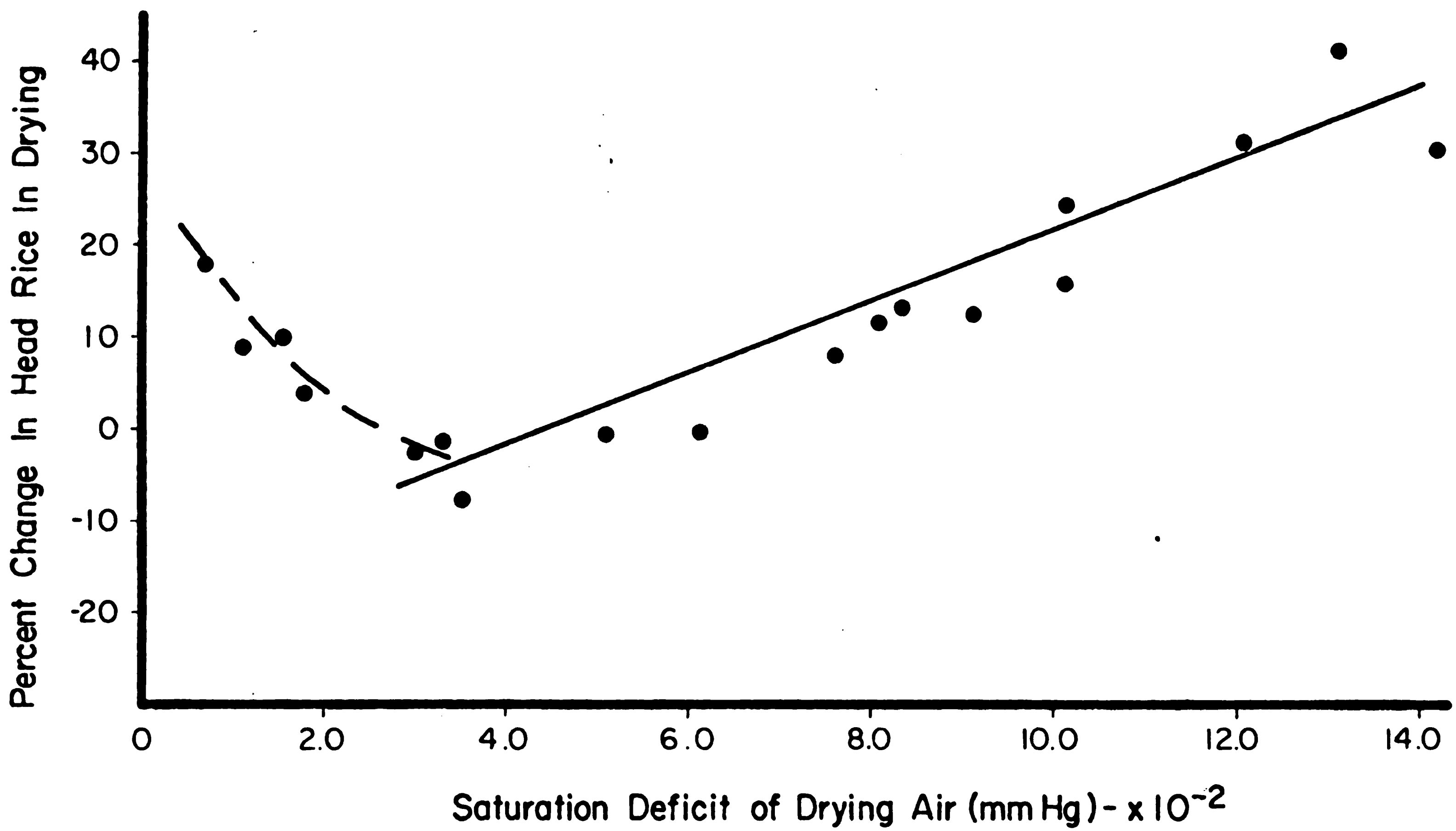


Figure 5-16. Percent loss of head rice versus saturation deficit of the drying air.

Source: Schmidt and Jebe (1959)

More research has to be conducted on moisture movement from the grain to the environment before an adequate model can be developed for predicting head losses. Until better models are developed, the dryer designer will have to rely on field tests to determine the effect of drying air temperature, initial moisture content and tempering on head yield losses. From the experiments conducted by this author, it can be concluded that rice can be safely dried at temperatures as high as 121.1°C provided that the other drying variables are within the range listed in Table 5-16.

IV. SUMMARY AND CONCLUSION

Two computer models of multistage concurrent flow drying were developed and verified by limited pilot scale, field experiments with a long grain rice variety called "Labelle." Both models are based on radial moisture diffusion. One model employes a convective type boundary condition to describe moisture transfer at the grain surface. The other model uses an EMC boundary condition. Although this investigation was conducted with one rice variety, the results obtained can be extrapolated to other varieties, because the radii, r, of the other varieties are approximately the same, and the drying rate is proportional to $1/r^2$.

Both models yield acceptable approximations to the drying process. However, the results are obtained by traveling two different paths. The magnitude and position of the maximum rate of change of the moisture content, $\partial M/\partial X$ and the maximum rate of change of the grain temperature $\partial \theta/\partial X$ are different for the two models. This is of little significance if the models are only being used to predict the amount of moisture removed and the final grain temperature. However, if the models are also used to predict the maximum stresses due to the moisture gradients, then the models will predict different quality changes for the same drying condition.

For this investigation the EMC model was used to obtain the operating characteristics of a multistage dryer. The EMC model was selected because it predicts the final moisture content more accurately, which is important for the determination of the number of passes needed to dry rice to 14.5% w.b.

The following conclusions were drawn from the dryer simulations and field experiments:

1. Under constant drying conditions, an increase in the initial moisture content results in an increase in the moisture removal rate and the energy efficiency of the dryer and a reduction in the maximum and final grain temperature.

2. An increase in the initial grain temperature under constant drying conditions results in an increase in the moisture removal rates, higher grain temperatures, and higher energy efficiencies.

3. Under constant drying conditions, an increase in the drying air temperature results in an increase in the moisture removed and the maximum grain temperature. Also, for the standard drying conditions used in this investigation (Table 5-1) the energy efficiency of the dryer decreased with an increase in the drying air temperature. However, an increase in air temperature coupled with a higher grain flow or lower air flow would result in better energy efficiencies.

4. The field experiments have shown that rice can be dried at air temperatures as high as 121.1°C provided that the air flow is 2.27 m^3/min, and the grain flow is 0.17 m^3/hr. It may be possible to dry rice at 150°C with higher grain flow. However, more field work will have to be conducted to prove the feasibility of operating at 150°C.

5. Both airflow and grainflow can be used to control grain temperature and moisture gradient. However, this is best achieved by using grainflow.

6. An increase in the bed depth results in an increase in the moisture removed, a lowering of the final grain temperature, and a more uniform moisture distribution. In addition, an increase in bed depth results in an increase in static pressure and horsepower requirements.

7. Ambient air temperature has no effect on the moisture removal rate, the maximum grain temperature, nor the final grain temperature. However, it does have a significant effect on the energy required to raise the air to the desired drying temperature.

8. Absolute humidity has a marginal effect on the moisture removal rate, the maximum and final grain temperature, and energy efficiency. The moisture removal rate and the energy efficiency of the dryer decrease with an increase in absolute humidity, but only slightly.

9. Tempering does not significantly improve the drying rate of rice in a concurrent flow dryer. The reason for this is that rice dried in a concurrent flow dryer has a fairly uniform final moisture distribution. For the standard conditions listed in Table 5-1, the maximum difference between the surface and center moisture content is 6.3% w.b. However, the final difference is 4.6% w.b., a reduction of 27%. Also, the final surface moisture content out of the first stage is within 85% of the average moisture content of the kernel. At 176.7°C drying air temperature and an initial moisture content of 22% w.b., the maximum difference is 9.4% w.b. and the final difference is 6.5% w.b., a reduction of 31%. For this simulation the surface moisture content is within 82% of the final average moisture content. Because the drying rate is proportional to $1/r^2$ the moisture distribution would have a lesser effect on the drying of rice (radius: r = 0.098 cm) than on corn (radius: r = 0.296 cm). Therefore, tempering would have a greater effect on corn drying than on rice drying.

10. Rice can be dried in a three stage dryer to a desired moisture content of 14.5% w.b. However, this may not be the optimum number of stages. To determine the best number of stages and operating conditions, an optimization study needs to be conducted. The success of this would

depend on the development of a model to predict head yield as a function of temperature, time, and moisture gradient. Without such a model it is difficult to determine the benefits derived from increasing the number of stages and lowering drying temperatures.

11. As stated earlier the concurrent flow drying of rice results in a fairly uniform kernel moisture distribution. The moisture gradient reaches a maximum in the first 5 minutes of drying and then decreases with time and bed depth. This feature of a concurrent flow dryer should result in better grain quality. This conclusion is based on observations of Kunze (1977). He concluded that rice cracking and fissures are caused by: (1) the grain surface readsorbing moisture from the environment; (2) the grain surface adsorbing moisture from the center of the kernel; (3) the grain surface adsorbing moisture from both the environment and from the center of the kernel, following drying. Because concurrent drying of rice results in a fairly uniform final moisture distribution, the moisture movement from the center of the kernel and the surrounding environment is reduced. This should result in better grain quality. This conclusion is also supported by the good head yields obtained during the field trials.

More research must be done before a model can be developed to predict head losses. Grain temperatures and saturation deficit alone cannot be used to predict head losses.

VI. SUGGESTIONS FOR FURTHER RESEARCH

As a result of this investigation, the following recommendations are made:

1. <u>The Convective Mass Transfer Coefficient</u>

The relation derived in this study for the convective mass transfer coefficient can be improved considerably if more experimental data is obtained.

2. <u>Multistage Concurrent Flow Dryer</u>

A demonstration model of a multistage concurrent flow rice dryer should be constructed and tested in the field to gain further insight into the operating characteristics.

3. <u>Optimization</u>

An optimization study needs to be conducted to determine the optimum number of stages, the bed depth, drying temperature, and other drying variables.

4. <u>Head Yield</u>

Recent work by Kunze (1977) has shown that rice fissures and cracking are caused by the grain surface adsorbing moisture from the environment, the center of the kernel, or both. Therefore, any model design to predict head losses must be a function of the moisture distribution in the kernel and not just the grain temperature or the saturation deficit of the drying air. More research needs to be conducted on moisture movement from the grain to the environment and from the environment to the grain from both the environment and from the center of the kernel. Therefore, a head yield model must be based on the moisture distribution and gradient to successfully predict head loss.

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APPENDICES

APPENDIX A

COMPARISON OF DIFFUSION EQUATION AND THIN-LAYER EQUATION

APPENDIX A

Wang, C. Y., and Singh, R. P. (1978) conducted a series of thin-layer drying experiments. The experimental data were fitted to four equations using nonlinear regression analysis. The results of the regression analysis for the four models are shown in Table A-1.

