This is to certify that the

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A New Rice-Drying System

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A NEW RICE-DRYING SYSTEM

By

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ABSTRACT

A NEW RICE-DRYING SYSTEM

By

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An existing MSU drying model was modified to simulate in-bin counterflow heating/cooling of grain. The model is based on four differential equations. Numerical solution by finite difference substitution in the derivatives was employed to solve the equations. Experimental maize heating/drying data from a maize-preheater system was used to validate the simulation model. Good agreement was obtained between the experimental and simulated results.

The modified model was first utilized to analyze the effects of various parameters on the performance of an in-bin counterflow heater for maize. Subsequently, the model was employed for the design of a new in-bin counterflow dryer for rice.

The top-bin/in-bin-counterflow rice drying system was build near Shanghai, China. The system consists of three drying bins, each with a top-bin (TB) dryer and an in-bin counterflow (IBCF) dryer, and two aeration/storage bins. The system has particularly advantageous features for the drying of rice because of the requirement of stepwise drying and intermittent tempering.

At a capacity of 12 tonnes per hour and a bed-depth of 0.3 m in the TB dryers and 1.5 m in the IBCF dryers, the tempering time between the TB and IBCF drying treatments in the new rice-drying system is 7.5 hours. The drying-air temperatures in the

TB dryers are 52°C, 46°C and 41°C in the first, the second and the third bin, respectively. The drying-air temperature in the IBCF dryers is 27°C (i.e. the average ambient temperature) in each of the bins. The airflows in each bin are 50 m^3/min.tonne in the TB dryers and 1 m^3/min.tonne in the IBCF dryers. The total drying time in the system for rice being dried from 24 to about 13% is 27 hours. The new rice-drying system will go on-line during the fall of 1993.

Approved ______________________
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a	Specific surface area, m^2/m^3
C	Specific heat, kJ/kg °C
D	Depth, m
D	Diffusion coefficient, m^2/hr
E	Energy, kW
G	Dry weight flow rate, $kg/hr.m^2$
H	Humidity ratio, kg/kg
h	Enthalpy, kJ/kg
h_{fg}	Heat of vaporization, kJ/kg
IBCF	In-bin counterflow
k	Latent heat of vaporization, kJ/kg
M	Moisture content, % wet basis or % dry basis
Me	Equilibrium moisture content, decimal dry basis
MR	Moisture ratio, (M-Me)/(Mo-Me)
p	Pressure, kPa
Q	Airflow rate, $m^3/s.m^2$
R	Equivalent product kernel radius, m
rh	Relative humidity, percent
RH	Relative humidity, decimal
SECO	Specific energy consumption, kJ/kg-H2O
SP	Pressure drop, Pa/m

T	Air temperature, °C
TB	Top bin
t	Time, hr
tm	Drying time, min
W	Water, kg
x	Bed depth coordinate, m
Y	Volumetric airflow rate, m^3/min
α	Thermal diffusivity, m^2/hr
ϱ	Dry weight density, kg/m^3
θ	Grain temperature, °C

<u>Subscripts</u>

a	Air
e	Equilibrium
i	ith cycle
o	At time t = 0
p	Product
t	Time
v	Vapor
w	Water
x	Bed depth coordinate

1. INTRODUCTION

1.1 Background

There are three main types of rice grain: long-grain, medium-grain, and short-grain. Long-grain varieties have characteristics of being dry and fluffy after cooking ; medium- and short-grain varieties are moist and tend to clump together. In the United States, long-grain varieties are grown mainly in Louisiana, Arkansas, and Texas, medium- and short-grain varieties in California. Medium-grain varieties are the main type of rice grown in Indonesia.

Rice grain is harvested at an average moisture content varying from 20 to 26%, wet basis (w.b.), depending on the harvesting method, the rice type and variety, and the growth location. In Indonesia, the maximum head rice of medium-grain varieties is obtained when the crop is harvested during the wet season at 20-24% (w.b.) moisture, and at 18-20% (w.b.) during the dry season [in this thesis, all moisture values are given on a wet basis (w.b.) unless specifically designated as dry basis (d.b.)].

In the Humid Tropics, the harvested grain deteriorates quickly after about 24 hours of storage due to the high ambient temperatures and humidities. Mold development leads to rapid deterioration of stored rice if the grain is not treated immediately. There are four effective preservation treatments in use: drying, chilling, sealed storage, and chemical treatment.

Drying is the most widely practiced grain-preservation method. The method is used for over 80% of the maize produced in the US (ICLRS,1984); about 60% of the total energy required to produce maize is used for drying (Brooker et al., 1992). Chilling, sealed storage and chemical treatment are too costly in the Humid Tropics. Drying is therefore a crucial step in the production and processing of rice.

Various types of mechanical drying systems for rice have been developed, and are used successfully throughout the world. Basically, a mechanical dryer consists of a heater to heat the drying air, ducting to move the air to the grain mass, a fan to blow the drying air thorough the grain mass, and a structure to hold the grain. Commonly, two kinds of mechanical dryer types are employed : (a) batch drying systems, and (b) continuous-flow drying systems.

Drying grain in batches within a bin, and subsequently moving the dried grain to storage, is called batch-in-bin drying. The operating principle of such dryers is to dry a relatively shallow layer of moist grain to the desired moisture content by forcing a large quantity of heated air through it.

Based on the relative direction of the grain and air through the dryer, continuous-flow drying systems fall into four categories: cross-flow, concurrent-flow, counterflow, and mixed-flow. In this thesis, only counterflow drying will be studied in more detail.

In a conventional in-bin counterflow (IBCF) dryer, the grain moves downward while the drying air moves upward. The grain just above the false floor is removed from the bin as soon as it is dried to a predetermined moisture content. An on-floor tapered sweep-auger rotates around the bin, sweeping a thin layer of grain to the bin center from where the partially-dried and hot grain is either elevated by a vertical auger to a transfer auger, or is carried from the bin by an unloading auger. The activation of the sweep auger is controlled by a temperature-sensor. The sensor is calibrated to correspond to the target moisture content, with the grain temperature used as an indication of the desired final moisture content. When a predetermined temperature is reached, the sweep auger is activated. As the auger completes the cycle, damp grain moves into the sensor's region and the temperature at that point drops. As a result, the auger stops, and waits for the next cycle to start.

Marks et al. (1988) studied by simulation the optimal operating conditions of IBCF maize drying. They found that the bed depth and drying temperature most significantly affect the drying capacity and the specific energy consumption of the IBCF maize dryer. For minimum energy consumption, while maintaining the maximum drying capacity, the optimal operating bed depth is 1.4 m for the case the dryer is continuously refilled with wet maize. This thesis studies an alternative operation scheme in which the sweep auger is activated at a preselected time (i.e. the auger is activated when the drying time reaches a preselected value).

The use of high drying air temperature in conventional in-bin drying systems is restricted because of the destructive effect of overdrying on rice quality. This thesis studies a new-rice drying system which allows the use of moderately-high drying temperatures while maintaining high grain quality. This new system consists of a combination of cross-flow and in-bin counterflow dryers placed in series, and has built in near Shanghai, China. This investigation also studies the performance of the use of the IBCF dryer in combination with two other dryer types , the concurrent-flow dryer and the cross-flow dryer.

1.2 Objectives of the Study

The general objective of this study is to determine experimentally and by simulation the effect of various operating parameters on the performance of the IBCF dryer. The simulation model will be validated with experimental maize drying data.

The specific objectives are:

(1) to update and modify an existing IBCF heating/drying (and cooling) model for rice and maize

(2) to study the effect of the inlet-grain moisture, the inlet-air temperature, and the grainflow rate on the outlet-grain moisture and outlet-grain temperature in an IBCF maize-preheater, and

(3) to design the operating conditions of a series of top bin (TB)/IBCF drying systems to be operating for drying rice under Chinese conditions.

2. LITERATURE REVIEW

2.1 Rice Kernel Properties

The drying behavior of rice depends on the physical and thermal properties of the single kernels and of the bed of kernels. A knowledge of the properties of rough rice is therefore essential when investigating heat and mass transfer phenomena in rice drying (Morita and Singh, 1977).

2.1.1 Physical Properties of Rough Rice

In dryer simulation models, the kernel dimensions, the bulk density, the bed porosity, the specific surface area, and the kernel diffusion coefficient should be known. The physical properties of rough rice have been reported by Wratten et al. (1969), Morita and Singh (1977), Webb (1980), and Steffe and Singh (1982). The dimensions, length-to-width ratio, and 1,000-kernel weight of long-, medium-, and short-grain rough rice at 13% moisture content are tabulated in Table 2.1. The bulk densities are given in Table 2.2. The effect of moisture content on the bulk density is shown in Table 2.3; the effect on porosity in Table 2.4. The specific surface areas per unit volume of rice kernels for three rice classes are tabulated in Table 2.5. The equivalent radii of rough rice kernel and rough rice components assuming spherical kernels are given in Table 2.6. The diffusion coefficients for rice kernel and rice kernel-components are listed in Table 2.7. The effect of temperature on the diffusion coefficient is shown in Table 2.8. The values in Tables 2.1-2.8 are self-explanatory.

Table 2.1 Range in dimensions and kernel weight of commercial US long-, medium-, and short-grain rough rice varieties at 13% moisture Content (w.b.).

Grain Type	Length (mm)	Width (mm)	Thickness (mm)	Length/Width Ratio	1,000 Kernel Weight (g)
Long	8.9 - 9.6	2.3 - 2.5	1.8 - 1.9	3.8 - 3.9	21 - 24
Medium	7.9 -8.2	3.0 - 3.2	1.9 - 2.1	2.5 - 2.6	23 - 25
Short	7.4 - 7.5	3.1 - 3.6	2.1 - 2.3	2.1 - 2.4	26 - 30

Sources: Webb (1980); Steffe and Singh (1982)

Table 2.2 Bulk density of commercial US long-,medium-,and short-grain rough rice varieties at 13% moisture content (w.b.).

Rice Type	Bushel Weight (lb/bu)	Bulk Density (kg/m^3)
Long	42 - 45	541 - 579
Medium	44 - 47	566 - 605
Short	45 - 48	579 - 618

Source: Webb (1980)

Table 2.3 Bulk density of commercial US long-, medium-,and short-grain rough rice as a function of moisture content.

Moisture Content	Bulk Density (kg/m^3)		
(% w.b.)	Long-Grain*	Medium-Grain*	Short-Grain**
10	572	583	626
15	599	625	648
20	625	666	669
25	652	708	690

Source: * Wratten et al. (1969); ** Morita and Singh (1977)

Table 2.4 Porosity of commercial US long-,medium-grain rough rice as a function of moisture content.

Moisture Content (% w.b.)	Porosity (%)	
	Long - Grain	Medium - Grain
10	61	60
15	58	56
20	56	51
25	54	47

Source: Wratten et al. (1969).

Table 2.5 Specific surface area of commercial US long-, medium-, and short-grain rough rice at 18 % moisture content (w.b.).

Rice Type	Specific Surface Area (m^2/m^3)
Long	2,437
Medium	2,361
Short	2,050

Source: Fontana (1983)

Table 2.6 Equivalent radius of the endosperm sphere, and the thickness of bran and hull layers, in long-, medium-, and short-grain rice.

Type of Product	Equivalent Radius (mm)		
	Long*	Medium*	Short**
Endosperm	0.88	1.38	1.58
Bran	0.05	0.08	0.08
Hull	0.07	0.10	0.11
Rough Rice	1.00	1.56	1.77

Sources : * Fontana (1983); ** Steffe (1979)

Table 2.7 Diffusion coefficients of rough rice kernel and rough rice components assuming spherical kernels [Ta = absolute temperature (°K), D = diffusion coefficient (m^2/hr)].

Diffusivity (m^2/h)	D = A exp (B/Ta)	
	A	B
Rough rice starchy endosperm (1)	0.00257	- 2880.
Rough rice bran (1)	0.79700	- 5110.
Rough rice hull (1)	484.00000	- 7380.
Whole rough rice kernel (2)	0.00983	- 4151.
Whole rough rice kernel (3)	33.60000	- 6420.
Whole rough rice kernel (4)	33,029.00000	- 8624.
Whole brown rice kernel (4)	0.79790	- 4933.
Whole parboiled rough kernel (4)	411.86000	- 6978.
Whole parboiled brown kernel (4)	401.62000	- 6744.

(1) Steffe and Singh (1980a) : short-grain smooth hulled variety S6, 35.4 - 54.8°C, equivalent radius 0.177 cm
(2) Wang and Singh (1978) : medium-grain smooth hulled variety CSM5, 30.0 - 55.0°C, equivalent radius 0.184 cm
(3) Steffe and Singh (1982) : short-grain smooth hulled variety S6, 35.4 - 54.8°C, equivalent radius 0.177 cm
(4) Bakshi and Singh (1979) : short-grain smooth hulled variety S6, 40.0-55.0°C, equivalent radius 0.177 cm

Table 2.8 Diffusion coefficient of rough rice kernel and rough rice components as a function of temperature assuming spherical kernels.

Temp. (°C)	Diffusivity (m^2/h)*(10**9)				
	Short - Grain		Medium-Grain		
	Endosperm(1)	Bran(1)	Hull(1)	Kernel(2)	Kernel(3)
0	68	6	1	2	2
10	199	12	2	5	4
20	140	22	6	10	7
30	193	38	13	22	11
40	262	66	28	42	17
50	348	109	59	80	26
60	455	175	117	145	38
70	585	274	224	254	55
80	748	417	411	432	78
90	938	621	730	712	107
100	1152	906	1258	1143	146

(1) Steffe (1979); (2) Steffe and Singh (1982); (3) Wang and Singh (1978)

2.1.2 Thermal Properties of Rough Rice

The thermal properties of rice of importance in the rice drying models are: the specific heat, convective heat transfer coefficient, latent heat of vaporization, thermal conductivity, and thermal diffusivity.