Table A-2 is a comparison of Wang and Singh (1978) equations and Husian et al. (1973) equation (Equation 2-9). The comparisons are based on an air temperature of 50°C and a relative humidity of 25%. Equations A and B predict higher moisture content than Equation (2-9) as shown in Figure (A-2). Equation C agrees with Equation (2-9) for the first two hours, but deviates considerably after two hours. Equation D compares favorable with Equation (2-9) for the first hour, but becomes unstable.

Table A-1. Regression analysis results for the four model.

Empirical Thin-Layer Equations

(A) $$\frac{M - M_e}{M_i - M_e} = \frac{6}{\pi^2} \sum_{n=1} \frac{1}{n^2} \text{Exp} \frac{-n^2 \pi^2 D \Theta}{R^2}$$

where

$$D = 1.6377 \text{ Exp } - \frac{4151}{T_{abs}}$$

$$R = 0.18 \text{ cm}$$

(B) $$\frac{M - M_e}{M_i - M_e} = a \text{ Exp } (-b\Theta)$$

where

$$a = 0.96 - 0.00008826\ T_a + 0.02324\ rh$$

$$b = 0.002814 + 0.0001267\ T - 0.003620\ rh$$

(C) $$\frac{M - M_e}{M_i - M_e} = \text{Exp } (-X\Theta^Y)$$

where

$$X = 0.01579 + 0.001746\ T_a - 0.01413\ rh$$

$$Y = 0.6545 + 0.002425\ T_a - 0.07867\ rh$$

(D) $$\frac{M - M_e}{M_i - M_e} = 1 + A\Theta + B\Theta^2$$

where

$$A = -0.001308 \times T^{0.4687} \times rh^{-0.3187}$$

$$B = 0.00006625 \times T^{0.03408} \times rh^{-0.4842}$$

Source: Wang and Singh (1978).

Table A-2. Comparison of Equation (2-9) and Equation A, B, C and D of Table A-1. The comparisons are based on an air temperature of 50°C and a relative humidity of 25%.

Time hr.	Moisture Content % d.b.				
	Husian (1973: Eq. 2-9)	Wang, C. Y. and Singh, R. P. (1978) Equations A	B	C	D
0.0	26.0	26.0	26.0	26.0	26.0
0.17	23.0	23.4	24.5	23.4	23.6
0.42	20.0	22.1	23.5	21.1	21.2
1.0	17.0	20.3	21.3	17.3	21.3
2.0	14.0	18.3	18.2	13.4	—
3.0	13.0	16.8	15.7	11.0	—
4.0	12.0	15.7	13.6	9.4	—
5.0	10.5	14.7	12.0	8.3	—
6.0	10.0	13.9	10.7	7.5	—

APPENDIX B

PHYSICAL AND THERMAL PROPERTIES

Table A-3. Summary of physical and thermal properties.

	Source
$a = 98.8$ m	Chan (1976)
$C_a = 1.3020 \times 10^{-3}$ KJ/	Holman (1976)
$C_p = 3.4004 \times 10^{-3}$	Wratten *et al.* (1969)
$C_v = 2.4211 \times 10^{-3}$	Holman (1976)
$C_w = 0.0054$	Holman (1976)
$D = $ $D(\bar{M}) = g(\Theta)\ \mathrm{Exp}\ \{f(\Theta) \cdot \bar{M}\}$; $g(\Theta) = 9.48787\ \mathrm{Exp}\ \{-13914.9/\Theta_{abs}\}$; $f(\Theta) = 4.90722 \times 10^{-4}\ \Theta_{abs} - 0.3788$	Husian *et al.* (1973)
$h = 1.064\ C_pG \ \frac{D_pG}{\mu}^{-0.41} \ \frac{C_p\mu}{K}^{-2/3}$ Re > 450	Gamson *et al.* (1943)
$h = 1.95\ C_pG \ \frac{D_pG}{\mu}^{-0.51} \ \frac{C_p\mu}{K}^{-2/3}$ Re < 40	Wethe and Hougen (1945)
$h_D = 0.0043\ C_pG \ \frac{C_p\mu}{K}^{-2/3} \ \frac{D_pG}{K}^{-0.51} \ \frac{D_pG}{\mu} < 350$	Derived
$h_{fg} = (1.0 + 23.0\ \mathrm{Exp}\ (-40.0\ \bar{M}))\ h_v$	Gallaher (1951)
$M_e = 4.510 + 0.069\ rh + 8.837\ rh^{0.5} - 0.015\ rh^{0.5}\ T_{abs}$	Kachrer and Matthes (1973)
$r = 0.09756$* cm	Husian *et al.* (1973)
$\rho = 17.45$ kg	Wratten *et al.* (1969)

APPENDIX C

CONVERSION FACTORS

	Multiply	By	To Obtain
a	ft^2/ft^3	3.28	m^2/m^3
C_a	Btu/lb	2.3236	KJ/Kg
C_p	Btu/lb	2.3236	KJ/Kg
C_v	Btu/lb	2.3236	KJ/Kg
C_w	Btu/lb	2.3236	KJ/Kg
D	ft^2/hr	929.0	cm^2/hr
D_p	ft	0.3048	m
G_a	lb/hr ft^2	4.8827	Kg/hr m^2
G_p	lb/hr ft^2	4.8827	Kg/hr m^2
h_c	Btu/hr ft^2	11.3455	KJ/m^2
h_D	ft/hr	30.48	cm/hr
h_{fg}	Btu/lb	2.3236	KJ/Kg
H	lb/lb	1	Kg/Kg
j	--	--	--
K	--	--	--
L	ft	0.3048	m
$\bar{M}$	% w.b.	1	% w.b.
M	Decimal d.b.	1	Decimal d.b.
M_e	Decimal d.b.	1	Decimal d.b.
M_i	% w.b.	1	% w.b.
$\bar{M}_o$	% w.b.	1	% w.b.
M_s	Decimal d.b.	1	Decimal d.b.
M_R	% w.b.	1	% w.b.
P_v	^{2}psi a	0.0703	Kgf/cm^2
P_{sv}	^{2}psi a	0.0703	Kgf/cm^2

	Multiply	By	To Obtain
R	ft	30.48	cm
r	ft	30.48	cm
S	ft^2	0.0929	m^2
T	°F	—	°C
T_e	°F	—	°C
T_w	°F	—	°C
T_{abs}	°F	—	°K
t	hr	1	hr
v	ft^3	0.02832	m^3
V_G	ft/hr	0.3648	m/hr
Y	—	1	—
α*	—	1	—
α*	—	1	—
$\underline{\bar{X}}$	ft	0.3048	m