2.1.2.1 Specific Heat

Morita and Singh (1977) developed equations for the specific heat as a function of moisture content for various rice types:

Long-grain rice	$C_p = 1.10953 + 0.04480 * Mw$	(2.1)
Medium-grain rice	$C_p = 0.92145 + 0.05447 * Mw$	(2.2)
Short-grain rice	$C_p = 1.26947 + 0.03488 * Mw$	(2.3)

where C_p = specific heat (kJ/kg.°C)
Mw = moisture content (% w.b.)

2.1.2.2 Convective Heat Transfer Coefficient

To predict the convective heat transfer coefficient in a bed of medium-grain rice, Wang et al. (1979) proposed the following equation:

$$h = 86900. * G_a ** 1.30 \qquad (2.4)$$

where h = volumetric heat transfer coefficient (W/m^3.K)
G_a = airflow rate through the bed of grain (kg dry air/s.m^2)

2.1.2.3 Latent Heat of Vaporization

Fontana (1982) recommended the following equation for the latent heat of vaporization of rough rice as a function of rice temperature and moisture content (Brook and Foster, 1979):

$$h_{fg} = 2.323[1090. - 1.026(\theta + 17.78)][1 + 2.9462*\exp(-21.733*M)] \qquad (2.5)$$

where h_{fg} = latent heat of vaporization (kJ/kg)
θ = rice temperature (°C)
M = moisture content (decimal, dry basis)

Another equation for the latent heat of vaporization of rough rice was developed by Zuritz and Singh (1985):

$$h_{fg} = R\,T_a^2\left(\frac{\ln ERH}{T_a^2}(c_1 + c_2\,c_3\,T_a^{c_3}M) + \frac{6887}{T_a^2} - \frac{5.31}{T_a}\right) \qquad (2.6)$$

where R = gas constant (0.4614 kJ/kg.°K)
T_a = absolute temperature (°K)
ERH = equilibrium relative humidity (decimal)
c_1 = - 3.52486
c_2 = - 1.1205E-4
c_3 = 1.30047
h_{fg} and M are defined in equation (2.5).

Equation (2.5) and 2.6 give similar results, with a maximum difference of 14% at 10°C and 10% moisture content. However, the values of the latent heat of vaporization calculated with equation (2.6) are more sensitive to temperature changes at lower moisture contents. Thus, equation (2.6) is used in the computer simulation program.

2.1.2.4 Thermal Conductivity and Thermal Diffusivity

The thermal conductivity and thermal diffusivity of medium-grain rough rice as functions of moisture content have been reported by Morita and Singh (1977):

$$k = 0.086560 + 0.00132700 * Mw$$

$$\alpha = 0.000456 - 0.00000896 * Mw \tag{2.7}$$

where k = thermal conductivity (W/m.K)
Mw = moisture content (% w.b.)
α = thermal diffusivity (m^2/h)

2.2 Pressure Drop

When air is forced through a layer of grain, the resistance to the flow, the so-called pressure drop, develops as a result of the energy lost through friction and turbulence. The resistance is overcome either by providing a positive pressure on the air entrance side of the grain mass or by providing a negative pressure on the air-exit side. The pressure drop for airflow through a layer of rice depends on:

(a) the rate of airflow
(b) the surface and shape characteristics of the grain
(c) the number, size and configurations of the voids in the grain bed
(d) the variability of the kernel size, and
(e) the depth of the grain bed.

The following equation is recommended to calculate the pressure drop through a bed of grain of average moisture content (13%), fines concentration, and bulk density (Brooker et al., 1992):

$$SP = a\,Q^{b} \tag{2.8}$$

where SP = pressure drop (Pa/m)
Q = airflow rate ($m^3/m^2.s$)
a and b = product constants

The values of the product constants of a and b for rice are listed in Table 2.9. Short-grain rice offers more resistance to airflow than long-grain rice (Calderwood, 1973).

Table 2.9 Values of product constants a and b in the static pressure equation (2.8) for short-, medium-, and long-grain rough rice at 13 % moisture content (w.b.).

Rice Type	Airflow ($m^3/m^2.s$)	a	b
Short*	0.08 - 0.41	7,319.0	1.5006
Medium**	0.08 - 0.41	9,261.0	1.4628
Long**	0.01 - 0.15	4,832.0	1.1671

Sources: * Cervinka (1971); ** Calderwood (1973)

2.3 Rice Equilibrium Moisture Content

The equilibrium moisture content (Me) of a cereal grain is defined as the final moisture content which the grain displays after it has been exposed to a given environment for an infinitely long period of time. Factors that affect the Me of the grain are: (a) the species, variety and maturity of the grain, (b) the grain "history", and (c) the temperature and humidity of the air. The Me of the grain is important because it determines the minimum moisture content to which the grain is dried at a certain drying condition.

Various Me equations have been developed for rice. The Me appears to be independent of the rice type. Brook and Foster (1981) recommended two Me equations: (a) the Henderson-Thompson equation, and (b) the Chung-Pfost equation.

The Henderson-Thompson equation for rough rice is:

$$Me = [(\ln(1 - RH))/(-K(\theta + C))]^{1/N} /100 \qquad (2.9)$$

where Me = moisture content (decimal, dry basis)
RH = relative humidity (decimal)
θ = rice temperature (°C)
K = 0.000019187
N = 2.4451
C = 51.161

The Chung-Pfost equation for rough rice is:

$$Me = B - C \ln [-1.98 (\theta + A) * \ln (RH)] \qquad (2.10)$$

where A = 35.703 ; B = 0.325535 ; C = 0.046015
Me, θ, and RH are defined in equation (2.9).

Brooker et al. (1992) recommended the following empirical relationship for the Me of rough rice at temperatures below 50°C (Zuritz and Singh, 1985):

$$Me = 0.001 + (A/B) ** C \qquad (2.11)$$

where A = $- \ln (1.0 - RH) * \theta_a$
B = $2.667E-7 * (1.0 - \theta_a / 641.7) ** -23.438$
C = $1.0 / (4.0E5 * \theta_a ** -2.1166)$
θ_a = absolute rice temperature (°K)
Me and RH are defined in equation (2.9).

Equation (2.11) appears to be the best available in the literature in the range of temperatures at which the equation is utilized. Thus, equation (2.11) is used in the computer simulation program. Figure 2.1 shows the Me values of rough rice at different kernel temperatures using equation (2.11).

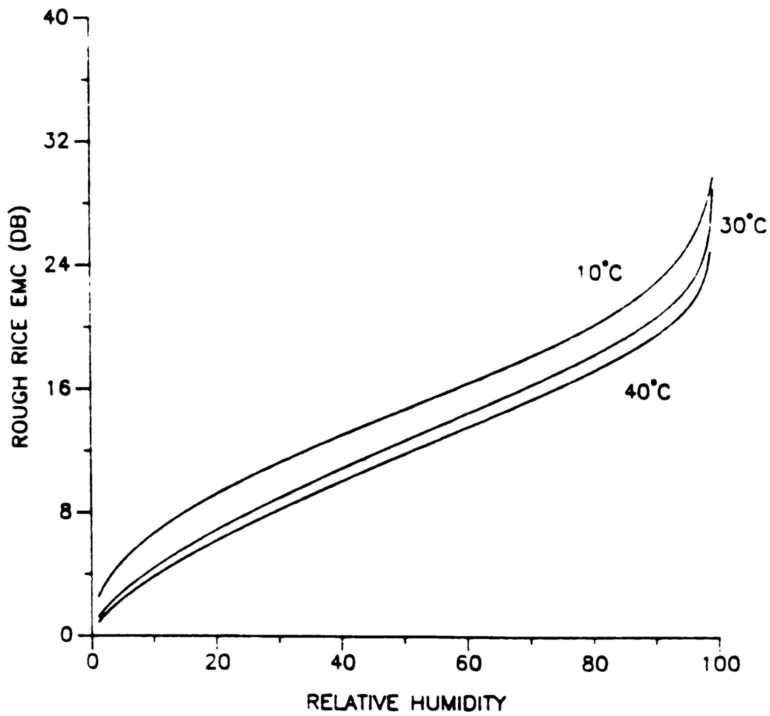

Figure 2.1 Equilibrium moisture content of rough rice according to equation (2.11) (Brooker et al., 1992).

2.4 Rice Drying Model

The basic drying theory for grains is reported in the literature in two categories: (a) the single kernel or thin-layer drying, and (b) deep-bed drying.

2.4.1 Thin-Layer Drying Models

The term "thin-layer" refers to a layer of grain that is approximately one kernel deep. The equations describing the drying of a single kernel are often called thin-layer equations. These equations predict the drying rate of a thin-layer of the product under known drying conditions.

The drying rate of a thin layer of rough rice can be expressed by an empirical thin-layer equation or by a semi-theoretical diffusion equation. Wang and Singh (1978) proposed the following empirical relationship for drying of medium-grain rough rice:

$$MR = \exp(-X * t ** Y) \tag{2.12}$$

where X = $0.01579 + 0.0001746*T - 0.01413*RH$

Y = $0.6545 + 0.002425*T + 0.078867*RH$

MR = moisture ratio (M-Me/Mo-Me)

M = moisture content (decimal, dry basis)

Me = equilibrium moisture content (decimal, dry basis)

Mo = initial moisture content (decimal, dry basis)

t = drying time (min)

T = air temperature (°C)

RH = relative humidity (decimal)

Figure 2.2 shows the drying curves for medium-grain rough rice dried with air of 20% relative humidity as calculated from equation (2.12).

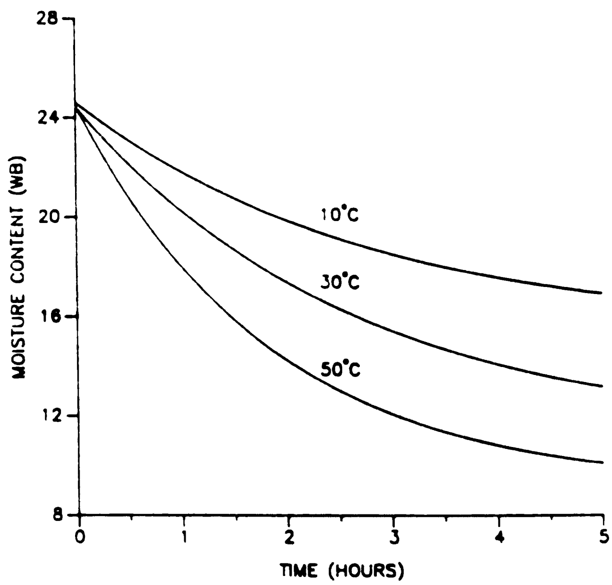

Figure 2.2 Drying of medium-grain rough rice using equation (2.12); RH = 20 % (Brooker et al., 1992).

Brooker et al. (1992) recommended the spherical diffusion equation by Wang and Singh (1978) to calculate the moisture content distribution during the drying and tempering process of rice at the temperature range between 0 and 60°C (32-140°F):

$$MR = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(\frac{-D\,\pi^2\,n^2\,t}{R^2}\right) \qquad (2.13)$$

where D = diffusion coefficient (m^2/h)

R = equivalent rice kernel radius (m)

MR and t have been defined in equation (2.12).

The equivalent kernel radii of the three rice types and the values of the diffusion coefficient (D) for rough rice and for rough rice components, assuming spherical kernels, can be seen in Table 2.7 and Table 2.9, respectively. Figure 2.3 shows curves of medium-grain rice, using equation (2.13).

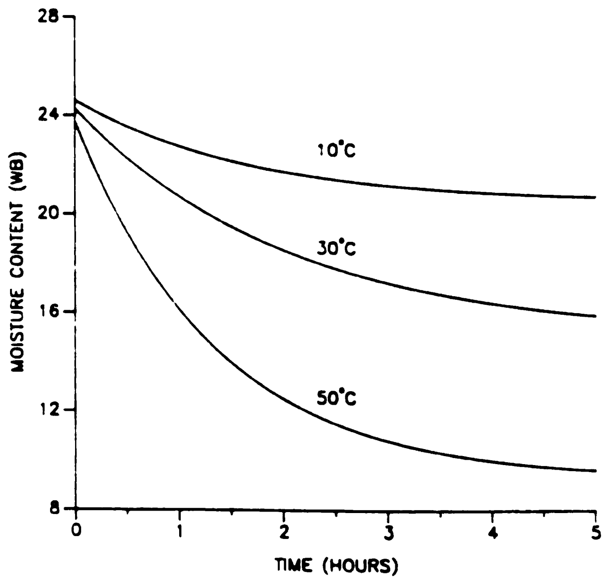

Figure 2.3 Drying of medium-grain rough rice using equation (2.13); RH = 20 % (Brooker et al., 1992).

An empirical thin-layer type model [i.e. equation (2.12)] does not allowed calculation of the moisture gradient during tempering. The equation is based on the average of moisture content of the specified grain layer. A diffusion thin-layer type model [i.e. equation (2.13)] is able to calculate the moisture content distribution during drying and tempering process. For simplicity, only the empirical thin-layer type model is used in the computer program simulation.

2.4.2 In-Bin Counterflow Drying Model

Figure 2.4 shows the configuration of a typical IBCF drying system. In the IBCF grain dryer, the grain and the air flow in opposite directions. Wet grain is loaded into the drying bin from the top of the dryer while hot air is forced through the perforated floor. A temperature-sensor approximately 45 centimeters above the false floor controls the activation of the sweep auger. As drying progresses, less evaporation occurs in the bottom layer and the temperature of the grain increases at the sensing point. When activated, the tapered sweep auger makes one complete sweep around the bin, removing a layer (13 to 18 cm) of partially-dried rice. The wet grain moves down, and the process is repeated. The system can be labeled an intermittent IBCF dryer.

Bakker-Arkema et al. (1974) developed a fixed-bed grain drying model , the so called the Michigan State University dryer simulation model (MSU model). The model is based on the fundamental laws of heat and mass transfer, and can be used to predict the drying, heating and cooling of grains and other biological products that satisfy the basic assumptions of the MSU model. Marks et al (1988) modified the MSU fixed-bed model to account for in-bin counterflow drying; the intermittent nature of periodic grain removal from the bottom of the bin was simulated. In the Marks model, a layer of grain is dumped on the bed equal to the thickness of the removed layer of the dried grain. The depth of the grain in the dryer remains the same throughout the drying process.

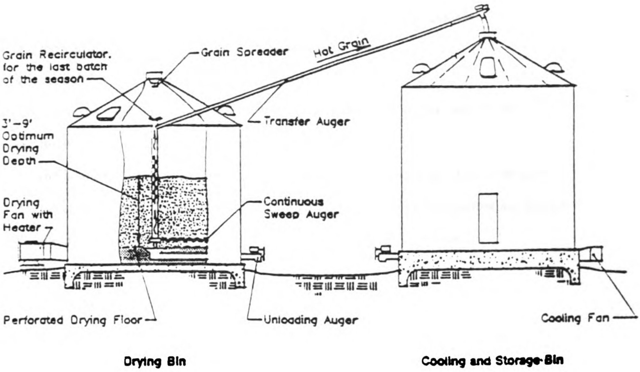

Figure 2.4 System configuration of the in-bin counterflow dryer (Midwest Plan Service, 1988).

Several basic assumptions are made in the development of the Michigan State University grain drying model (Brooker et al., 1992):

1. the volume shrinkage is negligible during the drying process
2. the temperature gradients within the individual kernels are negligible
3. the kernel-to-kernel conduction is negligible
4. the airflow and grain flow are plug type and constant
5. the terms $\partial T/\partial t$ and $\partial W/\partial t$ are negligible compared with $\partial T/\partial x$ and $\partial W/\partial x$
6. the bin walls are adiabatic and have negligible heat capacity
7. the heat capacities of moist air and grain are constant during short time periods
8. the single-kernel drying equation and the moisture equilibrium equation are known
9. the moisture evaporation takes place at the drying-air temperature.

In the model, four unknowns must be solved:

1. M the kernel moisture content
2. H the humidity ratio of the air
3. T the air temperature, and
4. θ the kernel temperature.

To solve the unknown variables, four energy and mass balances are made on a differential volume (Sdx), located at an arbitrary location in the grain layer (Brooker et al.,1992). This results in the following four equations:

1. for the enthalpy of the air

$$\frac{\partial T}{\partial x} = \frac{-\,h\,a\,(T - \theta)}{G_a C_a + G_a C_v\, H} \tag{2.14}$$

2. for the enthalpy of the grain

$$\frac{\partial \theta}{\partial x} = \frac{h\,a\,(T - \theta)}{G_p\, C_p + G_p\, C_w\, M} + \frac{h_{fg} + C_v\,(T - \theta)}{G_p\, C_p + G_p\, C_w\, M}\, G_a\, \frac{\partial H}{\partial x} \tag{2.15}$$

3. for the humidity ratio of the air

$$\frac{\partial H}{\partial x} = -\,\frac{G_p}{G_a}\,\frac{\partial M}{\partial x} \tag{2.16}$$

4. for the moisture content of the grain

$$\frac{\partial M}{\partial t} = \text{an appropriate thin-layer equation} \tag{2.17}$$

2.4.3 Numerical Solution Techniques

Numerical solution with finite difference substitution in the derivatives is employed to solve the four differential equations (2.14, 2.15, 2.16, and 2.17).

The grain bed is divided into a large number of layers. Because the layer thickness (i.e. the distance step) is very small, about $1.5\mathrm{x}10^{-2}$ m or less, the grain in each layer is assumed to be of uniform moisture content and temperature. The inlet air conditions to a layer are considered to be equal to the outlet air conditions of the previous layer.

Numerical integration is applied to solve the equations with a time step of about 10^{-2} hour (i.e. 0.60 seconds).

Figure 2.5 shows schematically the indexing scheme of the finite difference equations used in the program. Since zero subscripts are not allowed on digital computers, node (1,1) corresponds to the bottom of the dryer at the start of drying. T and H are indexed at the start of a node while M and θ are indexed at the middle of a node. Thus, T and H must be dimensioned one number greater than M and θ in order to account for the extra T and H nodes at the top of the dryer.

To solve the counterflow simulation dryer model numerically, the initial and the boundary conditions of the grain and the drying air must be known, and must be furnished as input data. The initial and boundary conditions for the IBCF drying model are:

a. $T(0,t) = T$ inlet

b. $\theta(x,0) = \theta$ initial

c. $H(0,t) = H$ inlet

d. $M(x,0) = M$ initial

In the simulation, the IBCF drying model is programmed using the following order;

(1) input data

(2) initialize arrays

(3) evaluate constants

(4) solve the differential equations, and

(5) output when requested.

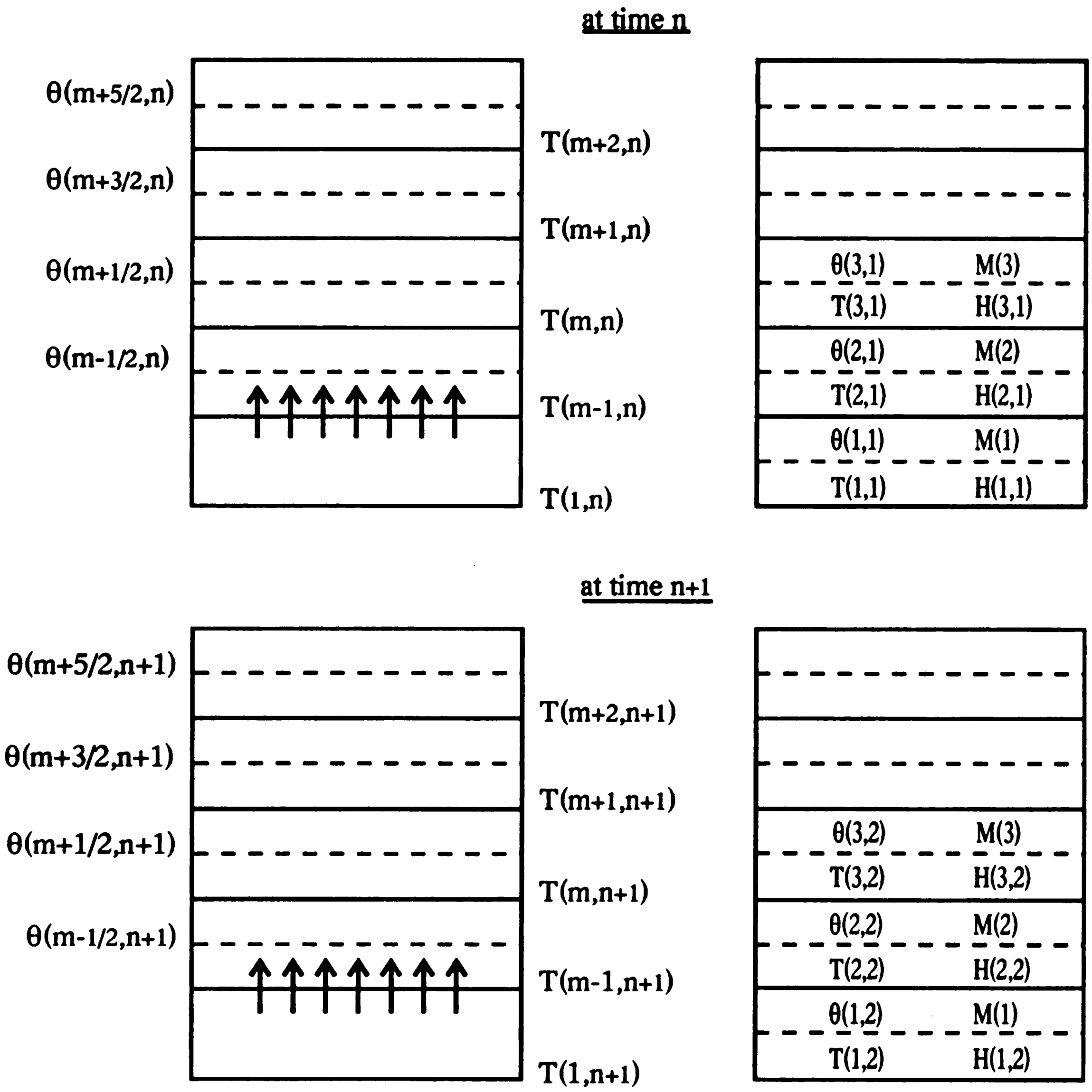

Figure 2.5 Indexing scheme for air-temperature, grain-temperature, humidity ratio, and moisture content arrays in the simulation model.

Equations used more than one time (e.g. the thin-layer drying, equilibrium moisture content, static pressure/airflow, and psychrometric equations) are programmed as separate subroutines or function subprograms. The input data for the air and grain properties is handled through a DATA subroutine.

Most of the parameters passed between the main program and the subprograms are transferred through labeled common statements in order to decrease the required processing time. The use of temporary storage locations for the quantities required several times within the program is employed to execute the program with maximum speed and efficiency.

Using forward differences, equation (2.14) is written as:

$$\frac{T(x+\Delta x,t+\Delta t) - T(x,t+\Delta t)}{\Delta x} = \frac{-h\,a\,[T(x+1/2\Delta x,t+\Delta t) - \theta(x+1/2\Delta x,t+\Delta t)]}{G_a C_a + G_a C_v\, H(x+1/2\Delta x,t+\Delta t)} \tag{2.18}$$

where $T(x+1/2\Delta x,t+\Delta t) = \dfrac{T(x+\Delta x,t+\Delta t) + T(x,t+\Delta t)}{2}$

Rearranging equation (2.18) results in the air temperature equation of the IBCF drying model:

$$T(x+\Delta x,t+\Delta t) = \frac{T(x,t+\Delta t)\,[2G_a C_a + 2G_a C_v\, H(x+1/2\Delta x,t+\Delta t) - ha\Delta x] + \theta(x+1/2\Delta x,t+\Delta t)(2ha\Delta x)}{2G_a C_a + 2G_a C_v\, H(x+1/2\Delta x,t+\Delta t) + ha\Delta x} \tag{2.19}$$

Equation (2.15) can be written as:

$$\frac{\theta(x+1/2\Delta x,t+\Delta t) - \theta(x+1/2\Delta x,t)}{\Delta x} = \frac{ha\,[T(x+1/2\Delta x,t) - \theta(x+1/2\Delta x,t)]}{G_pC_p + G_pC_wM(x+1/2\Delta x,t)} + \frac{h_{fg} + C_v\,[T(x+1/2\Delta x,t) - \theta(x+1/2\Delta x,t)]}{G_pC_p + G_pC_w\,M(x+1/2\Delta x,t)}\;G_a\;\frac{[H(x+\Delta x,t) - H(x,t)]}{\Delta x} \tag{2.20}$$

Rearranging equation (2.20) yields the grain temperature equation:

$$\theta(x+1/2\Delta x,t+\Delta t) = \theta(x+1/2\Delta x,t) + \frac{ha\Delta x\,(TMTH) + [G_ah_{fg} + G_aC_v\,(TMTH)]\,[H(x+\Delta x,t) - H(x,t)]}{G_pC_p + G_pC_w\,M(x+1/2\Delta x,t)} \tag{2.21}$$

where $(TMTH) = [T(x+1/2\Delta x,t) - \theta(x+1/2\Delta x,t)]$.