APPENDIX D

PROGRAMS

```
      PROGRAM MULTI(INPUT,OUTPUT)
C ******
C ******
C ****** MICHIGAN STATE UNIVERSITY AGRICULTURE ENGINEERING
C ****** DEPARTMENT MULTISTAGE CONCURRENT FLOW GRAIN DRYER
C ****** MODEL
C ******
C ******
C ****** F. W. BAKKER-ARKEMA, PROJECT LEADER
C ******
C ****** L. P. WALKER, PROGRAMMER
C ******
C ******
C ****** USAGE
C ******
C ****** MAIN PROGRAM FOR THE SIMULATION OF A MULTISTAGE CON-
C ****** CURRENT FLOW DRYER.
C ******
C ******
C ****** SUBROUTINES USED
C ******
C ****** CONCUR
C ****** BLOCKDATA
C ****** DERFUN
C ****** DIFEQ
C ****** RKAMSUB--LASTMAN, G. J.  COOP ID D2 UTEX RKAMSUB(1964)
C ****** START--LASTMAN, G. J. COOP ID D2 UTEX RKAMSUB(1964)
C ******
C ******
C ****** FUNCTION SUBPROGRAMS USED
C ******
C ****** EMC
C ****** SYCHART PACKAGE
C ******
C ******
      COMMON/MAIN/XMO,CFM,GVEL
      COMMON/CONSTNT/CON1,CON2,CON3,CON4,CON5,CON6,GA,COND,NTMPR,XME
     +,W(10)
      COMMON /PRPRTY/SA,CA,CP,CV,CW,RHOP,HFG
      COMMON/PRESS/PATM
      COMMON/NAME/INAME,IPROD
      COMMON/GRID/DELR,CONF1(12),CONF2(12),CONF0,CONF3
      COMMON/RKAM/Y(202)
      COMMON/TEST/AM
      DIMENSION TINM(10),BPHM(10),BEDM(10),DBTPRM(10),CFMM(10),TEMPL(10)
      DATA IPROD/5H RICE/
C ******
C ****** INPUT INFORMATION
C ******
      PRINT 215,IPROD
      PRINT 225
      PRINT 100
      READ 105, NSTAGE
      PRINT 110
      READ 115, NTEMP
      PRINT 120
      READ 125, TAMB
      PRINT 130
      READ 125, HIN
      PRINT 220
      PRINT 205
      READ 125, XMO
      PRINT 210
      XMO=XMO/(100-XMO)
      READ 125,THIN
      PRINT 135
      EN=0.0
      WA=0.0
      DO 25 J=1,NSTAGE
      PRINT 140, J
      PRINT 145
      READ 125, TINM(J)
      PRINT 150
      READ 125, CFMM(J)
      IF(J.GT.1)GO TO 1
      PRINT 160
      READ 125, BPHM(J)
1     CONTINUE
      BPHM(J)=BPHM(1)
      PRINT 165
      READ 125, BEDM(J)
```

```
      PRINT 170
      READ 125, DBTPRM(J)
      IF(NTEMP.EQ.2)GO TO 25
      IF(J.EQ.NSTAGE)GOTO25
      PRINT 250
      READ 125,TEMPL(J)
25    CONTINUE
      DELR=0.09756/9.0
      CALL WEIGHT
      DO 10 N=1,10
      Y(N)=XMO
      Y(12)=XMO
      Y(16+N)=0.0
10    CONTINUE
      DO 14 N=1,4
      Y(26+N)=0.0
14    CONTINUE
      DO50 J=1,NSTAGE
      TIN=TINM(J)
      CFM=CFMM(J)
      XLENGTH=BEDM(J)
      BPH=BPHM(J)
      DBTPR=DBTPRM(J)
      PRINT 179
      PRINT 230,J
      PRINT 180
      NTMPR=0.0
      CALL CONCUR(THIN,HIN,TAMB,BPH,XLENGTH,XMONEW,ENER,WAT,
     +TIN,DBTPR,NTEMP)
      THIN=Y(14)
      IF(NTEMP.EQ.2)GO TO 40
      IF(J.EQ.NSTAGE)GO TO 40
      PRINT 179
      PRINT 240,J
      PRINT 180
      NTMPR=1
      TEMPLEN=TEMPL(J)
      CALL CONCUR(THIN,HIN,TAMB,BPH,TEMPLEN,XMONEW,ENERGY,WATER,TIN
     +,DBTPR,NTEMP)
      Y(12)=AM
40    CONTINUE
      ENER=EN + ENER
      EN=ENER
      WAT=WA+WAT
      WA=WAT
50    CONTINUE
      BTUH2O=ENER/WAT
      PRINT 179
      PRINT 185
      PRINT 190, ENER
      PRINT 195, WAT
      PRINT 200,BTUH2O
      PRINT 180
100   FORMAT(*0*,1X,*HOW MANY STAGES ≡*)
105   FORMAT(I1)
110   FORMAT(*0*,1X,*IS TEMPERING DESIREABLE ≡*/2X,*(YES=1, NO=2)
     +*)
     +)
115   FORMAT(I1)
120   FORMAT(*0*,*ENVIRONMENTAL CONDITIONS:*//5X,*AMBIENT TEMP, F*)
125   FORMAT(F10.0)
130   FORMAT(5X,*INLET ABS HUM RATIO ≡*)
135   FORMAT(*0*,*DRYING VARIABLES*)
140   FORMAT(*0*,10X,*STAGE*,I2)
145   FORMAT(* *,4X,*INLET AIR TEMP, F*)
150   FORMAT(5X,*AIRFLOW RATE, CFM/SQFT (AT AMBIENT CONOITIONS)*
     +)
160   FORMAT(5X,*GRAIN FLOW RATE, BU/HR-SQ FT*)
165   FORMAT(5X,*BED DEPTH, FT*)
170   FORMAT(5X,*OUTPUT INTERVAL, FT*)
179   FORMAT(*0*,*XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX*)
180   FORMAT(*0*,*XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX*)
185   FORMAT(*0*,10X,*TOTAL DRYER PERFORMANCE*)
190   FORMAT(5X,*TOTAL ENERGY REQUIREMENT =*,1X,F6.1)
195   FORMAT(5X,*TOTAL AMOUNT OF WATER REMOVED (LBS) =*,F6.2)
200   FORMAT(5X,*BTU/LB =*,1X,F8.2)
205   FORMAT(5X,*INTIAL MOISTURE CONTENT, PERCENT W.B.*)
210   FORMAT(5X,*INTIAL GRAIN TEMP., F*)
215   FORMAT(*0*,1X,*M.S.U. AGRICULTURE ENGINEERING DEPARTMENT*
     +/2X,*SIMULATION OF MULTISTAGE*,1X,A5,1X,*DRYER*)
220   FORMAT(*0*,*GRAIN STATUS*)
```

```
230    FORMAT('0',10X,' D R Y E R   S T A G E   N O ',2X,I1)
240    FORMAT('0',10X,' T E M P E R I N G   S T A G E   N O . '
      +,2X,I1)
250    FORMAT('0',4X,'LENGTH OF TEMPERING SECTION - FT ')
225    FORMAT(2X,'WITH EMC B.C.')
       END
       SUBROUTINE CONCUR(THIN,HIN,TAMB,BPH,XLENG,WB,ENERGY,WATER,TI
      +N,DBTPR,NTEMP)
C*****
C*****           M I C H I G A N   S T A T E   U N I V E R S I T Y
C   A G R I C U L T U R A L   E N G I N E E R I N G   D E P A R T M E N
C      C O N C U R R E N T   F L O W   G R A I N   D R Y E R   M O D E L
C*****                    F.W. BAKKER-ARKEMA, PROJECT LEADER
C*****                         L.E. LEREW, PROGRAMMER
C*****
C*****
C*****
C*****
C*****
C*****           MAIN PROGRAM FOR THE SIMULATION OF A CONCURRENT FLOW DRYER
C*****      SUBROUTINES USED
C*****           BLOCKDATA
C*****           DERFUN
C*****           DIFEQ
C*****           RKAMSUB--LASTMAN,G.J. COOP ID  D2 UTEX RKAM SUB (1964)
C*****           START  --LASTMAN,G.J. COOP ID  D2 UTEX RKAM SUB (1964)
C*****      FUNCTION SUBPROGRAMS USED
C*****        EMC
C*****           SYCHART PACKAGE
       COMMON /MAIN/XMO,CFM,GVEL
       COMMON/CONSTNT/CON1,CON2,CON3,CON4,CON5,CON6,GA,COND,NTMPR,XME
      +,W(10)
       COMMON/GRID/DELR,CONF1(12),CONF2(12),CONF0,CONF3
       COMMON /PRPRTY/SA,CA,CP,CV,CW,RHOP,HFG
       COMMON /PRESS/PATM
       COMMON /NAME/INAME,IPROD
       COMMON /RKAM/Y(202)
       COMMON/TEST/AM
       DIMENSION XMD(60,12)
       DIMENSION DMDX(60),DTDX(60),DTHDX(60),DHDX(60)
       F(T)=T+459.69
       PRL=0.0
       IEXIT=0
       PATM=14.696
C*****      INPUT CONDITIONS OF DRYER TO BE SIMULATED
       XMO=Y(12)
       XMEND=.01
C*****      COMPUTE INLET RH AND INITIALIZE Y ARRAY
       RHIN=RHDBHA(F(TIN),HIN)
       Y(11)=TIN
       Y(13)=HIN
       Y(14)=THIN
       Y(15)=0.0
       RH=RHIN
       SP=0.0
       IC=1
C*****      CONVERT AIRFLOW TO LB/HR AND COMPUTE CONVECTIVE HEAT TRANS-
C*****      FER COEFFICIENT AND EQUILIBRIUM MOISTURE CONTENT
       GA=60.*CFM/VSDBHA(F(TAMB),HIN)
       CFMHOT=GA*VSDBHA(F(TIN),HIN)/60.
       IF(GA-500.) 2,1,1
1      HC=0.0308*GA**0.59
       GO TO 3
2      HC= 0.0715*GA**0.49
    3  XME=EMC(RHIN,TIN)
C*****      CONVERT GRAIN FLOW TO FT/HR AND LB/HR AND COMPUTE AIR-GRAIN
C*****      RATIO
       GVEL=BPH*1.244
       GP=GVEL*RHOP
       CALL FINITE
       AFGR=GA/GP
C*****      PRINT HEADER PAGE OF CONDITIONS AND PROPERTIES
       XMEW=XME/(XME+1.)*100.
       IF(NTMPR.EQ.1)GO TO 12
       PRINT 310,RH,GA,CFMHOT,HC,XMEW,XME,XMO,GVEL,GP
       PRINT 311
C*****      COMPUTE CONSTANTS USED BY EQUATIONS IN SUBROUTINE DERFUN
12     CON1=GA*CA
       CON2=GA*CV
       CON3=HC*SA
       CON4=GP*CP
```

```
      CON5=GP*CW
      CON6=1./AFGF
      TMAX=0.0
      DMMAX=0.0
      DTMAX=0.0
      DTHMAX=0.0
      DHMAX=0.0
      COND=GP/GA
C*****    CALL START TO INITIALIZE SOLUTION BY TAKING RUNGE-KUTTA STEPS
      HFG=HGVAP(Y(11),Y(12))
      CALL START(14,3,1,1.E-6,1.E-4,1.E-8,.01,1.E-6,.5)
C*****    BEGINNING OF LOOP
C*****    CHECK MOISTURE CONTENT...IF .LT. .17 COMPUTE NEW HFG
4     HFG=HGVAP(Y(11),Y(12))
C*****    CHECK ABSORPTION AND CONDENSATION FLAG...IF SET EXIT
C*****    CALL RKAMSUB TO TAKE NEXT STEP
    5 CALL RKAMSUB
      IF(Y(14).GT.TMAX)XTMAX=Y(15)
      IF(Y(14).GT.TMAX)TMAX=Y(14)
      IF(ABS(Y(28)).GT.DMMAX)XDMAX=Y(15)
      IF(ABS(Y(28)).GT.DMMAX)DMMAX=ABS(Y(28))
      IF(ABS(Y(27)).GT.DTMAX)XDTMAX=Y(15)
      IF(ABS(Y(27)).GT.DTMAX)DTMAX=ABS(Y(27))
      IF(Y(30).GT.DTHMAX)XTHMAX=Y(15)
      IF(Y(30).GT.DTHMAX)DTHMAX=Y(30)
      IF(Y(29).GT.DHMAX)XDHMAX=Y(15)
      IF(Y(29).GT.DHMAX)DHMAX=Y(29)
C*****    COMPUTE RH
      RH=RHDBHA(F(Y(11)),Y(13))
      IF(RH.GE.1.0)Y(13)=HADBRH(Y(11)+460.,RH)
      IF(RH.GE.1.)RH=1.