Equation (2.16) can be written as:

$$\frac{H(x+\Delta x,t+\Delta t) - H(x,t+\Delta t)}{\Delta x} = \frac{-G_p}{G_a}\;\frac{M(x+1/2\Delta x,t+\Delta t) - M(x+1/2\Delta x,t)}{\Delta x} \tag{2.22}$$

Rewriting equation (2.22) results in the humidity-ratio equation:

$$H(x+\Delta x,t+\Delta t) = H(x,t+\Delta t)\frac{-G_p}{G_a}\,[M(x+1/2\Delta x,t+\Delta t) - M(x+1/2\Delta x,t)] \tag{2.23}$$

Equation (2.17) can be written as:

$$\frac{M(x+1/2\Delta x,t+\Delta t) - M(x+1/2\Delta x,t)}{\Delta t} = \text{appropriate thin-layer equation} \tag{2.24}$$

Those terms in equations (2.19, 2.21, and 2.23) which are constant for a given drying problem are evaluated outside of the bed-calculation loops. The constants can be written as:

$$CON1 = 2G_aC_a \tag{2.25}$$

$$CON2 = 2G_aC_v \tag{2.26}$$

$$CON3 = ha\Delta x \tag{2.27}$$

$$CON4 = 2ha\Delta x \tag{2.28}$$

$$CON5 = G_a\, h_{fg} \tag{2.29}$$

$$CON6 = G_aC_v \tag{2.30}$$

$$CON7 = G_pC_p \tag{2.31}$$

$$CON8 = G_pC_w \tag{2.32}$$

$$CON9 = \frac{G_p}{G_a} \tag{2.33}$$

The IBCF drying equations then become:

$$T(x+\Delta x,t+\Delta t) = \frac{[CON1 + CON2\; H(x+1/2\Delta x,t+\Delta t) - CON3]T(x,t+\Delta t) + CON4\; \theta(x+1/2\Delta x,t+\Delta t)}{CON1 + CON2\; H(x+1/2\Delta x,t+\Delta t) + CON3} \tag{2.34}$$

$$\theta(x+1/2\Delta x,t+\Delta t) = \theta(x+1/2\Delta x,t) + \frac{CON3(TMTH) + [CON5 + CON6(TMTH)]\,[H(x+\Delta x,t+\Delta t) - H(x,t)]}{CON7 + CON8\,M(x+1/2\Delta x,t)} \tag{2.35}$$

$$H(x+\Delta x,t+\Delta t) = H(x,t+\Delta t) + CON9\,[M(x+1/2\Delta x,t+\Delta t) - M(x+1/2\Delta x,t)] \tag{2.36}$$

$$\frac{M(x+1/2\Delta x,t+\Delta t) - M(x+1/2\Delta x,t)}{\Delta t} = \text{appropriate thin-layer drying rate equation} \tag{2.37}$$

2.4.4 Solving the Equations for a Fixed Bed

To solve the model equations (2.34, 2.35, 2.36 and 2.37), the values of T, H, θ, and M must be specified at each position within the bed before the simulation process is started. The following initialization process is followed:

(1) set the initial and boundary conditions

(2) for stability, set $\theta(0,0)$ equal to the average of the inlet air and the initial grain temperature:

$$\theta(0,0) = (T_{inlet} + \theta_{initial})/2 \tag{2.38}$$

(3) solve equations (2.34, 2.35, 2.36 and 2.37) for all x (i.e. from the bottom to the top of the drying bed.

After the calculations for the first time step are completed, the following calculation scheme is used:

(1) increment time $t = t + \Delta t$

(2) solve equation (2.35) for $\theta(x+1/2\Delta x,t+\Delta t)$

(3) solve equation (2.37) for $M(x+1/2\Delta x,t+\Delta t)$

(4) solve equation (2.36) for $H_{(x+\Delta x,t+\Delta t)}$

(5) solve equation (2.34) for $T_{(x+\Delta x,t+\Delta t)}$

(6) increment x and repeat steps (2) through (5) until the top of the dryer is reached, and

(7) go back to step (1) unless the end of the drying time has been reached.

Applying the above solution technique to equations (2.34, 2.35, 2.36 and 2.37) requires that the H and T values must be known at all x nodes at times t and t+Δt. Therefore, the T, θ and H arrays must be dimensioned in the program according to the maximum number of depth nodes. The M array needs only to be one dimensional if temporary storage is provided for $M_{(x+1/2\Delta x,t+\Delta t)}$.

2.4.5 Solving the Equations for an IBCF Bed

In the IBCF drying model, one removal of grain is called one cycle, and the time needed for one cycle is named the cycle time. The model calculates the properties of the drying system ,and the nodal positions and values of T, H, θ, and M for each successive cycle.

To solve the equations (2.34 through 2.37) for the IBCF bed by computer simulation, the following calculation scheme is applied:

(1) For the initialization process:
  - (a) set the input conditions of the dryer to be simulated
  - (b) set the physical and thermal properties of the grain being dried
  - (c) calculate the number of nodes of the removing layer as well as the whole bed
  - (d) specify the boundary conditions and the initial values of T, H, θ, and M at each position within the bed

(e) set $\theta(0,0) = (T_{inlet} + \theta_{initial})/2$ for the grain temperature at the first node, and

(f) make the preliminary calculations for the airflow rate and static pressure at initial bed depth and ambient conditions.

(2) For the program execution process:

(g) increment time $t = t + \Delta t$

(h) solve equation (2.35) for $\theta(x+1/2\Delta x, t+\Delta t)$

(i) solve equation (2.37) for $M(x+1/2\Delta x, t+\Delta t)$

(j) solve equation (2.36) for $H(x+\Delta x, t+\Delta t)$

(k) solve equation (2.34) for $T(x+\Delta x, t+\Delta t)$

(l) increment x and repeat steps (h) through (k) until the top of the dryer is reached,

(m) check if the cycle time has been reached, if not go back to step (g),

(n) if (m) is satisfied, print the depth profiles prior to removal, a listing of some calculation results for the removing layer, and other quantities relevant to the drying of a bed of grain

(o) calculate a new bed depth after removal and shift the array (the number of nodes, positions and values of T, H, θ, and M within the new bed); the first node of the new array is equal to the last node of the removing layer

(p) recalculate the airflow rate and the static pressure

(q) check if cycle time ≥ time to refill the grain; if not go back to step (g)

(r) if (q) is satisfied:

- calculate the new bed depth (i.e. by adding the previous bed depth with a discrete distance of the grain being added), airflow, and static pressure
- print the bed profile after refilling the grain.

(s) check if the end of the simulation time has been reached; if not go back to step (g), and

(t) if (s) is satisfied stop the program.

2.4.6 Condensation Modeling

A model for the psychrometric chart (to calculate the humidity ratio of the drying air and to check for possible condensation) developed by Lerew (1972) is used in the solution of equations (2.34, 2.35, 2.36 and 2.37).

After equations (2.34 and 2.36) are solved for T and H, the corresponding relative humidity is calculated. If this value is greater than 0.9999999999, saturation or supersaturation is assumed and condensation is modeled. Condensation may occur when a large amount of moisture is adsorbed by the air, and the moist air is cooled as it passes through cool grain. The model also predicts condensation to occur if the grain looses excessive moisture, since thin layer equations are insensitive to air humidity. The same course of action is followed in either case:

(1) the air temperature is set equal to the wet-bulb temperature: (T,H) represents an infeasible point at RH > 1.0 but the corresponding wet-bulb temperature can be found mathematically

(2) the air humidity ratio is set equal to the saturation humidity associated with the wet-bulb temperature found under (1)

(3) a H2O mass balance is made

mass in air + mass in grain before condensation = mass in air + mass in grain after condensation, or

$$G_a \Delta t\, H + \varrho_p \Delta x\, M = G_a \Delta t\, H' + \varrho_p \Delta x\, M'$$

yields for the adjusted moisture content:

$$M' = M + \frac{G_a \Delta t}{\varrho_p \Delta x}(H - H') \tag{2.39}$$

where M' = the new grain moisture after condensation
H' = the new humidity ratio after condensation

(4) an energy balance is made

energy of air + energy of grain before condensation = energy of air + energy of grain after condensation, or

$$T\, G_a\, \Delta t\, (C_a + C_v H) + \theta\, \varrho_p\, \Delta x\, (C_p + C_w M) =$$

$$T'\, G_a\, \Delta t\, (C_a + C_v H') + \theta' \varrho_p\, \Delta x\, (C_p + C_w M') = G_a\, \Delta t\, h_{fg}\, (H' - H) \qquad (2.40)$$

where T' = the new-air temperature after condensation
θ' = the new-grain temperature after condensation

Since the air is saturated with water vapor during the condensation process, water condenses out of the air as soon as the temperature drops. The humidity ratio of the air will then be decreased. During this process, instead of loosing moisture the grain gains moisture from the air. New values of T and H are found by solving equations (2.39 and 2.40).

2.4.7 Values of Δt and Δx

The size of the depth increment Δx and the time step Δt and their relationship, are important for the stability of the program. In general, if Δx and/or Δt are too large or too small, the numerical solutions will diverge from the true values. Very small values of Δx and/or Δt require excessive computer time.

The relationship between Δx and Δt can be derived from equations (2.34 and 2.35). Rewriting equation (2.34) for the air temperature at time t yields:

$$T(x+\Delta x) = Tx\left(\frac{B - A}{B + A}\right) + 2\theta(x+1/2\Delta x)\left(\frac{A}{B + A}\right) \tag{2.41}$$

where $A = \text{CON3}$
$B = \text{CON1} + \text{CON2}\ H(x+1/2\Delta x)$

Since $T(x+\Delta x) > \theta(x+1/2\Delta x)$, it follows that

$$\theta(x+1/2\Delta x) < Tx\left(\frac{B - A}{B + A}\right) + 2\theta(x+1/2\Delta x)\left(\frac{A}{B + A}\right) \tag{2.42}$$

Simplifying equation (2.42), gives $B > A$ or

$$\Delta x < aG_a(C_a + C_v H) \tag{2.43}$$

By neglecting mass transfer, and substituting $\varrho_p = Gp\Delta t/\Delta x$, equation (2.35) can be written as:

$$\theta(x+1/2\Delta x,t+\Delta t) = \theta(x+1/2\Delta x,t) + \frac{\Delta t\ G_a C_v + G_a C_v\ H(x+\Delta x,t)}{\Delta x\ \varrho_p C_p + \varrho_p C_w\ M(x+1/2\Delta x,t)}\left[T(x,t) - T(x+\Delta x,t)\right] \tag{2.44}$$

Following a similar analysis as for Δx, it is found that

$$\Delta t < \Delta x\ \frac{\varrho_p C_p + \varrho_p C_w M}{G_a C_a + G_a C_v H} \tag{2.45}$$

Equation (2.45) is only an approximation since mass transfer has been neglected. A new Δt is calculated before every time step. After every simulation run, the results are checked by making an energy and a water balance:

$$E_a = G_a A(C_a + C_v H_{inlet})(T_{inlet} - T_{amb}) \tag{2.46}$$

$$E_g = G_p C_p(\theta_{outlet} - \theta_{initial}) \tag{2.47}$$

$$W_a = (E_a - E_g) / h_{fg} \tag{2.48}$$

$$W_g = M_{initial} G_p - M_{outlet} G_p (1 - M_{initial})(1 - M_{outlet}) \tag{2.49}$$

where E_a = total energy supplied by the drying air (kW)
E_g = total energy required to heat/cool the grains (kW)
W_a = potential water removed by available energy in the air (kg-H2O/hr)
W_g = actual water removed in the drying process (kg-H2O/hr)

If the result of equation (2.46) does not match the result of equation (2.47), or if equation (2.48) does not match the result of equation (2.49), within ± 10% (i.e. the difference acceptable for engineering purpose), the program is rerun by choosing a set of different Δx and Δt values.

2.4.8 Convergence

A mixture of linear interpolation, extrapolation and bisection techniques, based on the algorithm by Dekker (1967) was used in the computer simulation program to solve the basic model [i.e. equations (2.34, 2.35, 2.36, and 2.37)] until convergence is reached.

The Dekker algorithm was used by Lerew (1972) to solve the functions in the psychrometric-simulation package. The algorithm is completely independent and can be freely used for other purposes. The technique is programmed in the computer simulation program as Function ZEROIN.

Function ZEROIN takes the following form:

FUNCTION ZEROIN (A,B,EPS,FUNC)

where A and B = the end points of the interval containing a zero
EPS = the largest acceptable final interval containing a zero
FUNC = the name of supplied function subprogram containing the function for which a zero is to be found.

Either A or B or their average can be used as the zero. ZEROIN checks the function values of the interval endpoints to indicate either multiple roots or no roots within the given interval.

In the case of multiple roots, one of the roots will be found through a minimum-searching technique. ZEROIN will converge to the point at which the function has minimum value. In the case of no roots, ZEROIN will converge to the point where the absolute value of the function is a minimum, whether this occurs at an end point or at an arbitrary value within the interval.

2.4.9 Program Termination

The IBCF drying model terminates normally when:

(1) a specified drying time has been modeled, or

(2) the average moisture content in the bed falls below a specified level.

2.4.10 Program Output

The output from a simulation run consists of a listing of the data input, of some preliminary calculations, and of the bed profiles (i.e. grain moisture content, grain temperature, air temperature, humidity ratio, and relative humidity), followed by a listing of the properties of the removed layer (i.e. cycle number, cycle time, depth of removing layer, weight of grain removed, amount of grain dried, average outlet-grain moisture, average outlet-grain temperature, and drying rate), and of general quantities relevant to the drying of a bed of grain (such as total airflow, static pressure, horsepower, average grain moisture of the bed, average grain temperature of the bed, water removed, total energy, specific energy consumption, and total simulation time).

An example of program output of IBCF rice drying in combination to cross-flow drying system can be seen in Appendix A.

2.5 Performance of IBCF Dryer

The performance of a typical IBCF drying system for maize was tested experimentally and compared to other on-farm grain drying systems by Bakker-Arkema et al. (1980) and Kalchik et al. (1981) (see Table 2.10). The drying-air temperature in the IBCF system ranged from 50 to 93°C, the energy consumption was 5,110 kJ/kg of water at 50°C and 4,390 kJ/kg at 93°C. The authors found that in-bin counterflow drying compares well with automatic batch drying with respect to four quality parameters [i.e. stress cracks, breakage tests, BCFM, and viability changes (see Table 2.11)].

Table 2.10 Specific energy consumption for six on-farm drying methods

Drying Method	Specific Energy Consumption (MJ/kg-H2O)
Natural air	3.222
Low-temperature	3.750
In-bin dryeration	4.133
In-bin counterflow	4.540
Automatic batch	7.806

Source: Kalchik et al. (1979)

Silva (1980) compared five maize drying methods and found that the drying cost per ton of maize of IBCF drying is lower than of other on-farm drying methods except for in-bin dryeration. The author recommended the following formula to calculate the specific energy consumption or SECO of each cycle of an IBCF dryer simulation run :

$$SECO = \frac{G_{ai}\, C\, \Delta T\, \Delta t_i + E_i}{W_i} \qquad (2.50)$$

where SECO = specific energy consumption (kJ/kg H2O)
G_{ai} = airflow rate of the ith cycle (kg/hr)
C = specific heat of air (kJ/kg°C)
ΔT = temperature difference between ambient and drying air (°C)
Δt_i = cycle time of the ith cycle (hr)
E_i = electrical energy used in the ith cycle (kJ)
W_i = water removed in the ith cycle (kg H2O)

Table 2.11 Maize quality parameters for six on-farm drying methods.

Drying Method	Stress Cracks	Breakage Tests	BCFM	Viability Changes
Natural air	2.8	11.9	0.0	43.4
Low-temperature	3.4	13.1	0.0	41.8
In-bin dryeration	9.0	13.8	0.0	63.7
In-bin counterflow	64.0	29.0	0.2	28.5
Automatic batch	87.3	46.3	0.5	78.0

Source: Kalchik et al. (1979)

The Midwest Plan Service (1988) recommended a range of 0.9 to 2.75 m as the optimum bed depth for drying grain in IBCF dryers. Marks et al.(1988), through simulation, found that for minimum energy consumption while maintaining maximum drying capacity, the optimal bed depth is 1.8 m when the dryer is operated with no refilling.

When the dryer is operated as a continuous system by periodically refilling wet maize, the optimal bed depth is 1.4 m.

Salleh (1990) studied the performance of IBCF rice drying through simulation. The experimental results of IBCF maize drying were used to validate the Michigan State University simulation model of the dryer. The simulated performance of IBCF rice drying under Malaysian conditions is listed in Table 2.12.

Table 2.12 The simulated performance of a 5.5 m diameter IBCF rice dryer under Malaysian operating conditions.

Performances	IBCF36
Overall capacity (t/hr.m^2)	0.026
Capacity (t/hr)	2.448
Specific energy consumption (MJ/kg-H2O)	6.408
Fuel, LPG (L/t-rice)	19.820

Operating conditions:	
Drying air temperature	47.2 °C
Ambient air temperature	29.4 °C
Ambient relative humidity	85.0 %
Initial grain temperature	29.4 °C
Initial moisture content (w.b.)	23.0 %
Final moisture content (w.b.)	13.5 %
Bed depth with refill	1.4 m
Total simulation time	7.0 hr

Source: Salleh (1990)

2.6 IBCF Grain Pre-heating

The grain temperature and inlet moisture content have a significant effect on the capacity of a continuous-flow grain dryer (Brooker et al., 1992). It has been claimed that pre-heating of the grain in a dryer can increase the capacity up to 33% and reduce the fuel cost by 10% (Behlen, 1968). Muhlbauer (1974) reported that pre-heating improves the quality of the grain in comparison to conventionally dried grain.

In this thesis, the modified MSU IBCF dryer model was used to predict the performance of a particular IBCF maize pre-heater; it was validated with experimental data.

3. UPDATING THE EXISTING IBCF DRYING MODEL

In the Marks IBCF model, the actual bed depth of the grain in the dryer remains the same throughout the drying process. A fixed-bed model was modified to account for dumping a relatively thin grain-layer (1.5 cm or 0.05 ft) on top of the bed after grain removal at the bottom of the bed. This system can be considered to represent a continuous IBCF drying system, or IBCF dryer/cooler.

In the model modified by the author, the thickness of grain dumped is not equal to the thickness of the removed layer of the dried grain; thus, the bed depth of the grain and the flow rate of the drying air vary throughout the drying process. The model recalculates these parameters of the drying system (i.e. the bed depth, the airflow and the static pressure) after every cycle of removing/dumping grain.

Also, the subprogram called SECANT was added to the Marks program to model the output of a particular fan for the drying of different grains (i.e. maize, rice, wheat, and barley). This subprogram is executed every time the bed depth is changed during the drying process.

The subroutine DATA containing the grain properties was updated to account for different grain types (i.e. rice, wheat, and barley). Also the Me equation and the thin-layer equation for drying rice were added to the computer program. The Me equation for rice is programmed as function EMCR, and the thin-layer equation as subroutine LAYEQR.

The calculation of the values of the depth increment Δx and the time step Δt used in the program has been modified. At every successive simulation run, the results are checked by making an energy balance and a moisture balance [see equations (2.44 through 2.47)]. If the results do not balance within ± 10%, the program is rerun by choosing a set of different Δx and Δt values.

The modified model terminates normally if the following condition is reached:

$$ABS\,[\,M_{(i)} - M_{(i-1)}\,] \leq 0.001 \tag{2.51}$$

where ABS = function of absolute value

$M_{(i)}$ = average outlet-grain moisture content at the ith cycle (%w.b.)

$M_{(i-1)}$ = average outlet-grain moisture content at the (i-1) cycle (%w.b.)

4. EXPERIMENTAL INVESTIGATION

The IBCF dryer design was tested with maize in a Meiners drying system in Colfax, Illinois (October 14 - 17, 1992). The Meiners system consists of a MW concurrent-flow grain dryer, model 650, and a hopper-bottom wet-holding bin (see Figure 4.1). The bin can be considered to represent an IBCF dryer/preheater, which has a diameter of 5.5 m (18 ft) and a height of 7.3 m (24 ft). It holds about 140 tonnes (4885 bu) of wet maize. The height of the hopper is 2.1 m (7.0 ft). The hopper angle is 60 degrees and has a volume of 35 m^3 (1245 ft^3) holding about 30 tonnes (995 bu) of wet maize.

The airflow is forced into the bottom of the hopper bin by a 8 kW (10 HP) fan at a rate of about 3.8 m^3/s (7,500 cfm) at 1.75 kPa (7 in-H2O). A 11.2 x 10^5 kJ per hour (2x 10^6 BTU/hr) natural-gas burner is used to control the inlet-air temperature. Test were conducted without recycling exhaust air from the MW concurrent-flow dryer.

The maize was loaded into the preheating bin at a temperature of 5 to 19°C (41 to 66°F), and a moisture content of 22 to 25 %, and heated in the preheating bin before entering the MW concurrent-flow grain dryer. Since the grain and the air flow in opposite directions, and the dryer calls for grain intermittently, the preheating bin can be considered to represent an intermittent IBCF heater/dryer.

The grain moisture content and temperature of every load of maize dumped into and unloaded from the preheater bin were measured. The moisture contents were determined in the laboratory (130°C for 72 hours). Grain inlet and outlet moistures and temperatures were taken at one hour intervals at the preheater bin. The grain temperatures were measured with a multi-probe meter (Solomat, model MPM 500e).

The same meter was used to determine the temperatures and static pressures in the plenum of the preheating bin. The ambient dry-bulb temperature and wet-bulb temperature were measured with a sling psychrometer. Occasionally, the dry-bulb temperature and wet-bulb temperature of the air exhausting from the top of the preheating bin were recorded. The relative humidity was calculated using the psychrometric computer program developed by Lerew (1972).

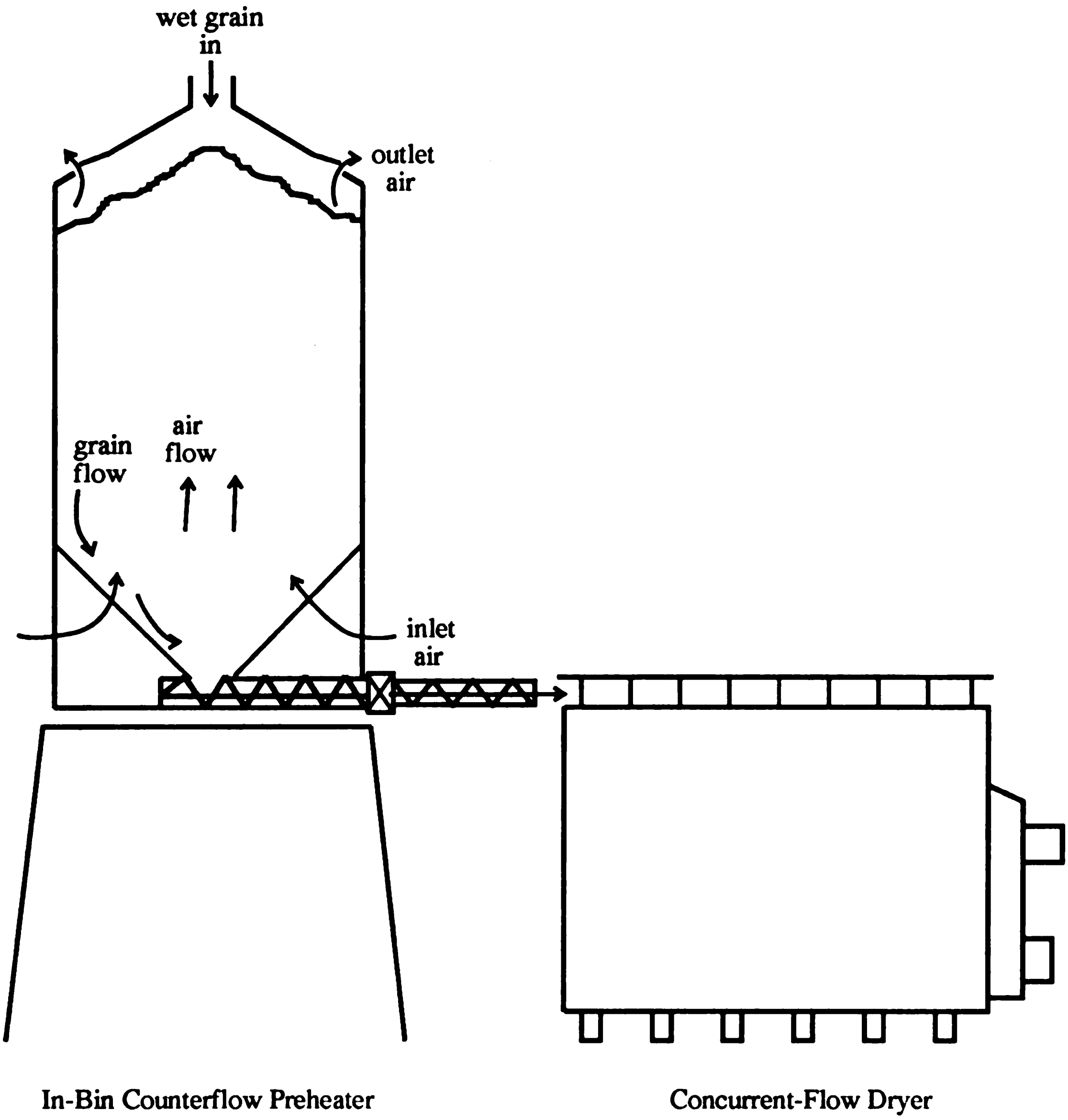

Figure 4.1 IBCF preheater/dryer system coupled to a concurrent-flow dryer.

5. RESULTS AND DISCUSSION

5.1 Validation Technique

Brook and Bakker-Arkema (1978) validated the MSU concurrent-flow grain drying model using corn. The authors found that the model predict the performance of commercial concurrent-flow grain dryers well.

Fontana (1983) used the MSU concurrent-flow grain drying model to predict the performance of the concurrent-flow rice dryer. The author tested the dryer and found that there is good agreement between the experimental data and the simulation results.

In this thesis, the same technique was followed .The experimental results of the IBCF maize-preheater were used to validate the modified Michigan State University simulation model of the device. The model was then changed from maize to rice to predict the performance of the IBCF dryer in a rice drying system.

5.2 Performance of the IBCF Preheater in Combination with a Concurrent-Flow Dryer

The results from the drying tests conducted with the IBCF maize-preheater combined with the concurrent-flow dryer are presented in Table 5.1 and Table 5.2.

The harvest moisture of the maize just before it was loaded in the preheating bin was in the range of 22.1-24.9%, with an average of 24.4% (see Table 5.1). The maize temperature varied between 13.3 and 19.6°C (56-67°F), with an average of 15.7°C (60.3°F). The average ambient-air temperature and relative humidity during the three-day tests were 12.8°C (55°F) and 60%, respectively.

Tests were conducted with the plenum temperature in the pre-heater controlled at 71, 77 and 93°C (160, 170 and 200°F), and the airflow rate of 1.9 m^3/min.tonne (1.7 cfm/bu). For removing about 10 points of moisture in the system, the grain flow rate in the concurrent-flow dryer, and thus also in the preheater, was 17 tonnes per hour (600 bu/hr).

Table 5.2 shows the experimental and simulated temperatures and moisture contents of the preheater system. There is good agreement between the experimental data and the simulated results.

Table 5.1 Experimental moisture content and temperature of different loads of maize loaded into the Meiners IBCF pre-heating system (10/14-10/17/1992).*

Number of Loading	Moisture Content (%w.b.)	Maize Temperature (°C)
1	24.2	14.8
2	24.8	15.7
3	22.2	15.3
4	24.4	14.7
5	24.9	17.3
6	23.5	13.5
7	22.1	13.3
8	24.3	19.6
9	22.9	15.4
10	24.6	16.2
Average	24.4	15.7

*ambient-air temperature 13°C; relative humidity 60 %

Table 5.2 Experimental and simulated temperatures and moistures of 24.4% moisture, 15.7°C maize pre-heated at different air temperatures.*

Air Temperature (°C)	Maize Temp. (°C)		Maize M.C. (%w.b.)	
	Exp.	Sim.	Exp.	Sim.
71	34	35	24.2	23.7
77	36	37	23.9	23.6
93	40	41	23.7	23.4

*grainflow rate 17 t/hr ; airflow rate 1.9 m^3/min.tonne

The simulated effects of the inlet-grain moisture content, the inlet-air temperature, and the grainflow rate on the maize temperature for a range of airflows are shown in Tables 5.3, 5.4 and 5.5.