      CFMT=GA*VSDBHA(F(Y(11)),Y(13))/60.
      SP=SP + (CFMT/40.77)**(1.0/0.86173)*Y(16)
C*****    CHECK IF LONG ENOUGH, MOISTURE CONTENT LOW ENOUGH OR TIME TO
C*****    PRINT...IF NONE OF THESE GO TO BEGINNING OF LOOP
      IF(Y(15)-XLENG)6,6,8
    6 IF(Y(12)-XMEND)8,8,7
    7 IF(Y(15)-PRL)4,9,9
C*****    SET FLAG IF EXIT CONDITION MET
    8 IEXIT=1
    9 PRL=PRL+DBTPR
C*****    MAKE FINAL CALCULATIONS AND PRINT
      ETIME=Y(15)/GVEL
      WATER=(XMO-Y(12))*RHOP*1.244
      WB=Y(12)/(Y(12)+1.)*100.
      IF(NTMPR.EQ.1)GO TO 10
      PRINT 312,Y(15),ETIME,Y(11),Y(13),RH,Y(14),WB,Y(12)
10    XMD(IC,1)=Y(15)
      XMD(IC,2)=ETIME
      DO 450 N1 = 3,12
      XMD(IC,N1)=Y(N1-2)
      DMDX(IC)=Y(28)
      DTDX(IC)=Y(27)
      DTHDX(IC)=Y(30)
      DHDX(IC)=Y(29)
450   CONTINUE
      IC=IC+1
550   FORMAT(10(2X,F8.3))
C*****    CHECK IF EXIT CONDITION HAS BEEN MET...IF NOT RETURN TO BEGIN
C*****    NING OF LOOP
      IF(IEXIT-1) 4,11,4
C*****    EXIT HERE FOR ABSORPTION OR CONDENSATION
   11 CONTINUE
      EAIR=GA*(CA+CV*HIN)*(TIN-TAMB)/BPH
      HP=CFM*SP/6350.
      EFAN=.746*HP*3413./(.5*BPH)
      EAUG=0.0
      ENERGY=EAIR+EFAN+EAUG
      BTUH2O=ENERGY/WATER
      IF(NTMPR.EQ.1)GO TO 666
      PRINT 406,TMAX,XTMAX
      PRINT 407,DMMAX,XDMAX
      PRINT 408,DTMAX,XDTMAX
      PRINT 409,DTHMAX,XTHMAX
      PRINT 410,DHMAX,XDHMAX
      PRINT 314,SP,HP,EFAN,EAIR,EAUG,ENERGY,WATER,BTUH2O
666   PRINT 370
      PRINT 380
      PRINT 390,(I,I=1,10)
      IC=IC-1
      DO 400 I=1,IC
```

```
      PRINT 405,(XMD(I,J),J=1,12)
400   CONTINUE
      PRINT 401
      PRINT 402
      DO 404 I=1,IC
      PRINT 403,XMD(I,1),XMD(I,2),DMDX(I),DTDX(I),DTHDX(I),DHDX(I)
404   CONTINUE
309   FORMAT(//* ADDITIONAL INPUT FROM BLOCKDATA*//
     +* HEAT CAPACITIES, BTU/LB/F**/
     +* DRY AIR*F6.3*    WATER VAPOR*F6.3*    DRY GRAIN*F6.3
     +*     LIQUID WATER*F6.3/* SPECIFIC SURFACE AREA, SQ FT/CU FT*F6.0/
     +* BULK DRY MATTER DENSITY, LB/CU FT*F6.2/
     +* HEAT OF VAPORIZATION (MC.GT.14.5 PERCENT WB)*F6.0/
     +* ATMOSPHERIC PRESSURE, PSI*F6.2)
310   FORMAT(//* PRELIMINARY CALCULATED VALUES*//* REL HUM, DECIMAL*
     +F6.4*  AIRFLOW RATE, LB DRY AIR/HR/SQ FT*F6.1*  CFM AT TIN*F6.1/
     +* HEAT TRANSFER COEF, BTU/HR/SQ FT/F*F8.3/
     +* EQUIL MC, WB PERCENT*F6.2*   DRY BASIS, DECIMAL*F6.4/
     +* INLET MC, DRY BASIS DECIMAL*F6.4/
     +* GRAIN VELOCITY, FT/HR*F6.2* LB DRY MATTER/HR/SQ FT*F8.2)
311   FORMAT(//3X5HDEPTH4X4HTIME5X3HAIR5X3HABS5X3HREL3X5HGRAIN6X2HMC
     +6X2HMC/20X4HTEMP5X3HHUM5X3HHUM4X4HTEMP6X2HWB6X2HDB/
     +6X2HFT6X2HHR7X1HF3X5HLB/LB8H DECIMAL7X17HF PERCENT DECIMAL)
312   FORMAT(2F8.2,F8.1,2F8.4,F8.1,F8.2,F8.4)
  213 FORMAT(///+6HSITUATION ENCOUNTERED WHICH CAN NOT BE MODELED//A10,2
     112H FLAG SET AT LENGTH OF F6.3,3H FT)
314   FORMAT(//31H STATIC PRESSURE, INCHES OF H2OF6.2/17H HORSEPOWER/SQ
     +FTF6.2//22H ENERGY INPUTS, BTU/BU/10X12HFAN (.5 EFF)F7.0/10X8HHEAT
     + AIR4XF7.0/10X10HMOVE GRAIN2XF7.0/10X5HTOTAL7XF7.0//21H WATER REMO
     +VED, LB/BUF7.2//11H BTU/LB H2OF9.2)
315   FORMAT(5X*AMBIENT TEMP, F  *)
370   FORMAT(*0*,25X,*M O I S T U R E*,3X,*D I S T R I B U T I O N*)
380   FORMAT(*0*,1X,*DEPTH*,3X,*TIME*,30X,*NODES*)
390   FORMAT(5X,*FT*,5X,*HR*,2X,I2,9(4X,I2))
405   FORMAT(2X,F5.2,2X,F4.2,10(2X,F4.3))
401   FORMAT(*0*,1X,*DEPTH*,3X,*TIME*,3X,*DMDX*,6X,*DTDX*,4X,
     +*DTHDX*,4X,*DHDX*)
402   FORMAT(3X,*FT*,6X,*HR*,4X,*1/FT*,6X,*F/FT*,5X,*F/FT*,4X,
     +*1/FT*)
403   FORMAT(1X,F6.2,2X,F5.2,1X,F7.4,1X,F9.2,2X,F7.2,1X,F6.4)
406   FORMAT(*0*,1X,*MAXIMUM GRAIN TEMP. =*,F6.2,*DEG.F*/3X,*
     +AT DEPTH OF *,F5.2,1X,*FT.*)
407   FORMAT(*0*,1X,*DM/DX MAX. = *,F9.2/3X,*AT DEPTH OF *,
     +F5.2,1X,*FT.*)
408   FORMAT(*0*,1X,*DT/DX MAX. = *,F9.2/3X,*AT DEPTH OF *,
     +F5.2,1X,*FT.*)
409   FORMAT(*0*,1X,*DTH/DX MAX. = *,F9.2/3X,*AT DEPTH OF *,
     +F5.2,1X,*FT.*)
410   FORMAT(*0*,1X,*DH/DX MAX. = *,F9.2/3X,*AT DEPTH OF *,
     +F5.2,1X,*FT.*)
      END
      SUBROUTINE DERFUN
C*****
C*****       SUBPROGRAM DESIGN TO CALCULATE DERIVATIVES USING FINITE DIF
C*****
C*****          L. P. WALKER
C*****
      COMMON/PRPRTY/SA,CA,CP,CV,CW,RHOP,HFG
      COMMON/CONSTNT/CON1,CON2,CON3,CON4,CON5,CON6,GA,COND,NTMPR,XME
     +,W(10)
      COMMON/RKAM/Y(202)
      COMMON/GRID/DELR,CONF1(12),CONF2(12),CONF0,CONF3
      COMMON/TEST/AM
      AM=0.0
      DO 1 N1 = 1,9
      AM=AM+(W(N1+1)*Y(N1+1) + W(N1)*Y(N1))
1     CONTINUE
C*****
C*****          CALCULATE DERV. AT FIRST NODE OF KERNEL
C*****
      DC=CMOS(AM,Y(14))
      Y(17)=DC*(Y(2)-Y(1))*CONF0
C*****
C*****          CALCULATE DERV. AT OTHE NODES OF KERNEL
C
      RH=RHDBHA(Y(11)+460.,Y(13))
      XME=EMC(RH,Y(11))
      IF(RH.GE.1.)Y(13)=HADBRH(Y(11)+460.,RH)
      IF(XME.LT.0.00)XME=0.00
      IF(RH.GT.1.0)XME=EMC(1.0,Y(11))
      IN=17
```

```
      DO 5 K=2,9
      IN=IN+1
      Y(IN)=DC*(CONF1(K)*Y(K+1) + CONF2(K)*Y(K-1) - CONF3*Y(K))
    5 CONTINUE
      IF(NTMPR.GT.0)GO TO 14
      IF(RH.GE.1.)GO TO 14
C*****
C*****  DERIVATIVE FOR MOISTURE AT SURFACE OF KERNEL
C*****
      Y(26)=DC*(CONF1(10)*KME + CONF2(10)*Y(9) - CONF3*Y(10))
C*****
C*****  DERIVATIVE OF AVERAGE MOISTURE CONTENT
C*****
      AVE=0.0
      DO 10 N=1,9
      AVE=AVE+(W(N+1)*Y(17+N) + W(N)*Y(16+N))
10    CONTINUE
      Y(28)=AVE
C*****
C*****           DERIVATIVE FOR AIR HUMIDITY - DH/DX
C*****
      Y(29)=-COND*Y(28)
C*****
C*****           DERIVATIVE FOR GRAIN TEMPERATURE - DTHETA/DX
C*****
      Y(30)=(CON3*(Y(11)-Y(14))-(HFG+CV*(Y(11)-Y(14)))*GA*Y(29))/(CON4+C
     +ON5* Y(12))
C*****
C*****           DERIVATIVE FOR AIR TEMPERATURE  -  DT/DX
C*****
      Y(27)=-CON3*(Y(11)-Y(14))/(CON1+CON2*Y(13))
      RETURN
C*****
C*****           TEMPERING MODEL
C*****
14    Y(26)=CONF3*DC*(Y(9)-Y(10))
      Y(27) = 0.0
      Y(28)=0.0
      Y(29)=0.0
      Y(30)=0.0
      RETURN
      END
      SUBROUTINE FINITE
C
C           SUBROUTINE TO CALCULATE FINITE DIFF COEFF.
C
C           PROGRAMMER, L.P. WALKER
C
      COMMON/GRID/DELR,CONF1(12),CONF2(12),CONF0,CONF3
      COMMON/MAIN/XMO,CFM,GVEL
      SR=(DELR**2)*GVEL
      DO 1  J=2,12
      CONF1(J)=FLOAT(2*J-1)/(FLOAT(2*J-2)*SR)
      CONF2(J)=FLOAT(2*J-3)/(FLOAT(2*J-2)*SR)
    1 CONTINUE
      CONF0 = 4.0/SR
      CONF3 =2.0/SR
      RETURN
      END
      FUNCTION CMOS(C,T)
C
C     SUBROUTINE TO CALCULATE DIFUSSION COEFF.
C
C     L.P. WALKER . PROGRAMMER
C
      CM=C*100.0
      TA=T+460.
      CE=EXP(-7730.65/TA)
      GT=94.8787*CE
      FT=(8.8331E-4)*TA-0.3788
      DMT=GT*EXP(FT*CM)
      CMOS=DMT
      RETURN
      END
      FUNCTION EMC(RH,T)
C *****
C *****
C *****              L. P. WALKER, PROGRAMMER
C *****
C *****
C *****
```

```
C ****** DESCRIPTION
C ******    FUNCTION TO COMPUTE EQUILBRIUM MOISTURE CONTENT OF RICE FROM
C ****** RELATIVE HUMIDITY AND RICE TEMPERATURE. EQUATION FROM KACHRU,R.
C ******P. AND MATTHES, R. K.(1976).
C ******
C ******
C ****** USAGE
C ******
C ****** USED WITH A FIXED BED, CROSSFLOW, CONCURRENT AND COUNTERFLOW
C ****** GRAIN DRYER MODELS FOR RICE.
C ******
C ******
      TABS=T+459.69
      A0=4.510
      A1=0.069
      A2=8.837
      A3=-0.015
      IF(RH.GE..9999)RH=.9999
      RHP=RH*100.
      EMC=A0+A1*RHP+A2*SQRT(RHP)+A3*SQRT(RHP)*TABS
      EMC=EMC/100.
      RETURN
      END
      BLOCKDATA
      COMMON/PRPRTY/SA,CA,CP,CV,CW,BUKDEN,HFG
      COMMON/PRESS/PATM
      DATA SA,CA,CP,CV,CW,BUKDEN/324.,0.242,.632,0.45,1.0,38.46/
      DATA PATM/14.30/
      END
      FUNCTION HGVAP(T1,CM)
C*****
C*****   SUBPROGRAM DESIGN TO CALCULATE HEAT OF VAPORIZATION
C*****   OF WATER IN GRAINS BASED ON THE WORK OF GALLAHER (1951)
C*****
C*****   L. P. WALKER, PROGRAMMER
C*****
      W=CM
      TDB=T1+460.
      HV=1078.0
      HS=(1. + 23.0 * EXP(-40*W))*HV
      HGVAP=HS
      RETURN
      END
      SUBROUTINE WEIGHT
      COMMON/CONSTNT/CON1,CON2,CON3,CON4,CON5,CON6,GA,CONO,NTMPR,XME
     +,W(10)
      DO 100 M =1,10
      W(M)=(M-1)/81.0
100   CONTINUE
      RETURN
      END
```