Table 5.3 shows that the initial moisture content of the grain affects the outlet-grain temperature of the pre-heater. At lower moistures less of the available energy is used in the evaporation process, and thus 20% moisture content maize will reach a higher temperature in a IBCF drying/preheating system than 24% moisture grain, regardless of the airflow rate.

Table 5.3 The simulated effect of the airflow rate and the inlet-grain moisture content on the maize temperature exiting an IBCF preheating system.*

Airflow Rate (m^3/min.tonne)	Maize Temperature (°C)	
	20 %	24 %
1.1	41	40
3.3	48	47
6.7	52	51
10.0	54	53
13.4	55	54

*grainflow rate 17 t/hr ; inlet-maize temperature 16°C ; inlet-air temperature 93°C

Table 5.4 illustrates the effect of the inlet-air temperature on the temperature of the maize exiting the pre-heater, operating at different airflow rates. At any airflow, more energy is available at the higher inlet-air temperatures to heat the grain (and to evaporate the water), resulting in higher outlet-grain temperatures.

Table 5.4 The simulated effect of the airflow rate and the inlet-air temperature on the maize temperature exiting an IBCF preheating system.*

Airflow Rate (m^3/min.tonne)	Maize Temperature (°C)		
	71°C	82°C	93°C
1.1	33	35	40
3.3	38	40	47
6.7	40	43	51
10.0	41	44	53
13.4	42	45	54

*grainflow rate 17 t/hr; initial maize temperature 16°C; initial maize moisture content 22%

The effect of airflow rate and the grainflow rate on the temperature of the grain exiting the pre-heater is shown in Table 5.5. The exit-grain temperature from the pre-heater is influenced significantly by the grainflow rate. At the higher grain flow rate, the pre-heater will have lower exit-grain temperatures. Thus, when operating at a relatively high throughput, the heating of the grain in the system will be limited.

Table 5.5 The simulated effect of the airflow rate and the grainflow rate on the maize temperature exiting an IBCF preheating system.*

Airflow Rate (m^3/min.tonne)	Maize Temperature (°C)	
	17 Tonnes/hr	28 Tonnes/hr
1.1	40	33
3.3	47	36
6.7	51	38
10.0	53	40
13.4	54	41

*initial-maize temperature 16°C; initial-maize moisture content 22%; inlet-air temperature 93°C

Tables 5.3, 5.4 and 5.5 clearly show that by using relatively high airflow rates the pre-heater will have relatively high outlet-grain temperatures. At low airflows grain is heated only moderately while loosing little moisture.

5.3 Sensitivity of the Simulation Model

The effect of a slight change of the grain-moisture and ambient humidity values on the performance of the IBCF preheater were investigated.

Tables 5.6 and 5.7 show the sensitivity of the simulation model due to a small change in the input data of the initial grain-moisture content and of the ambient air humidity, respectively. The change do not cause significant changes in the output (outlet-grain temperature and outlet-grain moisture content). Thus, the simulation model is not sensitive to small changes in the input data in the range of ± 0.5% for the initial-grain moisture and ± 2.5% for the ambient humidity.

Table 5.6 Sensitivity of the IBCF model due to slight changes in the initial-grain moisture values.

% Change from the Standard Input Data*	% Changes on the Output	
	Grain Temperature	Grain Moisture
+ 0.5	- 0.05	+ 0.34
+ 0.4	- 0.02	+ 0.25
+ 0.3	0.00	+ 0.17
+ 0.2	0.00	+ 0.13
+ 0.1	0.00	0.00
0.0	0.00	0.00
- 0.1	0.00	- 0.08
- 0.2	0.00	- 0.13
- 0.3	+ 0.01	- 0.21
- 0.4	+ 0.02	- 0.25
- 0.5	+ 0.05	- 0.34

* initial-maize moisture content 24% (the other input data remain the same)

Table 5.7 Sensitivity of the IBCF model due to slight changes in the ambient humidity values.

% Change from the Standard Input Data*	% Changes on the Output	
	Grain Temperature	Grain Moisture
+ 2.5	+ 0.21	+ 0.04
+ 2.0	+ 0.16	+ 0.04
+ 1.5	+ 0.13	+ 0.04
+ 1.0	+ 0.08	0.00
+ 0.5	+ 0.04	0.00
0.0	0.00	0.00
- 0.5	- 0.04	0.00
- 1.0	- 0.09	0.00
- 1.5	- 0.13	- 0.04
- 2.0	- 0.16	- 0.04
- 2.5	- 0.20	- 0.04

* ambient relative humidity 60% (the other input data remain the same)

Conclusions

(1) An existing IBCF maize drying/preheating model has been modified. Experimental and simulated data show good agreement. Thus, the IBCF model can be used in the design of IBCF preheaters.

(2) The initial grain moisture has only a slight effect on the outlet-grain temperature in a preheater; at lower moistures, less of the available energy is used in the evaporation process.

(3) The effect of the inlet-air temperature on the temperature of maize exiting a preheater is significant.

(4) The grainflow rate in a preheater has a significant effect on the outlet-maize temperature.

(5) At low airflows, grain is heated only moderately in a preheater, and does not lose much moisture.

(6) The sensitivity of the IBCF model is acceptable.

5.4 Performance of the IBCF Dryer in Combination with a Cross-Flow Dryer

The IBCF maize drying/preheating model was modified for rice to design an IBCF rice dryer in combination with a cross-flow dryer. Equation (2.10) and equation (2.11) were used to calculate the equilibrium moisture content (Me) and the drying rate, respectively.

The new rice drying system consists of a combination of cross-flow dryers and IBCF dryers. It must be able to dry long-grain rice from 24 to 14% moisture content at capacity of 12 tonnes per hour. The new system will be built in near Shanghai, China.

The system should dry rice at a stepwise fashion, with each moisture extraction in the system to be limited. The temperatures of the rice exist the subsequent dryers should satisfy the recommended values for a safe-drying of rice [i.e. the grain temperature ≤ 50°C, (Hall, 1980)]; tempering stages need to be installed in the system.

The MSU cross-flow drying model (Brooker et al., 1992) together with the IBCF drying model were used to analyze the drying behavior of a combination of cross-flow dryers and IBCF dryers for preliminary design considerations. Based on the preliminary-simulation results, three bins each containing a cross-flow dryer in the top of the bin, a so called TB dryer, and an IBCF dryer in the bottom of the bin, were selected, followed by two aeration/storage bins. To match the required dryer capacity of 12 tonnes/hr, the chosen bin diameter were 11 m each.

In this system, high moisture content grain is subjected to six drying treatments and one aeration treatment during the drying/aeration process. Thus, the system consists of a hopper-type receiving bin, three top-bin intermittent-flow/in-bin continuous-flow drying bins, and two in-bin aeration/storage bins, placed in series. Each drying bin consists of a cross-flow dryer as a top-bin (TB) dryer in the top of the bin, and an IBCF dryer/cooler as an IBCF dryer/cooler at the bottom of the bin. The new system has been built in near Shanghai, China in the spring of 1993, and will be tested in October-December, 1993.

Figure 5.1 shows a schematic of a conventional TB dryer. In this dryer, the perforated floor is located near the roof of the bin; the depth of the grain layer is limited to 0.3-0.5 m. Wet grain is augered into the top of the bin and is spread by leveling rings to the desired uniform depth. A high airflow rate of 40-50 m^3/min.tonne combined with the relatively thin grain-layer results in fairly uniform drying of the layer. After the grain in the overhead drying system has dried for 30-90 minutes, it is dumped to the bottom of the bin via a large number (30-48) of dump gates built into the TB drying floor. The drying fan(s) is (are) mounted at the side of the bin directly under the elevated drying floor. Since the dumping of the grain through the dump spouts is accomplished in a minute or less, the time between batches is restricted only by the filling time of the TB dyer. The drying-air temperature depends on the grain type and initial moisture content, and ranges from 40-70 ^{o}C.

Figure 5.2 shows a schematic of a continuous IBCF drying system. A thin layer of 0.1-0.15 m of warm, partially-dried grain, located just above the perforated floor, is removed from the grain mass via an on-floor tapered auger as soon as the grain has to be dried to a preselected moisture content. The auger is of special design so that the wet grain remaining in the bin moves downward at a uniform rate. The hot grain is transferred by the tapered auger to a transport auger for conveying to another bin. The tapered-auger start/stop action is controlled by a temperature-sensor; the rotation of the sweep auger stops when the grain layer has not yet sufficiently dried for removal. The airflow in a conventional IBCF dryer is 5-10 m^3/min.tonne, the inlet-air temperature is 25-75^{o}C.

The new TB/IBCF drying system built in China is illustrated in Figure 5.3, and consists of three 11 m diameter drying bins and two 11 m diameter aeration/storage bins. Each of the TB dryers is supplied with two 12 kW (15 HP) fans with an output of 11.3-9.0 m^3/s of air in the static pressure range of 0.25-0.65 kPa. The fans on the IBCF dryers have a power rating of 2.4 kW (3 HP) and supply 2.8-2.4 m^3 of air at a static pressure of 0.12-0.37 kPa. The aeration fans on the storage bins are rated at 4 kW (5 HP) with an airflow of 5.7-4.2 m^3/s at 0.12-0.50 kPa. The air in the TB dryers is heated by steam-heated heat exchangers; the steam pressure is 241 kPa.

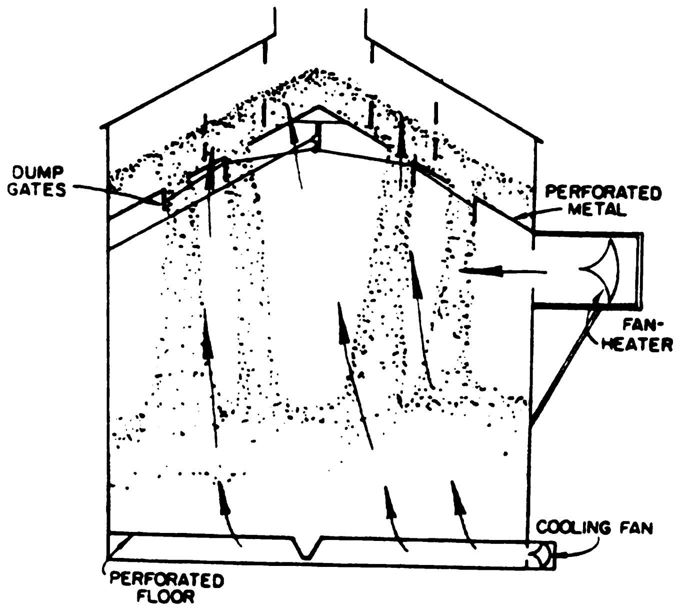

Figure 5.1 Top-bin (TB) grain drying system (Brooker et al., 1992).

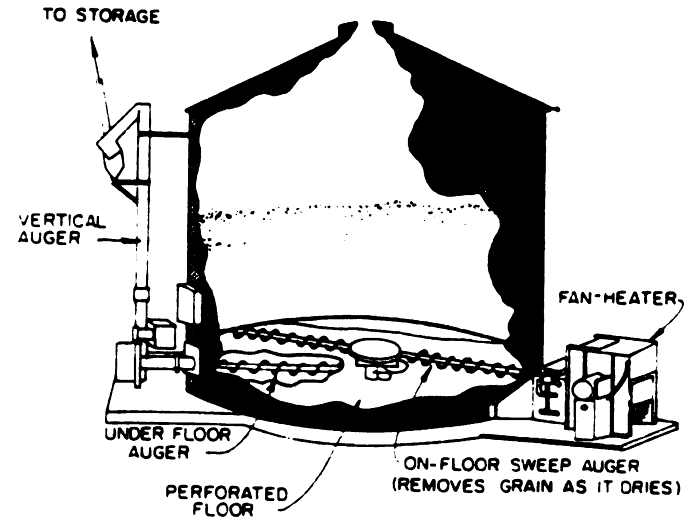

Figure 5.2 In-bin counterflow (IBCF) grain drying system (Brooker et al., 1992).