19.38.55..000009 PAGES PRINT. 000538 LINES PRINT. FOR $ 000.58 AT RG2.

```
      PROGRAM MULTI(INPUT,OUTPUT)
C ******
C ******
C ****** MICHIGAN STATE UNIVERSITY AGRICULTURE ENGINEERING
C ****** DEPARTMENT MULTISTAGE CONCURRENT FLOW GRAIN DRYER
C ****** MODEL
C ******
C ******
C ****** F. W. BAKKER-ARKEMA, PROJECT LEADER
C ******
C ****** L. P. WALKER, PROGRAMMER
C ******
C ******
C ****** JSAGE
C ******
C ****** MAIN PROGRAM FOR THE SIMULATION OF A MULTISTAGE CON-
C ****** CURRENT FLOW DRYER.
C ******
C ******
C ****** SUBROUTINES USED
C ******
C ****** CONCUR
C ****** BLOCKDATA
C ****** DERFUN
C ****** DIFEQ
C ****** RKAMSUB--LASTMAN, G. J.  COOP ID D2 UTEX RKAMSUB(1964)
C ****** START--LASTMAN, G. J. COOP ID D2 UTEX RKAMSUB(1964)
C ******
C ******
C ****** FUNCTION SUBPROGRAMS USED
C ******
C ****** EMC
C ****** SYCHART PACKAGE
C ******
C ******
      COMMON/MAIN/XMO,CFM,GVEL
      COMMON/CONSTNT/CON1,CON2,CON3,CON4,CON5,CON6,GA,CONO,NTMPR,XME
     +,W(10)
      COMMON /PRPRTY/SA,CA,CP,CV,CW,RHOP,HFG
      COMMON/PRESS/PATM
      COMMON/NAME/INAME,IPROD
      COMMON/GRID/DELR,CONF1(12),CONF2(12),CONF0,CONF3,CONF4
      COMMON/RKAM/Y(202)
      COMMON/TEST/AM,HD
      DIMENSION TINM(10),BPHM(10),BEDM(10),DBTPRM(10),CFMM(10),TEMPL(10)
      DATA IPROD/5H RICE/
C ******
C ****** INPUT INFORMATION
C ******
      PRINT 215,IPROD
      PRINT 225
      PRINT 100
      READ 105, NSTAGE
      PRINT 110
      READ 115, NTEMP
      PRINT 120
      READ 125, TAMB
      PRINT 130
      READ 125, HIN
      PRINT 220
      PRINT 205
      READ 125, XMO
      PRINT 210
      XMO=XMO/(100-XMO)
      READ 125,THIN
      PRINT 135
      EN=0.0
      WA=0.0
      DO 25 J=1,NSTAGE
      PRINT 140, J
      PRINT 145
      READ 125, TINM(J)
      PRINT 150
      READ 125, CFMM(J)
      IF(J.GT.1)GO TO 1
      PRINT 160
      READ 125, BPHM(J)
1     CONTINUE
      BPHM(J)=BPHM(1)
      PRINT 165
      READ 125, BEDM(J)
```

```
      PRINT 170
      READ 125, DBTPRM(J)
      IF(NTEMP.EQ.2)GO TO 25
      IF(J.EQ.NSTAGE)GOTO25
      PRINT 250
      READ 125,TEMPL(J)
25    CONTINUE
      DELR=0.09756/9.0
      CALL WEIGHT
      DO 10 N=1,10
      Y(N)=XMO
      Y(12)=XMO
      Y(15+N)=0.0
10    CONTINUE
      DO 14 N=1,4
      Y(26+N)=0.0
14    CONTINUE
      DO50 J=1,NSTAGE
      TIN=TINM(J)
      CFM=CFMM(J)
      XLENGTH=BEDM(J)
      BPH=BPHM(J)
      DBTPR=DBTPRM(J)
      PRINT 179
      PRINT 230,J
      PRINT 180
      NTMPR=0.0
      CALL CONCUR(THIN,HIN,TAMB,BPH,XLENGTH,XMONEW,ENER,WAT,
     +TIN,DBTPR,NTEMP)
      THIN=Y(14)
      IF(NTEMP.EQ.2)GO TO 40
      IF(J.EQ.NSTAGE)GO TO 40
      PRINT 179
      PRINT 240,J
      PRINT 180
      NTMPR=1
      TEMPLEN=TEMPL(J)
      CALL CONCUR(THIN,HIN,TAMB,BPH,TEMPLEN,XMONEW,ENERGY,WATER,TIN
     +,DBTPR,NTEMP)
      Y(12)=AM
40    CONTINUE
      ENER=EN + ENER
      EN=ENER
      WAT=WA+WAT
      WA=WAT
50    CONTINUE
      BTUH2O=ENER/WAT
      PRINT 179
      PRINT 185
      PRINT 190, ENER
      PRINT 195, WAT
      PRINT 200,BTUH2O
      PRINT 180
100   FORMAT(*0*,1X,*HOW MANY STAGES =*)
105   FORMAT(I1)
110   FORMAT(*0*,1X,*IS TEMPERING DESIREABLE =*/2X,*(YES=1, NO=2)
     +*)
     +)
115   FORMAT(I1)
120   FORMAT(*0*,*ENVIRONMENTAL CONDITIONS**//5X,*AMBIENT TEMP, F*)
125   FORMAT(F10.0)
130   FORMAT(5X,*INLET ABS HUM RATIO =*)
135   FORMAT(*0*,*DRYING VARIABLES*)
140   FORMAT(*0*,10X,*STAGE*,I2)
145   FORMAT(* *,4X,*INLET AIR TEMP, F*)
150   FORMAT(5X,*AIRFLOW RATE, CFM/SQFT (AT AMBIENT CONDITIONS)*
     +)
160   FORMAT(5X,*GRAIN FLOW RATE, BU/HR-SQ FT*)
165   FORMAT(5X,*BED DEPTH, FT*)
170   FORMAT(5X,*OUTPUT INTERVAL, FT*)
179   FORMAT(*0*,*XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX*)
180   FORMAT(*0*,*XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX*)
185   FORMAT(*0*,10X,*TOTAL DRYER PERFORMANCE*)
190   FORMAT(5X,*TOTAL ENERGY REQUIREMENT =*,1X,F6.1)
195   FORMAT(5X,*TOTAL AMOUNT OF WATER REMOVED (LBS) =*,F6.2)
200   FORMAT(5X,*BTU/LB =*,1X,F8.2)
205   FORMAT(5X,*INTIAL MOISTURE CONTENT, PERCENT W.B.*)
210   FORMAT(5X,*INTIAL GRAIN TEMP., F*)
215   FORMAT(*0*,1X,*M.S.U. AGRICULTURE ENGINEERING DEPARTMENT*
     +/2X,*SIMULATION OF MULTISTAGE*,1X,A5,1X,*DRYER*)
220   FORMAT(*0*,*GRAIN STATUS*)
```

```
230    FORMAT(*0*,10X,* D R Y E R   S T A G E   N O *,2X,I1)
240    FORMAT(*0*,10X,* T E M P E R I N G   S T A G E   N O . *
      +,2X,I1)
250    FORMAT(*0*,4X,*LENGTH OF TEMPERING SECTION - FT *)
225    FORMAT(2X,*WITH CONVECTIVE MASS B.C.*)
       END
       SUBROUTINE CONCUR(THIN,HIN,TAMB,BPH,XLENG,WB,ENERGY,WATER,TI
      +N,DBTPR,NTEMP)
C*****
C*****          M I C H I G A N   S T A T E   U N I V E R S I T Y
C    A G R I C U L T U R A L   E N G I N E E R I N G   D E P A R T M E N
C      C O N C U R R E N T   F L O W   G R A I N   D R Y E R   M O D E L
C*****               F.W. BAKKER-ARKEMA, PROJECT LEADER
C*****                        L.E. LEREW, PROGRAMMER
C*****
C*****
C*****
C*****
C*****
C*****
C*****          MAIN PROGRAM FOR THE SIMULATION OF A CONCURRENT FLOW DRYER
C*****     SUBROUTINES USED
C*****          BLOCKDATA
C*****          DERFUN
C*****          DIFEQ
C*****          RKAMSUB--LASTMAN,G.J. COOP ID  D2 UTEX RKAMSUB (1964)
C*****          START  --LASTMAN,G.J. COOP ID  D2 UTEX RKAMSUB (1964)
C*****     FUNCTION SUBPROGRAMS USED
C*****       EMC
C*****          SYCHART PACKAGE
       COMMON /MAIN/XMO,CFM,GVEL
       COMMON/CONSTNT/CON1,CON2,CON3,CON4,CON5,CON6,GA,COND,NTMPR,XME
      +,H(10)
       COMMON/GRID/DELR,CONF1(12),CONF2(12),CONF0,CONF3,CONF4
       COMMON /PRPRTY/SA,CA,CP,CV,CW,RHOP,HFG
       COMMON /PRESS/PATM
       COMMON /NAME/INAME,IPROD
       COMMON /RKAM/Y(202)
       COMMON/TEST/AM,HD
       DIMENSION XMD(60,12)
       DIMENSION DMDX(60),DTDX(60),DTHDX(60),DHDX(60)
       F(T)=T+459.69
       PRL=0.0
       IEXIT=0
       PATM=14.696
C*****     INPUT CONDITIONS OF DRYER TO BE SIMULATED
       XMO=Y(12)
       XMEND=.01
C*****     COMPUTE INLET RH AND INITIALIZE Y ARRAY
       RHIN=RHDBHA(F(TIN),HIN)
       Y(11)=TIN
       Y(13)=HIN
       Y(14)=THIN
       Y(15)=0.0
       RH=RHIN
       SP=0.0
       IC=1
C*****     CONVERT AIRFLOW TO LB/HR AND COMPUTE CONVECTIVE HEAT TRANS-
C*****     FER COEFFICIENT AND EQUILIBRIUM MOISTURE CONTENT
       GA=60.*CFM/VSDBHA(F(TAMB),HIN)
       CFMHOT=GA*VSDBHA(F(TIN),HIN)/60.
       IF(GA-500.) 2,1,1
1      HC=0.0308*GA**0.59
       GO TO 3
2      HC= 0.0715*GA**0.49
    3 XME=EMC(RHIN,TIN)
       HD=0.00267*GA**0.49
C*****     CONVERT GRAIN FLOW TO FT/HR AND LB/HR AND COMPUTE AIR-GRAIN
C*****     RATIO
       GVEL=BPH*1.244
       GP=GVEL*RHOP
       CALL FINITE
       AFGF=GA/GP
C*****     PRINT HEADER PAGE OF CONDITIONS AND PROPERTIES
       XMEW=XME/(XME+1.)*100.
       IF(NTMPR.EQ.1)GO TO 12
       PRINT 310,RH,GA,CFMHOT,HC,XMEW,XME,XMO,GVEL,GP
       PRINT 311
C*****     COMPUTE CONSTANTS USED BY EQUATIONS IN SUBROUTINE DERFUN
12     CON1=GA*CA
       CON2=GA*CV
       CON3=HC*SA
```

```
230   FORMAT(*0*,10X,* D R Y E R   S T A G E   N O *,2X,I1)
240   FORMAT(*0*,10X,* T E M P E R I N G   S T A G E   N O . *
     +,2X,I1)
250   FORMAT(*0*,4X,*LENGTH OF TEMPERING SECTION - FT *)
225   FORMAT(2X,*WITH CONVECTIVE MASS B.C.*)
      END
      SUBROUTINE CONCUR(THIN,HIN,TAMB,BPH,XLENG,WB,ENERGY,WATER,TI
     +N,DBTPR,NTEMP)
C*****
C*****      M I C H I G A N   S T A T E   U N I V E R S I T Y
C   A G R I C U L T U R A L   E N G I N E E R I N G   D E P A R T M E N
C     C O N C U R R E N T   F L O W   G R A I N   D R Y E R   M O D E L
C*****              F.W. BAKKER-ARKEMA, PROJECT LEADER
C*****                        L.E. LEREW, PROGRAMMER
C*****
C*****
C*****
C*****
C*****
C*****
C*****      MAIN PROGRAM FOR THE SIMULATION OF A CONCURRENT FLOW DRYER
C*****    SUBROUTINES USED
C*****          BLOCKDATA
C*****          DERFUN
C*****          DIFEQ
C*****          RKAMSUB--LASTMAN,G.J. COOP ID  D2 UTEX RKAMSUB (1964)
C*****          START  --LASTMAN,G.J. COOP ID  D2 UTEX RKAMSUB (1964)
C*****    FUNCTION SUBPROGRAMS USED
C*****       EMC
C*****          SYCHART PACKAGE
      COMMON /MAIN/XMO,CFM,GVLL
      COMMON/CONSTNT/CON1,CON2,CON3,CON4,CON5,CON6,GA,COND,NTMPR,XME
     +,W(10)
      COMMON/GRID/DELR,CONF1(12),CONF2(12),CONF0,CONF3,CONF4
      COMMON /PRPRTY/SA,CA,CP,CV,CW,RHOP,HFG
      COMMON /PRESS/PATM
      COMMON /NAME/INAME,IPROD
      COMMON /RKAM/Y(202)
      COMMON/TEST/AM,HD
      DIMENSION XMD(60,12)
      DIMENSION DMDX(60),DTDX(60),DTHDX(60),DHDX(60)
      F(T)=T+459.69
      PRL=0.0
      IEXIT=0
      PATM=14.696
C*****    INPUT CONDITIONS OF DRYER TO BE SIMULATED
      XMO=Y(12)
      XMEND=.01
C*****    COMPUTE INLET RH AND INITIALIZE Y ARRAY
      RHIN=RHOBHA(F(TIN),HIN)
      Y(11)=TIN
      Y(13)=HIN
      Y(14)=THIN
      Y(15)=0.0
      RH=RHIN
      SF=0.0
      IC=1
C*****    CONVERT AIRFLOW TO LB/HR AND COMPUTE CONVECTIVE HEAT TRANS-
C*****    FER COEFFICIENT AND EQUILIBRIUM MOISTURE CONTENT
      GA=60.*CFM/VSDBHA(F(TAMB),HIN)
      CFMHOT=GA*VSDBHA(F(TIN),HIN)/60.
      IF(GA-500.) 2,1,1
1     HC=0.0308*GA**0.59
      GO TO 3
2     HC= 0.0715*GA**0.49
    3 XME=EMC(RHIN,TIN)
      HD=0.00267*GA**0.49
C*****    CONVERT GRAIN FLOW TO FT/HR AND LB/HR AND COMPUTE AIR-GRAIN
C*****    RATIO
      GVEL=BPH*1.244
      GP=GVEL*RHOP
      CALL FINITE
      AFGF=GA/GP
C*****    PRINT HEADER PAGE OF CONDITIONS AND PROPERTIES
      XMEW=XME/(XME+1.)*100.
      IF(NTMPR.EQ.1)GO TO 12
      PRINT 310,RH,GA,CFMHOT,HC,XMEW,XME,XMO,GVEL,GP
      PRINT 311
C*****    COMPUTE CONSTANTS USED BY EQUATIONS IN SUBROUTINE DERFUN
12    CON1=GA*CA
      CON2=GA*CV
      CON3=HC*SA
```

```
      CON4=GP*CP
      CON5=GP*CW
      CON6=1./AFGF
      TMAX=0.0
      DMMAX=0.0
      DTMAX=0.0
      DTHMAX=0.0
      DHMAX=0.0
      CON3=GP/GA
C*****   CALL START TO INITIALIZE SOLUTION BY TAKING RUNGE-KUTTA STEPS
      HFG=HGVAP(Y(11),Y(12))
      CALL START(14,3,1,1.E-6,1.E-4,1.E-8,.01,1.E-6,.5)
C*****   BEGINNING OF LOOP
C*****   CHECK MOISTURE CONTENT...IF .LT. .17 COMPUTE NEW HFG
4     HFG=HGVAP(Y(11),Y(12))
C*****   CHECK ABSORPTION AND CONDENSATION FLAG...IF SET EXIT
C*****   CALL RKAMSUB TO TAKE NEXT STEP
    5 CALL RKAMSUB
      IF(Y(14).GT.TMAX) XTMAX=Y(15)
      IF(Y(14).GT.TMAX) TMAX=Y(14)
      IF(ABS(Y(28)).GT.DMMAX)XDMAX=Y(15)
      IF(ABS(Y(28)).GT.DMMAX) DMMAX=ABS(Y(28))
      IF(ABS(Y(27)).GT.DTMAX)XDTMAX=Y(15)
      IF(ABS(Y(27)).GT.DTMAX)DTMAX=ABS(Y(27))
      IF(Y(30).GT.DTHMAX)XTHMAX=Y(15)
      IF(Y(30).GT.DTHMAX)DTHMAX=Y(30)
      IF(Y(29).GT.DHMAX)XDHMAX=Y(15)
      IF(Y(29).GT.DHMAX)DHMAX=Y(29)
C*****   COMPUTE RH
      RH=RHDBHA(F(Y(11)),Y(13))
      IF(RH.GE.1.0)Y(13)=HADBRH(Y(11)+460.,RH)
      IF(RH.GE.1.)RH=1.
      CFMT=GA*VSDBHA(F(Y(11)),Y(13))/60.
      SP=SP + (CFMT/40.77)**(1.0/0.86173)*Y(16)
C*****   CHECK IF LONG ENOUGH, MOISTURE CONTENT LOW ENOUGH OR TIME TO
C*****   PRINT...IF NONE OF THESE GO TO BEGINNING OF LOOP
      IF(Y(15)-XLENG)6,6,8
    6 IF(Y(12)-XMEND)8,8,7
    7 IF(Y(15)-PRL)4,9,9
C*****   SET FLAG IF EXIT CONDITION MET
    8 IEXIT=1
    9 PRL=PRL+DBTPR
C*****   MAKE FINAL CALCULATIONS AND PRINT
      ETIME=Y(15)/GVEL
      WATER=(XMO-Y(12))*RHOP*1.244
      WB=Y(12)/(Y(12)+1.)*100.
      IF(NTMPR.EQ.1)GO TO 10
      PRINT 312,Y(15),ETIME,Y(11),Y(13),RH,Y(14),WB,Y(12)
10    XMD(IC,1)=Y(15)
      XMD(IC,2)=ETIME
      DO 450 N1 = 3,12
      XMD(IC,N1)=Y(N1-2)
      DMDX(IC)=Y(28)
      DTDX(IC)=Y(27)
      DTHDX(IC)=Y(30)
      DHDX(IC)=Y(29)
450   CONTINUE
      IC=IC+1
550   FORMAT(10(2X,F5.3))
C*****   CHECK IF EXIT CONDITION HAS BEEN MET...IF NOT RETURN TO BEGIN
C*****   NING OF LOOP
      IF(IEXIT-1) 4,11,4
C*****   EXIT HERE FOR ABSORPTION OR CONDENSATION
   11 CONTINUE
      EAIR=GA*(CA+CV*HIN)*(TIN-TAMB)/BPH
      HP=CFM*SP/6350.
      EFAN=.746*HP*3413./(.5*BPH)
      EAUG=0.0
      ENERGY=EAIR+EFAN+EAUG
      BTUH20=ENERGY/WATER
      IF(NTMPR.EQ.1)GO TO 666
      PRINT 406,TMAX,XTMAX
      PRINT 407,DMMAX,XDMAX
      PRINT 408,DTMAX,XDTMAX
      PRINT 409,DTHMAX,XTHMAX
      PRINT 410,DHMAX,XDHMAX
      PRINT 314,SP,HP,EFAN,EAIR,EAUG,ENERGY,WATER,BTUH20
666   PRINT 370
      PRINT 380
      PRINT 390,(I,I=1,10)
      IC=IC-1
```

```
      DO 400 I=1,IC
      PRINT 405,(XMD(I,J),J=1,12)
400   CONTINUE
      PRINT 401
      PRINT 402
      DO 404 I=1,IC
      PRINT 403,XMD(I,1),XMD(I,2),DMDX(I),DTDX(I),DTHDX(I),DHDX(I)
404   CONTINUE
309   FORMAT(//* ADDITIONAL INPUT FROM BLOCKDATA*//
     +* HEAT CAPACITIES, BTU/LB/F8*/
     +* DRY AIR*F6.3*   WATER VAPOR*F6.3*   DRY GRAIN*F6.3
     +*    LIQUID WATER*F5.3/* SPECIFIC SURFACE AREA, SQ FT/CU FT*F6.0/
     +* BULK DRY MATTER DENSITY, LB/CU FT*F6.2/
     +* HEAT OF VAPORIZATION (MC.GT.14.5 PERCENT WB)*F6.0/
     +* ATMOSPHERIC PRESSURE, PSI*F6.2)
310   FORMAT(//* PRELIMINARY CALCULATED VALUES*//* REL HUM, DECIMAL*
     +F6.4*   AIRFLOW RATE, LB DRY AIR/HR/SQ FT*F6.1*  CFM AT TIN*F6.1/
     +* HEAT TRANSFER COEF, BTU/HR/SQ FT/F*F8.3/
     +* EQUIL MC, WB PERCENT*F6.2*   DRY BASIS, DECIMAL*F6.4/
     +* INLET MC, DRY BASIS DECIMAL*F6.4/
     +* GRAIN VELOCITY, FT/HR*F6.2* LB DRY MATTER/HR/SQ FT*F8.2)
311   FORMAT(//3X5HDEPTH4X4HTIME5X3HAIR5X3HABS5X3HREL3X5HGRAIN6X2HMC
     +6X2HMC/20X4HTEMP5X3HHUM5X3HHUM4X4HTEMP6X2HWB6X2HDB/
     +6X2HFT6X2HHR7X1HF3X5HLB/LB8H DECIMAL7X17HF PERCENT DECIMAL)
312   FORMAT(2F8.2,F8.1,2F8.4,F8.1,F6.2,F8.4)
  213 FORMAT(///46HSITUATION ENCOUNTERED WHICH CAN NOT BE MODELED//A10,2
     12H FLAG SET AT LENGTH OF F6.3,3H FT)
314   FORMAT(//31H STATIC PRESSURE, INCHES OF H2OF6.2/17H HORSEPOWER/SQ
     +FTF5.2//22H ENERGY INPUTS, BTU/BU/10X12HFAN (.5 EFF)F7.0/10X8HHEAT
     + AIR4XF7.0/10X10HMOVE GRAIN2XF7.0/10X5HTOTAL7XF7.0//21H WATER REMO
     +VED, LB/BU=7.2//11H BTU/LB H2OF9.2)
315   FORMAT(5X*AMBIENT TEMP, F  *)
370   FORMAT(*0*,25X,*M O I S T U R E*,3X,*D I S T R I B U T I O N*)
380   FORMAT(*0*,1X,*DEPTH*,3X,*TIME*,30X,*NODES*)
390   FORMAT(5X,*FT*,5X,*HR*,2X,I2,9(4X,I2))
405   FORMAT(2X,F5.2,2X,F4.2,10(2X,F4.3))
401   FORMAT(*0*,1X,*DEPTH*,3X,*TIME*,3X,*DMDX*,6X,*DTDX*,4X,
     +*DTHDX*,4X,*DHDX*)
402   FORMAT(3X,*FT*,6X,*HR*,4X,*1/FT*,6X,*F/FT*,5X,*F/FT*,4X,
     +* 1/FT*)
403   FORMAT(1X,F6.2,2X,F5.2,1X,F7.4,1X,F9.2,2X,F7.2,1X,F6.4)
406   FORMAT(*0*,1X,*MAXIMUM GRAIN TEMP. =*,F6.2,*DEG.F*/3X,*
     +AT DEPTH OF *,F5.2,1X,*FT.*)
407   FORMAT(*0*,1X,*DM/DX MAX. = *,F9.2/3X,*AT DEPTH OF *,
     +F5.2,1X,*FT.*)
408   FORMAT(*0*,1X,*DT/DX MAX. = *,F9.2/3X,*AT DEPTH OF *,
     +F5.2,1X,*FT.*)
409   FORMAT(*0*,1X,*DTH/DX MAX. = *,F9.2/3X,*AT DEPTH OF *,
     +F5.2,1X,*FT.*)
410   FORMAT(*0*,1X,*DH/DX MAX. = *,F9.2/3X,*AT DEPTH OF *,
     +F5.2,1X,*FT.*)
      END
      SUBROUTINE DERFUN
C*****
C*****          SUBPROGRAM DESIGN TO CALCULATE DERIVATIVES USING FINITE DIF
C*****
C*****            L. P. WALKER
C*****
      COMMON/PRPRTY/SA,CA,CP,CV,CW,RHOP,HFG
      COMMON/CONSTNT/CON1,CON2,CON3,CON4,CON5,CON6,GA,COND,NTMPF,XME
     +,W(10)
      COMMON/RKAM/Y(202)
      COMMON/GRID/DELR,CONF1(12),CONF2(12),CONF0,CONF3,CONF4
      COMMON/TEST/AM,HD
      AM=0.0
      DO 1 N1 = 1,9
      AM=AM+(W(N1+1)*Y(N1+1) + W(N1)*Y(N1))
1     CONTINUE
C*****
C*****                CALCULATE DERV. AT FIRST NODE OF KERNEL
C*****
      DC=CMOS(AM,Y(14))
      Y(17)=DC*(Y(2)-Y(1))*CONF0
C*****
C*****                CALCULATE DERV. AT OTHE NODES OF KERNEL
C
      RH=RHDBHA(Y(11)+460.,Y(13))
      XME=EMC(RH,Y(11))
      IF(XME.LT.0.)XME=0.0
      IF(RH.GT.1.0)XME=EMC(1.0,Y(11))
      IN=17
```

```
      IF(RH.GT.1.)RH=1.
      IF(RH.GT.1.)Y(13)=HADBRH(Y(11)+460.,RH)
      DO 5 K=2,9
      IN=IN+1
      Y(IN)=DC*(CONF1(K)*Y(K+1) + CONF2(K)*Y(K-1) - CONF3*Y(K))
    5 CONTINUE
      IF(NTMPR.GT.0)GO TO 14
****
**** DERIVATIVE FOR MOISTURE AT THE SURFACE OF KERNEL
****
      Y(26)=CONF3*DC*(Y(9)-Y(10)) - HD*CONF4*(Y(10)-XME)
****
**** DERIVATIVE FOR AVERAGE MOISTURE CHANGE AT SURFACE
****
      AVE=0.0
      DO 10 N=1,9
      AVE=AVE+(W(N+1)*Y(17+N) + W(N)*Y(16+N))
      CONTINUE
      Y(28)=AVE
****
****           DERIVATIVE FOR AIR HUMIDITY - DH/DX
****
      Y(29)=-COND*Y(28)
*****
****           DERIVATIVE FOR GRAIN TEMPERATURE - DTHETA/DX
****
      Y(30)=(CON3*(Y(11)-Y(14))-(HFG+CV*(Y(11)-Y(14)))*GA*Y(29))/(CON4+C
     +ON5* Y(12))
****
****           DERIVATIVE FOR AIR TEMPERATURE  -  DT/DX
****
      Y(27)=-CON3*(Y(11)-Y(14))/(CON1+CON2*Y(13))
      RETURN
****
****           TEMPERING MODEL
****
      Y(26)=CONF3*DC*(Y(9)-Y(10))
      Y(27) = 0.0
      Y(28)=0.0
      Y(29)=0.0
      Y(30)=0.0
      RETURN
      END
      SUBROUTINE FINITE

            SUBROUTINE TO CALCULATE FINITE DIFF COEFF.

            PROGRAMMER, L.P. WALKER

      COMMON/GRID/DELR,CONF1(12),CONF2(12),CONF0,CONF3,CONF4
      COMMON/MAIN/XMO,CFM,GVEL
      SR=(DELR**2)*GVEL
      DO 1  J=2,12
      CONF1(J)=FLOAT(2*J-1)/(FLOAT(2*J-2)*SR)
      CONF2(J)=FLOAT(2*J-3)/(FLOAT(2*J-2)*SR)
    1 CONTINUE
      CONF0 = 4.0/SR
      CONF3 =2.0/SR
      CONF4=(1.0/(9.0*DELR*GVEL)) + (2.0/(DELR*GVEL))
      RETURN
      END
      FUNCTION CMOS(C,T)

      SUBROUTINE TO CALCULATE DIFUSSION COEFF.

      L.P. WALKER . PROGRAMMER

      CM=C*100.0
      TA=T+460.
      CE=EXP(-7730.65/TA)
      GT=94.8787*CE
      FT=(8.8331E-4)*TA-3.3788
      DMT=GT*EXP(FT*CM)
      CMOS=DMT
      RETURN
      END
      FUNCTION EMC(RH,T)
******
******
******               L. P. WALKER, PROGRAMMER
******
```

```
C ******
C ******
C ****** DESCRIPTION
C ******    FUNCTION TO COMPUTE EQUILBRIUM MOISTURE CONTENT OF RICE FROM
C ****** RELATIVE HUMIDITY AND RICE TEMPERATURE. EQUATION FROM KACHRU,R.
C ******P. AND MATTHES, R. K.(1976).
C ******
C ******
C ****** USAGE
C ******
C ****** USED WITH A FIXED BED, CROSSFLOW, CONCURRENT AND COUNTERFLOW
C ****** GRAIN DRYER MODELS FOR RICE.
C ******
C ******
      TABS=T+459.69
      A0=4.510
      A1=0.069
      A2=8.837
      A3=-0.015
      IF(RH.GE..9999)RH=.9999
      RHP=RH*100.
      EMC=A0+A1*RHP+A2*SQRT(RHP)+A3*SQRT(RHP)*TABS
      EMC=EMC/100.
      RETURN
      END
      BLOCKDATA
      COMMON/PRPRTY/SA,CA,CP,CV,CW,BUKDEN,HFG
      COMMON/PRESS/PATM
      DATA SA,CA,CP,CV,CW,BUKDEN/324.,0.242,.632,0.45,1.0,36.46/
      DATA PATM/14.30/
      END
      FUNCTION HGVAP(T1,CM)
C*****
C*****   SUBPROGRAM DESIGN TO CALCULATE HEAT OF VAPORIZATION
C*****   OF WATER IN GRAINS BASED ON THE WORK OF GALLAHER (1951)
C*****
C*****   L. P. WALKER, PROGRAMMER
C*****
      W=CM
      TDB=T1+460.
      HV=HLDB(TDB,800,1200,.1)
      HS=(1. + 23.0 * EXP(-40*W))*HV
      HGVAP=HS
      RETURN
      END
      SUBROUTINE WEIGHT
      COMMON/CONSTNT/CON1,CON2,CON3,CON4,CON5,CON6,GA,COND,NTMPR,XME
     +,W(10)
      DO 100 M =1,10
      W(M)=(M-1)/81.0
100   CONTINUE
      RETURN
      END
```