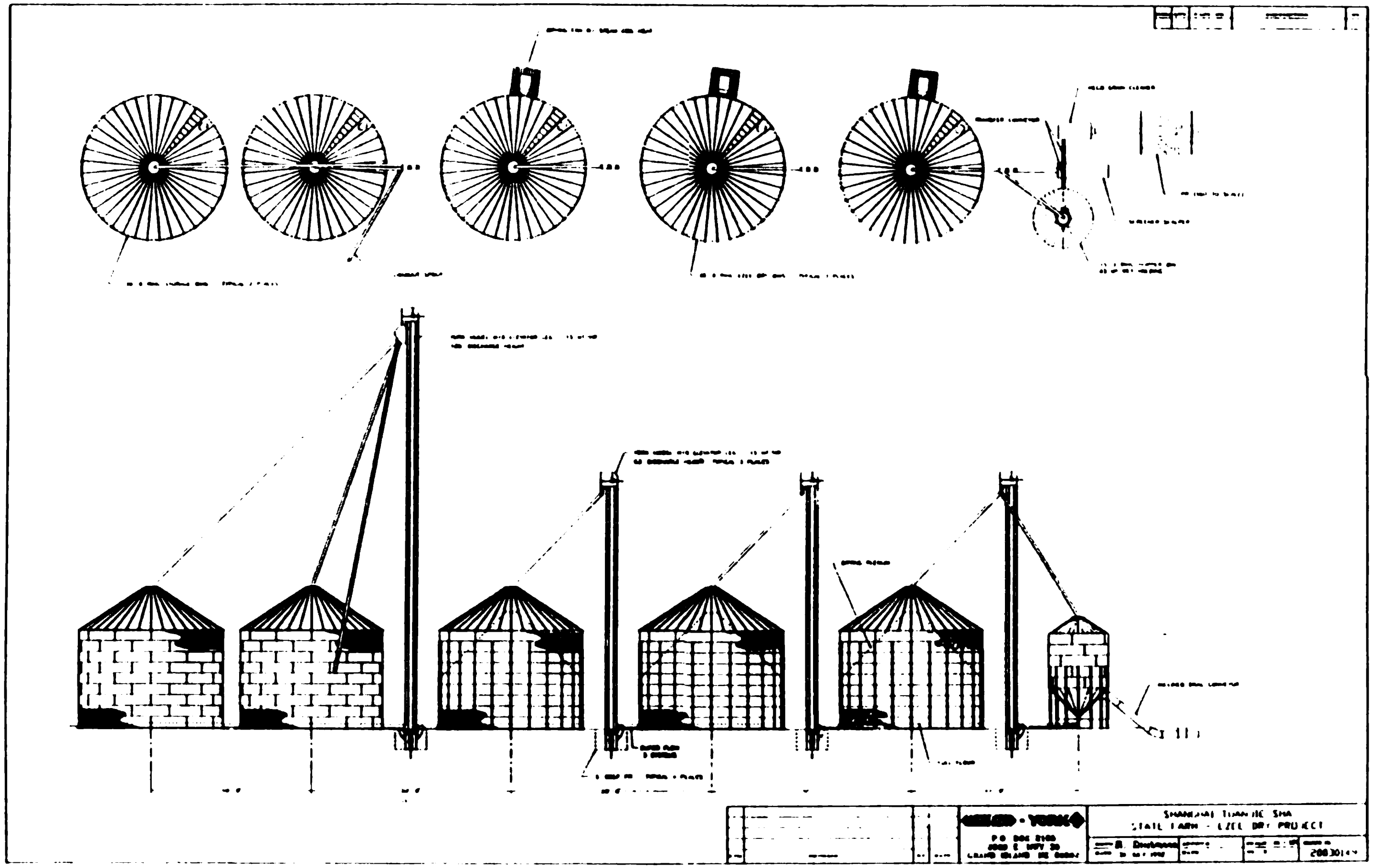

Figure 5.3 Configuration of the Shanghai, China, TB/IBCF drying system (Widayat et al., 1993).

The depth of the rice in the TB dyers should be limited to 0.3-0.6 m. The drying temperature is 35-50°C. The depth of the grain column in the IBCF drying stages has to be kept at 0.9-2.4 m depending on the required tempering time between the TB and IBCF drying processes. For rice, a tempering period of 6-8 hours is required, or a minimum grain depth of 1.8 m.

In the simulation of the TB/IBCF drying system, the grain-depth in the TB dryer is 0.3 m in each drying bin, and 1.5 m in the IBCF dryers. At a capacity of 12 tonnes per hour, the tempering time between the TB and IBCF drying treatments is 7.5 hours.

The air temperatures of the TB dryer are 52°C in the first bin, 43°C in the second bin, and 40°C in the third bin. The ambient air used in the IBCF dryers is assumed to be 27°C with 65% humidity in each of the bins. The airflows in each bin are 50 m3/min.tonne and 1 m3/min.tonne in the TB and IBCF dryers, respectively.

Long-grain rice is dried from 24 to 13% at a capacity of 12 tonnes per hour. Table 5.8 shows the approximate operating conditions of the system. The approximate operating conditions of the system at 27°C and 95% humidity are shown in Table 5.9.

Table 5.8 Approximate operating conditions of the TB/IBCF drying system in drying long-grain rice from 24% to 13% at a capacity of 12 tonnes per hour at ambient conditions of 27°C and 65% humidity.

Air/Grain	BIN 1		BIN 2		BIN 2	
Condition	TB	IBCF	TB	IBCF	TB	IBCF
Air Temperature(°C)	52	27	43	27	38	27
Airflow(m3/min.tonne)	50	1	50	1	50	1
Outlet M.C.(aver.,%)	21.5	20	17	16	14	13
Outlet Temp.(aver.,°C)	42	37	38	33	34	30

Table 5.9 Approximate operating conditions of the TB/IBCF drying system in drying long-grain rice from 24% to 13% at a capacity of 12 tonnes per hour at ambient conditions of 27°C and 95% humidity.

Air/Grain Condition	BIN 1		BIN 2		BIN 2	
	TB	IBCF	TB	IBCF	TB	IBCF
Air Temperature(°C)	52	27	43	27	38	27
Airflow(m3/min.tonne)	50	1	50	1	50	1
Outlet M.C.(aver.,%)	22	20	18	17	15	14.5
Outlet Temp.(aver.,°C)	43	38	39	35	36	32

Under 65% humidity (i.e. the less humid) conditions the moisture decrease in the successive drying stages is 2.5%, 1.5%, 3.0%, 1.0%, 2.0% and 1.0%, resulting in a final moisture content of the rice of about 13% (see Table 5.8). At 95% humidity (i.e. the less favorable drying conditions), the final moisture content is 14.5% (see Table 5.9). Thus, there is significant change in the moisture extraction of the system if the ambient relative humidity changes from 65% to 95%.

The average outlet temperature of the rice is little affected by a change in the ambient humidity; the rice never exceeds an average temperature of 43°C, and thus is expected not to decrease in head yield by more than 1-2 points.

Table 5.10 shows the approximate operating conditions of the drying system for the rice to reach the same final moisture content at ambient humidity of 95% as at 65% . The grain flow rate through the system has to be decreased from 12 to 9 tonnes per hour. The average rice temperatures are slightly higher when the system operates at 9 tonnes per hour than at 12 tonnes per hour.

Table 5.10 Approximate operating conditions of the TB/IBCF drying system in drying long-grain rice from 24% to 13% at a capacity of 9 tonnes per hour at ambient conditions of 27°C and 95% humidity.

Air/Grain Condition	BIN 1		BIN 2		BIN 2	
	TB	IBCF	TB	IBCF	TB	IBCF
Air Temperature(°C)	52	27	43	27	38	27
Airflow(m3/min.tonne)	50	1	50	1	50	1
Outlet M.C.(aver.,%)	22	20	17	16	14	13
Outlet Temp.(aver.,°C)	44	39	40	35	36	32

Conclusions

A modified IBCF dryer model was used to design the operating conditions of the IBCF dryers which operate in combination with a cross-flow drying system, the so called TB/IBCF drying system, in drying rice under Chinese conditions. The system is expected to dry rice from 24 to 13% moisture at a capacity 12 tonnes per hour under ambient conditions of 27°C and 65% humidity. This system consists of a series of top-bin (i.e. cross-flow type) dryers and IBCF dryers, in combination with several aeration/storage bins. The system has particularly advantageous features for the drying of rice because of the stepwise drying characteristics and the built-in tempering stages.

The followings are the important features and performance characteristics of the system :

(1) At capacity of 12 tonnes per hour, at 0.3 m grain-depths in the TB dryers and 1.5 m in the IBCF dryers, the tempering time between the TB and IBCF drying treatments is 7.5 hours. The total drying time in the system for rice being dried from 24 to about 13% is 27 hours.

(2) The drying-air temperatures in the TB dryers are 52°C, 43°C and 38°C in the first, the second and the third bin, respectively. The drying-air temperature in the IBCF dryers is 27°C in each of the bins. The airflows in each bin are 50 m^3/min.tonne in the TB dryers and 1 m^3/min.tonne in the IBCF dryers.

(3) There is a significant change in the moisture extraction of the system if the ambient relative humidity changes from 65% to 95%. Under the less humid conditions, the moisture-decrease of initially 24% moisture content rice is in the successive drying stages 2.5%, 1.5%, 3.0%, 1.0%, 2.0% and 1.0%, repectively, resulting in a final moisture content of the rice of about 13%. Under the less favorable drying conditions (i.e. 95% humidity) the final moisture content is approximately 14.5%.

(4) The average rice temperatures are slightly affected by a change in the ambient conditions; under the recommended drying conditions, the rice never exceeds an average temperature of 44°C, and does not exceed the recommended safe-rice temperature (i.e. not higher than 50°C).

(5) For the rice to reach the same final moisture content at 95% humidity as at 65% humidity, the grainflow rate through the system has to be decreased from 12 to 9 tonnes per hour. The average rice temperatures are slightly higher when the system operates at 9 tonnes per hour compared to at 12 tonnes per hour.

6. CONCLUSIONS

The following conclusions can be drawn from this study:

(1) An existing IBCF drying model has been modified successfully. The simulation results were validated with experimental data. Acceptable agreement was obtained.

(2) The modified IBCF model was utilized to analyze the effects of various parameters (i.e. initial grain moisture, inlet-air temperature, airflow rate and grainflow rate) on the outlet-grain moisture and outlet-grain temperature of a maize-preheating system. The analysis provides significant insights into the effects of the parameters on the preheating process.

(3) A new rice drying system was designed and analyzed with the use of the IBCF model, and built near Shanghai, China. The system has particularly advantageous features for the drying of rice because of the stepwise drying characteristics and the built-in tempering effects.

7. SUGGESTION FOR FURTHER WORK

(1) In order to further improve the efficiency of the pre-heating system, the heated air should be exhausted from the pre-heating bin as soon as the air becomes saturated at the existing inlet-grain temperature. This can best be accomplished by limiting the grain depth in the pre-heating bin. A system of inlet and outlet air-ducts should be installed at a distance of 1.8 m (6 ft) from the air inlet. The present grain depth of the pre-heating bin is 5.5 m (18 ft) which translates in an airflow rate of approximately 1.65-3.3 m^3/min.tonne (1.5-2.0 cfm/bu). The 8 kW (10 HP) fan will deliver 13.4 m/min.tonne (12 cfm/bu) in the modified system. The new system will be tested during the 1993 harvest season.

(2) The simulated results of the new-rice drying system should be validated with experimental data. This will be done in the fall of 1993. Further study on the optimal operating conditions of the system under different ambient conditions is recommended.

8. IMPLICATION OF THE STUDY FOR INDONESIA

Rice is the main staple in Indonesia. Through a national program called BIMAS (i.e. a national program to increase rice production and started in the mid-1970), Indonesia has been successful in increasing rice production substantially, and has been self-sufficient in rice since the early 1990s. At the present time, Indonesia is considered to be a potential rice-exporting country. Before the BIMAS became successful, Indonesia was one of the largest rice-importing countries in the world.

An increase in the rice production has lead to complicated problems in the preservation of rice in Indonesia. Effective preservation treatments are crucial in maintaining the required high quality of rice. One of the most effective and economical preservation treatments for rice is drying.

Much of the rough rice in Indonesia is sun-dried, a labor-intensive practice of spreading the moist rice kernels in a thin layer 3-5 cm thick on hard soil or a concrete floor, and exposing the material to the energy of the sun. Frequently the rice-kernel temperatures rise to 60-70°C, resulting in cracking of the kernels. Therefore, milled rice produced from sun-dried rough rice has a low head yield.

In order to produce high-quality rice at a high throughput, rice should be dried employing a mechanical drying system. The new rice TB/IBCF drying system studied in this thesis is an alternative solution. The system is relatively inexpensive compared to conventional high-temperature rice-drying systems, and requires a relatively low level of technical expertise.

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APPENDIX

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*****************************************
*                                       *
*     I N - B I N  C O U N T E R F L O W     *
*                                       *
*     G R A I N   D R Y E R   M O D E L     *
*                                       *
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F.W. BAKKER-ARKEMA, PROJECT LEADER
E.N. MWAURA, PROGRAMMER
B.P. MARKS, MODIFIER AND CONVERTER TO P.C. VERSION
AND CONVERTER TO SI INPUT AND OUTPUT
H.P. WIDAYAT, MODIFIER FOR RICE (JUNE 23, 1992)

DEVELOPED AT MICHIGAN STATE UNIVERSITY
DEPARTMENT OF AGRICULTURAL ENGINEERING

FOR INPUT, ( ) DENOTES INTEGER, [ ] DENOTES REAL VALUE.

```
INPUT DATA FROM (5=SCREEN,8=FILE,0=STOP):                      5

OUPUT DATA TO (5=SCREEN,9=FILE,0=STOP):                        9

YOUR OUTPUT FILENAME IS:  IBCF1.OUT

TYPE OF PRODUCT (1=CORN,2=WHEAT,3=RICE,4=BARLEY)               3

WHAT SYSTEM OF UNITS FOR INPUT (0=ENGLISH,1=SI)?               1

WHAT SYSTEM OF UNITS FOR OUTPUT (0=ENGLISH,1=SI)?              1

SYSTEM TYPE?   [ FIXED BED=2.
        COUNTERFLOW=1.
    REFILL COUNTERFLOW=0. ]                                    .0000

REFILL MODE? [    TIMED  =0
          AUTOMATIC =1
           UNSTEADY =2 ]                                       .0000

DIAMETER OF THE BIN [M]                                        11.0000
INIT.BED DEPTH, [M]                                            1.5000
TIME BETWEEN REFILLS, [HOURS]                                  .3000
ENTER THE CYCLE TIME [HOUR]                                    .3000

DEPTH OF GRAIN ADDED PER REFILL [M]                            .0562
DEPTH OF GRAIN REMOVED PER REFILL [M]                          .0562
```