19.39.43..000009 PAGES PRINT. 000540 LINES PRINT. FOR $ 000.58 AT RG2.

APPENDIX E

INPUT/OUTPUT EXAMPLE

```
M.S.U. AGRICULTURE ENGINEERING DEPARTMENT
SIMULATION OF MULTISTAGE  RICE DRYER
WITH EMC B.C.

HOW MANY STAGES =2

IS TEMPERING DESIREABLE =1
(YES=1, NO=2)'

ENVIRONMENTAL CONDITIONS:

    AMBIENT TEMP, F 78.0
    INLET ABS HUM RATIO = 0.009

GRAIN STATUS
    INTIAL MOISTURE CONTENT, PERCENT W.B. 20.0
    INTIAL GRAIN TEMP., F  75.0

DRYING VARIABLES

             STAGE 1
    INLET AIR TEMP, F  250.0
    AIRFLOW RATE, CFM/SQFT (AT AMBIENT CONDITIONS)  80.0
    GRAIN FLOW RATE, BU/HR-SQ FT 6.0
    BED DEPTH, FT  3.0
    OUTPUT INTERVAL, FT 0.5

    LENGTH OF TEMPERING SECTION - FT 10.00

             STAGE 2
    INLET AIR TEMP, F 250.0
    AIRFLOW RATE, CFM/SQFT (AT AMBIENT CONDITIONS)  80.0
    BED DEPTH, FT 3.0
    OUTPUT INTERVAL, FT 0.5

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

            D R Y E R   S T A G E   N O   1

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX


PRELIMINARY CALCULATED VALUES

REL HUM, DECIMAL .0070  AIRFLOW RATE, LB DRY AIR/HR/SQ FT 349.1   CFM AT TIN 105.6
HEAT TRANSFER COEF, BTU/HR.SQ FT/F   1.260
EQUIL MC, WB PERCENT  2.95   DRY BASIS, DECIMAL .0304
INLET MC, DRY BASIS DECIMAL .2500
GRAIN VELOCITY, FT/HR  7.46 LB DRY MATTER/HR/SQ FT  287.07
```