REFERENCES FOR COUNTERFLOW GRAIN DRYER SIMULATION
USING THE WANG-SINGH (1978) THIN LAYER EQUATION FOR RICE
AND EMC BY ZURITZ/CHEN-CLAYTON (1979)

INPUT AIR CONDITIONS :	
AMBIENT AIR TEMP, [C]	27.0000
AMBIENT REL HUM, [DEC]	.9500
DRYING AIR TEMP, [C]	27.5000
CALCULATED AMBIENT ABS HUM=	.0215
TYPE OF FUEL USED [1.=NO.2 FUEL 2.=NAT.GAS; 3.=L.P.GAS; 4.=BIOMASS; 5.=HEAT EXCHANGER] :	5.0000
CALCULATED INLET ABS HUM=	.0215
INPUT GRAIN CONDITIONS:	
INLET GRAIN TEMP, [C]	34.0000
INITIAL MOISTURE, [W.B.PERC.]	15.0000
[D.B.PERC.]	17.6471
TESTWEIGHT AT INIT.M.C., [KG/M3]	680.0000
HYBRID DRYING FACTOR, [DEC.]	1.0000
AIRFLOW RATE AT AMBIENT TEMP.[M3/MIN]	1.3500
PRELIMINARY CALCULATED VALUES AT INIT.DEPTH & AMB.TEMP. :	
AIRFLOW RATE, [M3/MIN/M2]	1.4607
[M3/MIN/MT]	1.3500
PLENUM PRESSURE, [PA]	60.5884
DRY AIRFLOW RATE, [KG/M2.SEC]	16.2112
SATISFIED WITH DEPTH/PRESSURE COMBINATION ? [YES=1.; NO=0.]	1.0000
INPUT CALCULATION DATA:	
TOTAL SIMULATION TIME, [HR]	7.5000
ENTER DELX [M]	.0080
CALCULATED DELT [HOURS] :	.1099
SATISFIED WITH DELX & DELT COMBINATION ? [YES=1.;NO=0.]	.0000
ENTER DELX [M]	.0080
ENTER DELTA ELAPSED TIME [HOURS]	.1500
SATISFIED WITH DELX & DELT COMBINATION ? [YES=1.;NO=0.]	1.0000

****
CYCLE NO.: 1
****

PROFILE OF THE LAYER JUST BEFORE REMOVING
(THIS IS PASS NUMBER 1 FOR THE AUGER)

DEPTH [M]	M C [%]	PROD.TEMP [C]	AIR TEMP [C]	HUM.RAT. [KG/KG']	REL.HUM. [%]
.00	14.05	30.49	27.50	.02150	79.26
.01	14.11	31.23	31.60	.02373	80.14
.02	14.17	31.89	32.27	.02593	84.02
.02	14.25	32.15	32.52	.02801	89.21
.03	14.32	32.35	32.69	.02995	94.19
.04	14.58	32.75	33.13	.03217	98.36
.05	14.77	33.24	33.42	.03329	100.00
.06	14.90	33.60	33.67	.03379	100.00
.06	14.94	33.78	33.83	.03411	100.00
.46	15.00	34.00	34.00	.03445	100.00
.86	15.00	34.00	34.00	.03445	100.00
1.26	15.00	34.00	34.00	.03445	100.00
1.50	15.00	34.00	34.00	.03445	100.00

CYCLE NUMBER	1
CYCLE TIME [HRS]	.300
DEPTH OF REMOVING LAYER [M]	.056
WEIGHT OF GRAIN REMOVED [KG]	3309.453
GRAIN DRIED [MT]	3.640
OUTLET AVER. GRAIN MOISTURE CONTENT [% W.B]	14.396
OUTLET AVER. GRAIN TEMPERATURE [C]	32.212
DRYING RATE, THIS CYCLE [MT/HR]	12.171
AVERAGE DRYING RATE [MT/HR]	12.132

TOTAL AIRFLOW [M3/MIN]	138.7369
STATIC PRESSURE [PA]	60.5884
HORSE POWER [KW/M2]	.0030
AVER.PROD.TEMP.OF THE PROFILE [C]	33.9215
AVER.MOISTURE OF THE PROFILE [% W.B]	14.9738
WATER REMOVED THIS CYCLE (MC) [KG-H2O/M2]	.1792
ENERGY THIS CYCLE (DRYING ONLY) [KJ/M2]	674.4864
ENERGY THIS CYCLE FOR FAN [KJ/M2]	10.6346
TOTAL ENERGY (DRYING ONLY) [KJ/M2]	674.4864
TOTAL ENERGY (WITH FAN) [KJ/M2]	685.1210

SECO (DRYING ONLY) THIS CYCLE [MJ/KG-H20]	3765.2628
SECO (DRYING AND FAN) THIS CYCLE [MJ/KG-H20]	3824.6298
AVERAGE SECO (DRYING ONLY) [MJ/KG-H20]	3765.2628
AVERAGE SECO (DRYING AND FAN) [MJ/KG-H20]	3824.6298
TOTAL DRYING TIME [HRS]	.3000
WATER REMOVED BY AVAILABLE ENERGY [KG-H2O/HR]	627.4904
WATER REMOVED BY DIFF. MOISTURES [KG-H2O/HR]	666.0746

BIN REFILLED WITH 3.6 MT(WEIGHT OF GRAIN ADDED 3336.3 KG) TO A DEPTH OF 1.5 M AFTER .3 HOURS

PROFILE OF THE LAYER JUST AFTER ADDING THE GRAIN

DEPTH [M]	M C [%]	PROD.TEMP [C]	AIR TEMP [C]	HUM.RAT. [KG/KG']	REL.HUM. [%]
.00	14.94	33.78	33.83	.03411	1.00
.01	14.97	33.88	33.91	.03427	1.00
.02	14.98	33.94	33.95	.03435	1.00
.02	14.99	33.97	33.98	.03440	1.00
.03	15.00	33.98	33.99	.03442	1.00
.04	15.00	33.99	33.99	.03444	1.00
.05	15.00	34.00	34.00	.03444	1.00
.06	15.00	34.00	34.00	.03445	1.00
.06	15.00	34.00	34.00	.03445	1.00
.46	15.00	34.00	34.00	.03445	1.00
.86	15.00	34.00	34.00	.03445	1.00
1.26	15.00	34.00	34.00	.03445	1.00
1.50	15.00	34.00	34.00	.03445	1.00

****
CYCLE NO.: 24
****

PROFILE OF THE LAYER JUST BEFORE REMOVING
(THIS IS PASS NUMBER 1 FOR THE AUGER)

DEPTH [M]	M C [%]	PROD.TEMP [C]	AIR TEMP [C]	HUM.RAT. [KG/KG']	REL.HUM. [%]
.00	14.05	30.44	27.50	.02150	92.26
.01	14.11	31.17	31.53	.02371	80.38
.02	14.17	31.85	32.23	.02590	84.15

.02	14.25	32.13	32.49	.02798	89.26
.03	14.32	32.33	32.67	.02992	94.19
.04	14.56	32.72	33.10	.03209	98.31
.05	14.77	33.21	33.40	.03325	100.00
.06	14.90	33.58	33.65	.03375	100.00
.06	14.94	33.77	33.82	.03409	100.00
.46	15.00	34.00	34.00	.03445	100.00
.86	15.00	34.00	34.00	.03445	100.00
1.26	15.00	34.00	34.00	.03445	100.00
1.50	15.00	34.00	34.00	.03445	100.00

CYCLE NUMBER	13
CYCLE TIME [HRS]	.300
DEPTH OF REMOVING LAYER [M]	.056
WEIGHT OF GRAIN REMOVED [KG]	3309.251
GRAIN DRIED [MT]	47.314
OUTLET AVER. GRAIN MOISTURE CONTENT [% W.B]	14.391
OUTLET AVER. GRAIN TEMPERATURE [C]	32.178
DRYING RATE, THIS CYCLE [MT/HR]	12.171
AVERAGE DRYING RATE [MT/HR]	12.132

TOTAL AIRFLOW [M3/MIN]	138.7369
STATIC PRESSURE [PA]	60.5884
HORSE POWER [KW/M2]	.0030
AVER.PROD.TEMP.OF THE PROFILE [C]	33.9199
AVER.MOISTURE OF THE PROFILE [% W.B]	14.9736
WATER REMOVED THIS CYCLE (MC) [KG-H2O/M2]	.1805
ENERGY THIS CYCLE (DRYING ONLY) [KJ/M2]	674.5957
ENERGY THIS CYCLE FOR FAN [KJ/M2]	10.6346
TOTAL ENERGY (DRYING ONLY) [KJ/M2]	8769.6277
TOTAL ENERGY (WITH FAN) [KJ/M2]	8907.8781
SECO (DRYING ONLY) THIS CYCLE [MJ/KG-H20]	3738.0460
SECO (DRYING AND FAN) THIS CYCLE [MJ/KG-H20]	3796.9743
AVERAGE SECO (DRYING ONLY) [MJ/KG-H20]	3740.3886
AVERAGE SECO (DRYING AND FAN) [MJ/KG-H20]	3799.3546
TOTAL DRYING TIME [HRS]	7.2000

WATER REMOVED BY AVAILABLE ENERGY [KG-H2O/HR]	627.2966
WATER REMOVED BY DIFF. MOISTURES [KG-H2O/HR]	665.7625

BIN REFILLED WITH 3.6 MT (WEIGHT OF GRAIN ADDED
3336.3 KG) TO A DEPTH OF 1.5 M AFTER 3.9 HOURS

PROFILE OF THE LAYER JUST AFTER ADDING THE GRAIN

DEPTH [M]	M C [%]	PROD.TEMP [C]	AIR TEMP [C]	HUM.RAT. [KG/KG']	REL.HUM. [%]
.00	14.94	33.77	33.82	.03409	1.00
.01	14.97	33.88	33.90	.03425	1.00
.02	14.98	33.94	33.95	.03435	1.00
.02	14.99	33.97	33.97	.03440	1.00
.03	15.00	33.98	33.99	.03442	1.00
.04	15.00	33.99	33.99	.03443	1.00
.05	15.00	34.00	34.00	.03444	1.00
.06	15.00	34.00	34.00	.03444	1.00
.06	15.00	34.00	34.00	.03445	1.00
.46	15.00	34.00	34.00	.03445	1.00
.86	15.00	34.00	34.00	.03445	1.00
1.26	15.00	34.00	34.00	.03445	1.00
1.50	15.00	34.00	34.00	.03445	1.00

****

CYCLE NO.: 25

****

PROFILE OF THE LAYER JUST BEFORE REMOVING
(THIS IS PASS NUMBER 1 FOR THE AUGER)

DEPTH [M]	M C [%]	PROD.TEMP [C]	AIR TEMP [C]	HUM.RAT. [KG/KG']	REL.HUM. [%]
.00	14.05	30.44	27.50	.02150	92.26
.01	14.11	31.17	31.53	.02371	80.38
.02	14.17	31.85	32.23	.02590	84.15
.02	14.25	32.13	32.49	.02798	89.26
.03	14.32	32.33	32.67	.02992	94.19
.04	14.56	32.72	33.10	.03209	98.31
.05	14.77	33.21	33.40	.03325	100.00
.06	14.90	33.58	33.65	.03375	100.00
.06	14.94	33.77	33.82	.03409	100.00
.46	15.00	34.00	34.00	.03445	100.00
.86	15.00	34.00	34.00	.03445	100.00
1.26	15.00	34.00	34.00	.03445	100.00
1.50	15.00	34.00	34.00	.03445	100.00

CYCLE NUMBER	14
CYCLE TIME [HRS]	.300
DEPTH OF REMOVING LAYER [M]	.056
WEIGHT OF GRAIN REMOVED [KG]	3309.251
GRAIN DRIED [MT]	50.953
OUTLET AVER. GRAIN MOISTURE CONTENT [% W.B]	14.391
OUTLET AVER. GRAIN TEMPERATURE [C]	32.178
DRYING RATE, THIS CYCLE [MT/HR]	12.171
AVERAGE DRYING RATE [MT/HR]	12.132

TOTAL AIRFLOW [M3/MIN]	138.7369
STATIC PRESSURE [PA]	60.5884
HORSE POWER [KW/M2]	.0030
AVER.PROD.TEMP.OF THE PROFILE [C]	33.9199
AVER.MOISTURE OF THE PROFILE [% W.B]	14.9736
WATER REMOVED THIS CYCLE (MC) [KG-H2O/M2]	.1805
ENERGY THIS CYCLE (DRYING ONLY) [KJ/M2]	674.5957
ENERGY THIS CYCLE FOR FAN [KJ/M2]	10.6346
TOTAL ENERGY (DRYING ONLY) [KJ/M2]	9444.2234
TOTAL ENERGY (WITH FAN) [KJ/M2]	9593.1084
SECO (DRYING ONLY) THIS CYCLE [MJ/KG-H20]	3738.0460
SECO (DRYING AND FAN) THIS CYCLE [MJ/KG-H20]	3796.9743
AVERAGE SECO (DRYING ONLY) [MJ/KG-H20]	3740.2211
AVERAGE SECO (DRYING AND FAN) [MJ/KG-H20]	3799.1845
TOTAL DRYING TIME [HRS]	7.5000
WATER REMOVED BY AVAILABLE ENERGY [KG-H2O/HR]	627.2966
WATER REMOVED BY DIFF. MOISTURES [KG-H2O/HR]	665.7625
FINAL AVERAGE MOISTURE (%W.B.) IN SECOND BIN	14.39
FINAL GRAIN TEMPERATURE [C] IN SECOND BIN	32.18

THIS IS THE END OF COUNTERFLOW