DEPTH FT	TIME HR	AIR TEMP F	ABS HUM LB/LB	REL HUM DECIMAL	GRAIN TEMP F	MC WB PERCENT	MC DB DECIMAL
.07	.01	205.2	.0112	.0165	88.3	19.91	.2486
.51	.07	113.4	.0231	.3738	101.3	18.89	.2329
1.02	.14	98.7	.0294	.7274	95.9	18.38	.2252
1.51	.20	94.6	.0320	.8945	93.4	18.17	.2220
2.02	.27	92.5	.0335	.9943	91.9	18.05	.2202
2.51	.34	91.3	.0348	1.0000	90.8	17.97	.2191
3.01	.40	90.2	.0357	1.0000	89.8	17.90	.2180

```
MAXIMUM GRAIN TEMP. =101.37DEG.F
             AT DEPTH OF    .33 FT.

DM/DX MAX. =          .04
 AT DEPTH OF    .21 FT.

DT/DX MAX. =      554.41
 AT DEPTH OF    .07 FT.

DTH/DX MAX. =     151.95
 AT DEPTH OF    .07 FT.

DH/DX MAX. =          .03
 AT DEPTH OF    .21 FT.

STATIC PRESSURE, INCHES OF H2O  7.19
```

HORSEPOWER/SQ FT .09

ENERGY INPUTS, BTU/BU

FAN (.5 EFF)	76.
HEAT AIR	2462.
MOVE GRAIN	-.
TOTAL	2536.

WATER REMOVED, LB/BU 1.53

BTU/LB H2O 1655.86

M O I S T U R E D I S T R I B U T I O N

DEPTH FT	TIME HR	NODES 1	2	3	4	5	6	7	8	9	10
.07	.01	.250	.250	.250	.250	.250	.250	.250	.250	.250	.238
.51	.07	.250	.250	.250	.250	.250	.250	.248	.242	.220	.163
1.02	.14	.250	.250	.250	.250	.249	.248	.243	.229	.201	.160
1.51	.20	.250	.250	.250	.249	.248	.245	.237	.220	.195	.167
2.02	.27	.250	.250	.250	.249	.247	.242	.232	.215	.194	.174
2.51	.34	.250	.250	.249	.248	.245	.239	.228	.212	.194	.179
3.01	.40	.249	.249	.248	.247	.243	.236	.225	.210	.194	.181

DEPTH FT	TIME HR	DMDX 1/FT	DTDX F/FT	DTHDX F/FT	DHDX 1/FT
.07	.01	-.0237	-554.41	151.95	.0236
.51	.07	-.0248	-61.12	-9.48	.0204
1.02	.14	-.0090	-13.05	-6.66	.0074
1.51	.20	-.0046	-5.46	-3.79	.0038
2.02	.27	-.0027	-2.99	-2.32	.0022
2.51	.34	-.0023	-2.20	-2.06	.0019
3.01	.40	-.0020	-1.96	-1.87	.0017

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

T E M P E R I N G S T A G E N O . 1

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

M O I S T U R E D I S T R I B U T I O N

DEPTH FT	TIME HR	NODES 1	2	3	4	5	6	7	8	9	10
.07	.01	.249	.249	.248	.246	.243	.236	.225	.210	.194	.182
.51	.07	.249	.249	.245	.245	.241	.233	.223	.209	.196	.189
1.02	.14	.248	.248	.247	.244	.239	.231	.221	.209	.199	.194
1.51	.20	.248	.247	.245	.242	.237	.229	.220	.209	.200	.197
2.02	.27	.247	.246	.244	.241	.235	.228	.219	.209	.202	.200
2.51	.34	.246	.245	.243	.239	.234	.227	.218	.210	.204	.202
3.01	.40	.244	.244	.242	.237	.232	.225	.218	.210	.205	.203
3.51	.47	.243	.242	.240	.236	.231	.225	.217	.211	.206	.205
4.01	.54	.242	.241	.239	.235	.230	.224	.217	.211	.208	.206
4.51	.60	.241	.240	.238	.234	.229	.223	.217	.212	.209	.207
5.01	.67	.239	.239	.236	.233	.228	.223	.217	.212	.209	.208
5.51	.74	.238	.237	.235	.232	.227	.222	.217	.213	.210	.209
6.01	.81	.237	.236	.234	.231	.226	.222	.217	.213	.211	.210
6.51	.87	.236	.235	.233	.230	.226	.221	.217	.214	.211	.211
7.01	.94	.234	.234	.232	.229	.225	.221	.217	.214	.212	.211
7.50	1.01	.233	.233	.231	.228	.225	.221	.217	.214	.212	.212
8.01	1.07	.232	.232	.230	.227	.224	.221	.217	.215	.213	.212
8.50	1.14	.231	.231	.229	.227	.224	.220	.217	.215	.213	.213
9.01	1.21	.230	.230	.228	.226	.223	.220	.217	.215	.214	.213
9.50	1.27	.230	.229	.228	.225	.223	.220	.217	.215	.214	.214
10.01	1.34	.229	.228	.227	.225	.223	.220	.218	.216	.214	.214

DEPTH FT	TIME HR	DMDX 1/FT	DTDX F/FT	DTHDX F/FT	DHDX 1/FT
.07	.01	0.0000	0.00	0.00	0.0000
.51	.07	0.0000	0.00	0.00	0.0000
1.02	.14	0.0000	0.00	0.00	0.0000
1.51	.20	0.0000	0.00	0.00	0.0000
2.02	.27	0.0000	0.00	0.00	0.0000
2.51	.34	0.0000	0.00	0.00	0.0000
3.01	.40	0.0000	0.00	0.00	0.0000
3.51	.47	0.0000	0.00	0.00	0.0000
4.01	.54	0.0000	0.00	0.00	0.0000
4.51	.60	0.0000	0.00	0.00	0.0000
5.01	.67	0.0000	0.00	0.00	0.0000
5.51	.74	0.0000	0.00	0.00	0.0000
6.01	.81	0.0000	0.00	0.00	0.0000

6.50	.87	0.0000	0.00	0.00	0.0000
7.01	.94	0.0000	0.00	0.00	0.0000
7.50	1.01	0.0000	0.00	0.00	0.0000
8.01	1.07	0.0000	0.00	0.00	0.0000
8.50	1.14	0.0000	0.00	0.00	0.0000
9.01	1.21	0.0000	0.00	0.00	0.0000
9.50	1.27	0.0000	0.00	0.00	0.0000
10.01	1.34	0.0000	0.00	0.00	0.0000

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

D R Y E R   S T A G E   N O   2

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

PRELIMINARY CALCULATED VALUES

REL HUM, DECIMAL .0070   AIRFLOW RATE, LB DRY AIR/HR/SQ FT 349.1   CFM AT TIN 105.6
HEAT TRANSFER COEF, BTU/HR/SQ FT/F   1.260
EQUIL MC, WB PERCENT 2.95   DRY BASIS, DECIMAL .0304
INLET MC, DRY BASIS DECIMAL .2182
GRAIN VELOCITY, FT/HR 7.46 LB DRY MATTER/HR/SQ FT 287.07

DEPTH	TIME	AIR TEMP	ABS HUM	REL HUM	GRAIN TEMP	MC WB	MC DB
FT	HR	F	LB/LB	DECIMAL	F	PERCENT	DECIMAL
.03	.00	227.4	.0196	.0113	96.8	17.87	.2175
.52	.07	124.1	.0232	.2793	112.0	16.73	.2010
1.01	.13	110.2	.0295	.5179	107.2	16.20	.1934
1.52	.20	105.5	.0325	.6532	104.1	15.94	.1897
2.01	.27	103.1	.0342	.7371	102.2	15.79	.1876
2.51	.34	101.5	.0354	.7931	100.9	15.69	.1861
3.01	.40	100.4	.0352	.8420	100.0	15.62	.1851

MAXIMUM GRAIN TEMP. =113.45DEG.F
AT DEPTH OF   .32 FT.

DM/DX MAX. =   .04
AT DEPTH OF   .19 FT.

DT/DX MAX. =   620.37
AT DEPTH OF   .03 FT.

DTH/DX MAX. =   184.69
AT DEPTH OF   .03 FT.

DH/DX MAX. =   .03
AT DEPTH OF   .19 FT.

STATIC PRESSURE, INCHES OF H2O 7.24
HORSEPOWER/SQ FT   .09

ENERGY INPUTS, BTU/BU
FAN (.5 EFF)   77.
HEAT AIR   2462.
MOVE GRAIN   0.
TOTAL   2539.

WATER REMOVED, LB/BU   1.58

BTU/LB H2O 1603.77

M O I S T U R E   D I S T R I B U T I O N

DEPTH FT	TIME HR	NODES 1	2	3	4	5	6	7	8	9	10
.03	.00	.229	.228	.227	.225	.223	.220	.218	.216	.214	.208
.52	.07	.227	.227	.226	.224	.222	.219	.215	.207	.183	.133
1.01	.13	.226	.226	.225	.223	.221	.217	.209	.194	.166	.130
1.52	.20	.225	.225	.224	.222	.219	.213	.203	.185	.161	.134
2.01	.27	.224	.224	.223	.220	.216	.210	.198	.181	.159	.139
2.51	.34	.223	.223	.222	.219	.214	.206	.194	.178	.159	.143
3.01	.40	.223	.222	.220	.217	.212	.203	.191	.176	.160	.147

DEPTH FT	TIME HR	DMDX 1/FT	DTDX F/FT	DTHDX F/FT	DHDX 1/FT
.03	.00	-.0253	-620.37	184.69	.0208
.52	.07	-.0239	-55.63	-16.69	.0196

1.01	.13	-.0099	-13.97	-7.86	.0082
1.52	.20	-.0054	-6.37	-4.69	.0044
2.01	.27	-.0034	-3.83	-3.08	.0028
2.51	.34	-.0023	-2.56	-2.15	.0019
3.01	.40	-.0017	-1.85	-1.61	.0014

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

TOTAL DRYER PERFORMANCE

TOTAL ENERGY REQUIREMENT = 5077.3

TOTAL AMOUNT OF WATER REMOVED (LBS) = 3.12

BTU/LB = 1629.40

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX