SIMULATION OF BATCH DRYING OF RICE

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ABSTRACT

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By

Nguyen Kim Chan

Knowledge of the drying parameters is essential in the design and evaluation of a grain dryer. Most designs, however, are based on a limited number of experimental results which are slow and expensive to obtain.

The computer simulation of grain drying has been studied by many researchers. The results of these studies revealed that simulation provides an accurate, fast and inexpensive tool for grain dryer design.

An attempt was made in this work (using the existing fixed bed Michigan State University corn drying model) to simulate the drying of rice. Appropriate changes were made in the basic MSU model to account for the differences in physical and thermal properties and in drying characteristics between the rice and corn. Chancellor's semi-empirical thin layer drying equation was used to describe the thin-layer drying behavior of rice. Henderson's equation provided the necessary equilibrium moisture content, after the two constants for rice were found. These equations, along with the MSU fixed bed program and related subroutines, constitutes the deep bin rice drying model.

The results were obtained for a number of runs and were plotted on a WANG 2200 computer to investigate the validity of the model and to analyze the influence of a drying parameter upon the drying rate. It was found that the model can be used to predict fixed bed drying of rice.

Though the accuracy of results obtained is still questionable because of questionable values used for the physical parameter, the methodology is valid. This means that rice drying can now be satisfactorily simulated on an electronic computer.

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SIMULATION OF BATCH DRYING OF RICE

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Nguyen Kim Chan

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This work is dedicated to my wife, Nguyen Bao Ngan, and to my son, Nguyan Kim Khanh. Their personal sacrifice during this long absence is recognized and deeply appreciated.

TABLE OF CONTENTS

TABLE OF CONTENTS (cont'd.)

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (cont'd.)

SYMBOLS

a	Specific product surface area, ft^2/ft^3
c	Specific heat, BTU/lb °F
h	Convective heat transfer coefficient, BTU/hr ft^2 °F
h_{fg}	Heat of vaporization, BTU/lb
rh	Relative humidity, decimal
t	time, hours
A	constant
B	Constant
D	Diffusion coefficient, ft^2/hr
G	Flow rate, lb of dry product/hr ft^2
H	Humidity ratio
K	Phenomenological coefficient
L	Length, ft
M	Local or average moisture content, decimal, dry basis
MR	Moisture ratio $(M - M_{eq}) / (M_{in} - M_{eq})$, dimensionless
P	Pressure, psia
R	Gas constant, ft lb/lb
S	Cross sectional bed area, ft^2

T	Air temperature, °F
T_{abs}	Absolute air temperature, °R

--Subscripts--

a	Air
e	Equilibrium
in	Inlet
o	At time t = 0
p	Product
s	Saturated vapor
t	At time t
v	Vapor
w	Water

INTRODUCTION

Rice is the most important crop in the world today and provides staple food for hundreds of millions of people in Asia.

The increase of rice production and improvement of rice quality are two of the major world agricultural needs of today.

Rice is a biological product with hygroscopic properties. High moisture content profoundly accelerates fungus growth, development of insects and mites, deterioration of starch and loss of nutrients. In order to maintain high quality over a long period of time rice must be dried. The harvest moisture content of 20 to 24 per cent wet basis must be reduced 13 to 14 per cent wet basis for safe storage (Esmay 1970).

Sun drying of high moisture content rice has been practiced for centuries. The grain is spread on concrete or a hard earth floor. The drying process takes place by an exchange of moisture and heat between the grain and the surrounding atmospheric air. Even under the most favorable conditions it has been found that considerable cracking results. For large scale production or for early maturing varieties of rice for which more than one harvest a year is possible, artificial drying is preferred.

Unlike most cereal grains, rice is consumed primarily in the whole kernel form so that the market premium for unbroken kernels is much greater. Therefore, to avoid cracked kernels, more care is required for drying rice than for other cereal grains.

Stress crack development depends on the rate of migration of moisture from the inside to the outside of the kernel. As the rice is dried, the outer portion shrinks, resulting in stress and strain. When too much moisture is removed too rapidly, checking or shattering of the kernel results. To reduce this effect, rice is dried with air at 100 to 130 degrees Farenheit in two or more passes through the dryer. Between passes through the dryer, the grain is held in a bin to allow moisture to equilibriate throughout the individual kernels. This tempering relieves stress (Wasserman 1957) and strain and facilitates drying in the next passes.

Though rice drying is a complicated process, the design of a rice dryer is based largely on a limited number of laboratory and field experiments. There has been little or no use of a powerful new tool for experimentation called simulation. In simulation the designer represents his dryer design by a number of equations of which the solutions predict the drying behavior of the equipment. Simulation models are usually solved on electronic computers; today's technology makes this type of solution possible. An advantage of computer simulation is that when a model satisfactorily predicts grain drying behavior, the effect of various parameters influencing this behavior can be investigated (Bakker-Arkema et al. 1973). Rather than return to the laboratory for more testing, answers can be obtained in minutes from the computer resulting in faster, better and less espensive design.

Grain drying simulation model has been available for corn but there is no existing model for rice.

The purpose of this study is to employ an existing corn drying model for the drying of rice. Changes were made to make the simulation model applicable. The resulting output from the computer has been compared with experimental data. Various drying parameters have been analyzed and discussed.

It is the hope of the author that this work will contribute to the existing literature in the field of rice drying and provide a good model for rice drying simulation and rice dryer design.

REVIEW OF LITERATURE

Rice Drying Methods

For the proper drying of rice, moisture must be removed from inside the grain kernel. To prevent internal checking or breaking of the kernel from drying too rapidly, drying is usually done in three to five stages or passes. In each stage, the rice passes through the dryer and then is tempered in a bin so that the kernel moisture will equilibriate.

Esmay and Chancellor (1970) found that for batch drying of rice at a temperature above 100 of deg. Far. tends to cause overdrying and thus a lower head yield of milled rice.

Smith and others (1959) reported on early research on artificial drying of rice in Arkansas and Texas concluded that a drying temperature of 120 deg. F could be used without injuring the rice if the moisture content was reduced only about 2 per cent at each drying operation and the rice was allowed to remain in storage 12 to 24 hours between drying periods. However, when necessary to dry a given lot of rice in one continuous operation, the drying air and temperature should not exceed 110 deg. F.

Stahel (1949) showed that a moisture content of 15 per cent is critical for crack formation, drying or wetting of the rice which passes this point increasing the internal cracks.

From experiments with combined rice, MacNeal (1949) concluded that in most cases head rice yield was increased and the total drying time was decreased as the number of drying passes was increased from one to four in the temperature range from 100 to 150 deg. F. The tempering between drying was important since it gave the moisture in the grain an opportunity to equalize and thereby reduce the drying time.

To increase dryer's efficiency Calderwood and Hutchinson (1961) conducted a series of experiments in Beaumont, Texas, and found a significant drop in moisture content in rice cooled by aeration following a pass through the dryer.

According to Hutchinson and Willms (1962) the practice of aerating is in widespread use in the Southwest of the United States. They indicated that aeration is used to: 1) maintain the quality of undried grain until it can be moved through the dryer, 2) remove harvest or dryer heat, 3) remove small amounts of moisture (1 to 2 per cent), and 4) maintain the quality of rice during storage.

Infrared drying of rice has not been found to be of practical importance. However, Wratten and Faulkner (1966) found that infrared energy could be used as a source of heat to preheat the rice before the drying operation.

Rice Drying Thin-layer Equations

The theory of drying of biological products has been treated by many workers and has been adapted to many cereal grains and drying systems in use.

Henderson and Perry (1966) reported that the moisture removal of thin layers of grain during the falling rate is inversely proportional to the moisture to be removed:

$$\frac{dM}{dt} = -K\ (M - M_e) \qquad (1)$$

Where: M : Moisture content, per cent

t : Time, hours

M_e : Equilibrium moisture content, per cent

K : Drying constant, hr^{-1}

Solution of equation (1) yields:

$$\frac{M - M_e}{M_o - M_e} = e^{-K\theta} \qquad (2)$$

The constant K is determined by the characteristics of the grain.

Equation (2) forms the basis for much thin-layer drying theory.

Thompson (1967) simulated the process of drying a deep bed of grain by consecutively calculating the changes that occur during short increments of time in thin layers of the bed. For thin-layer drying of corn Thompson's equation is:

$$t = A \ln (MR) + B \ln (MR)^2 \tag{3}$$

Where:

t : drying time, hours

$MR : \dfrac{M - M_e}{M_o - M_e}$

M_o : Initial moisture content, per cent dry basis

M : Moisture content, per cent dry basis

$A : 1,8617 + 0.0048843\ \theta$

For rice, Allen (1960) developed an equation for shallow bed drying:

$$\theta = \frac{1}{m} \log_{10} \frac{(M_c - M_e)}{(M_o - M_e)} \tag{4}$$

Where:

M_c : Moisture content at the end of the constant rate drying period, decimal

θ : Time, hours

m : Dimensional Drying Rate Constant, hr^{-1}

M_e : Equilibrium Moisture Content, decimal.

For intermittent system of drying rice in a shallow bed, Faulkner and Wratten (1967) developed the following equation:

$$M_R = C1 \left[\frac{M_i - (T_E - T_W)}{T_E} \right]^{n1} \left[1 - e^{C2(T_E/T_G)^{n2}(Vt/L)^{n3}} \right] \quad (5)$$

Where:

M_R : Moisture removed in time t, per cent dry basis

M_i : Initial moisture, per cent dry basis

T_E : Dry bulb temperature of entering air, deg. R.

T_W : Wet bulb temperature of entering air, deg. R.

T_G : Initial grain temperature, deg. R.

V : Air velocity, ft./min.

L : Length of air passage through the grain, ft.

t : Time, min.

Ramarao and Wratten (1969) developed a generalized equation to predict moisture removal from the Dawn variety of rice in the Louisiana State University model dryer. This equation is:

$$M_R = (73.109 - 59.819T_E/T_W) \quad (37.167 - 32.068T_E/T_G)$$

$$\left[\frac{(M_i - M_e)\ (T_E - T_L)}{T_W}\right]^{0.592}$$

$$\left[1 - e^{-7.963(Vt/X)^{1.45}(R_e)^{-0.438}\ (T_G/T_W)^{-1.108}}\right] \qquad (6)$$

Where: R_e : modified Reynolds number - $\rho V/\mu$

MR : Moisture removed at any time t, per cent dry basis

T_E : Dry bulb temperature of inlet air, deg. R.

T_W : Wet bulb temperature of inlet air, deg. R.

V : Velocity of air flow, ft./min.

X : Characteristic length of dryer, ft.

Equation (6) has not been tested for other dryer types or other varieties of rice. Only limited data for air, grain temperature were used to develop the equation. More work is therefore needed to verify its usefulness and accuracy.

Chancellor (1967) developed the following thin-layer equation for heated air drying of short grain rice.

$$\frac{M - M_e}{M_o - M_w} = 0.735\ (e^{-G\theta} + 1/4\ e^{-4G\theta} + 1/9\ e^{-9G\theta}) \qquad (7)$$

Where:

θ : time, hours

G : constant.

Chancellor determined experimentally that the value of G increases with an increase in grain temperature. This relationship is expressed as:

$$G = 8860 \frac{-6147}{T}$$

Where: T : grain temperature, deg. R.

Consequently, based on experimental results, the empirical thin-layer equation by Chancellor can be used to represent the characteristics of drying of rice.

Of all the various equation forms presented above, all have some limitation to a fixed bed grain dryer, besides their forms do not lend themselves to the application in the Michigan State University grain dryer model. Chancellor's equation was thought to be best suited for the model. Hence this study primarily uses this thin-layer equation.

Physical and Thermal Properties of Rice

Prerequisite to an accurate engineering design of the machines and equipment for processing rice is knowledge of the true values of the physical as well as thermal properties of the rice itself. It is these properties that distinguish the rice drying process from that of other cereal grains.

The magnitude of physical and thermal properties of rice must be evaluated as a function of moisture content (Wratten 1969). Rice will often range from a high of 22 to 24 per cent moisture at harvest time, down to a low of 10 to 12 per cent for safe storage.

Rice varieties divided by grain size and shape fall into three types: short, medium and long grain. The type must be considered when evaluating the physical and thermal properties of rice (Wratten 1970). Some of the physical and thermal properties of rice have been determined by various authors but only at specific levels of moisture content and most properties determined pertained to bulk condition. Only limited information on thermal properties of rice is available. The work by Wratten et al. (1968) is found to be more general and complete, therefore their values are used in this simulation model. The results of their findings are presented below.

Physical Properties

The values of length, width, thickness, volume, density, specific gravity and porosity for medium and long grain rice at a moisture content ranging from 12 to 18 per cent wet basis are shown in Table 1. Each property was found to vary linearly with moisture

TABLE 1. PHYSICAL PROPERTIES OF ROUGH RICE

	Individual Grain Properties							Bulk Properties		
Moisture Content %	Length in.	Width in.	Thickness in.	Volume cu. in x 1000	Density (true) lb/cu ft	Specific gravity	Area sq. in	Density lb/cu ft	Porosity %	Specific Gravity (apparent)
				Medium grain (saturn)						
12	0.311	0.123	0.077	0.98	82.67	1.374	0.0623	37.35	58.5	0.599
14	0.312	0.123	0.077	1.02	83.47	1.355		38.58	56.5	0.618
16	0.313	0.123	0.078	1.07	84.53	1.350		39.56	55.0	0.630
18	0.314	0.125	0.079	1.17	85.64	1.325	0.0658	40.49	53.1	0.653
				Long grain (Bluebonnet-50)						
12	0.381	0.102	0.075	1.12	85.05	1.384		36.56	56.6	0.586
14	0.384	0.103	0.076	1.13	85.59	1.378		36.72	59.3	0.589
16	0.388	0.104	0.076	1.17	86.00	1.372		37.79	57.9	0.606
18	0.395	0.106	0.078	1.20	86.34	1.358		38.40	56.9	0.615

Data from Wratten et al., 1968.

content over the 12 to 18 per cent moisture range (Wratten 1968). Regression analysis of average values at each moisture level yielded the following equations:

Length, in.

$$L_M = 0.305 + 0.0005M$$

$$r^2 = 1.00$$

$$L_L = 0.352 + 0.0023\ M$$

$$r^2 = 0.96$$

Width, in.

$$W_M = 0.119 + 0.0003M$$

$$r^2 = 0.60$$

$$W_L = 0.094 + 0.00065M$$

$$r^2 = 0.96$$

Thickness, in.

$$T_M = 7.25 \times 10^{-2} + 3.5 \times 10^{-4}M$$

$$r^2 = 0.89$$

$$T_L = 6.95 \times 10^{-2} + 4.5 \times 10^{-4}M$$

$$r^2 = 0.85$$

Volume, cubic in. per grain:

$$V_M = 5.94 \times 10^{-4} + 3.1 \times 10^{-5}M$$

$$r^2 = 0.95$$

$V_L = 9.4 \times 10^{-4} + 1.4 \times 10^{-5}M$

$r^2 = 0.95$

Specific gravity (true):

$C_{gM} = 1.465 - 0.0076M$

$r^2 = 0.94$

$C_{gL} = 1.436 - 0.0042M$

$r^2 = 0.95$

Specific gravity (bulk):

$C_{gaM} = 0.495 + 0.0087M$

$r^2 = 0.99$

$C_{gaL} = 0.521 + 0.0052M$

$r^2 + 0.94$

Bulk density, lb per cu. ft.:

$\rho_M = 31.195 + 0.52M$

$r^2 = 0.99$

$\rho_L = 32.425 + 0.33M$

$r^2 = 0.94$

Porosity, per cent:

$P_M = 69.05 - 0.88M$

$r^2 = 0.99$

$$P_L = 65.55 - 0.47M \qquad r^2 = 0.95$$

where subscripts M and L designate medium and long grans respectively.

Surface area determination for medium grain rice by Wratten et al. at 12 and 18 per cent are also included in Table 1.

Thermal Properties

Average values of thermal properties determined for medium grain rice were obtained from Wratten et al. and are shown in Table 2. Values of specific heat ranged from 0.396 BTU per lb. deg. F. at a moisture content of 19.5 per cent to 0.473 BTU per lb. deg. F at a moisture content of 19.5 per cent. The regression equation for predicting specific heat is:

$$C = 0.22008 + 0.01301M \qquad r^2 = 0.81$$

Where M is moisture content, per cent, wet basis.

Thermal conductivity varied from 0.0517 BTU per hour, ft.^{2} deg. F. for a moisture content of 9.9 per cent to 0.0649 BTU per hour, ft.^{2} deg. F. for a moisture content of 19.3 per cent. The regression equation for predicting thermal conductivity is:

$$K = 0.0500135 + 0.000767M \qquad r^2 = 0.87$$

Where M is moisture content in per cent, wet basis.

TABLE 2. THERMAL PROPERTIES OF MEDIUM GRAIN ROUGH RICE

Moisture Content %	Specific Heat BTU per hr deg F	Conductivity BTU per hr ft deg F	Diffusivity Sq ft per hr
12	0.382	0.0590	0.00408
14	0.405	0.0607	0.00387
16	0.429	0.0624	0.00368
18	0.452	0.0642	0.00350
20	0.476	0.0650	0.00332

Data from Wratten et al. 1968.

Bulk thermal diffusivity was found by Wratten to vary linearly with moisture content and could be expressed as:

$$\alpha = 0.00523 + 9.65 \times 10^{-5}M \qquad r^2 = 0.99$$

Thermal Diffusivity

The bulk thermal diffusivity of the medium grain rice (variety Saturn) can be calculated using the values for thermal conductivity K, specific heat C and bulk density ρ:

$$\alpha = \frac{K}{C\rho}$$

Drying Simulation of Other Cereal Grain

Models of deep bed drying analysis are based on the work of Hukill (1954); those models developed within the last few years involve rather sophisticated computer methods.

Thompson et al. (1968) developed a computer method for analyzing continuous flow drying of crossflow, concurrentflow and counterflow systems. Boyce (1961) developed a digital computer program to describe fixed bed drying.

Henderson and Henderson (1968) made an analysis of deep bed drying using an empirical model for thin-layer drying.

Recently Hamdy and Barre (1969) were successful in analyzing deep bed drying with mathematical model using a hybrid computer.

Bakker Arkema et al. (1967) solved numerically with a digital computer the coupled equations involved in the heat transfer balance in deep bed cooling of biological products. The MSU grain dryer models are based on the 1967 work and are presented in a paper (1970). The MSU grain drying models are based on the basic laws of heat and mass transfer.

Although simulation models mentioned above can be applied to all cereal grains, only limited application on cereal grain except corn and wheat (Spencer, 1969) has been made.

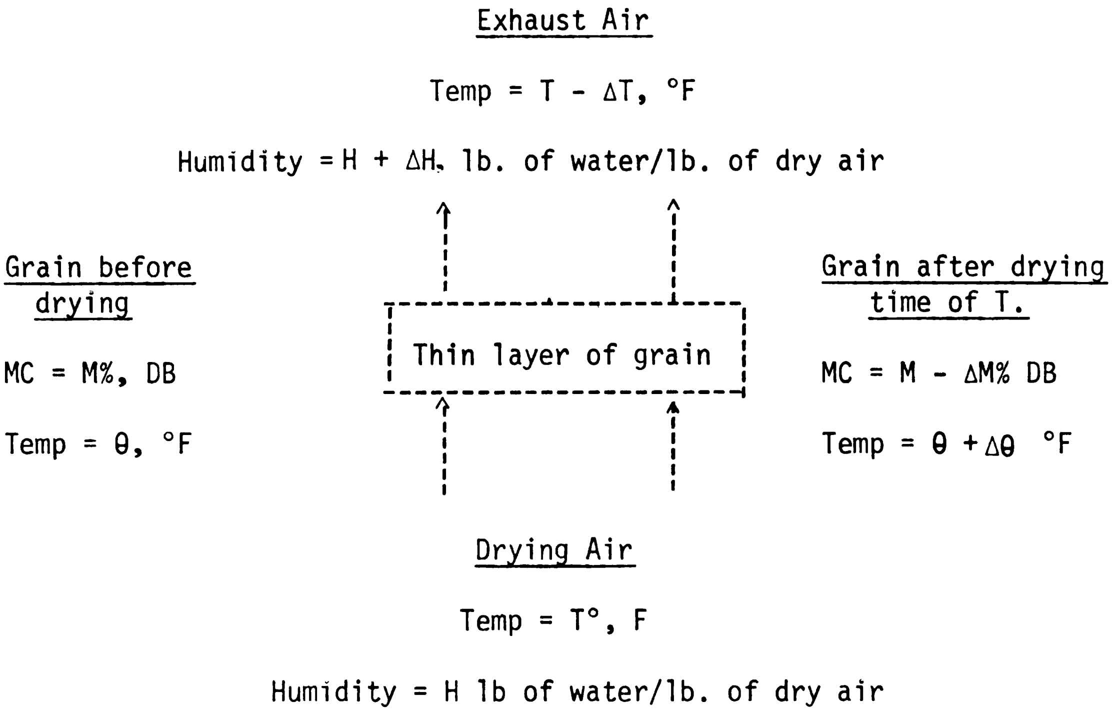
THEORY

Drying is a continuous process with simultaneous changes in grain moisture content, air and grain temperature, and the humidity of the air. In fact, these changes vary for different drying methods and for different locations in the drying bed.

The Michigan State University grain drying simulation model is a set of mathematical expressions which incorporate the factors that affect grain drying. It is capable of determining the effect of all the drying parameters.

The basic idea in describing the drying process was to divide a drying bed into small slices and simulate the heat and moisture transfer in the slices by consecutively calculating the changes that occur during a short increment of time. The drying performance of a thin layer of rice can be calculated and then combined into many thin layers to form the drying bed.

Drying air (T deg. F, H lb. of water per lb. of dry air) is passed through a thin layer of grain (M per cent moisture, θ deg. F. temperature) for a time interval Δt. During this interval, ΔM per cent moisture is evaporated from the grain into the air increasing its absolute humidity to H + ΔH lb. of water per lb. of dry air. During drying the temperature T of the drying air is decreased (ΔT deg. F.). The amount of drying is calculated with the thin-layer drying equation with constants depending on the drying air temperature. A heat balance is used to calculate the final air and grain temperature consistent with the evaporation cooling accompanying the moisture evaporation and with the initial temperature of the drying air and grain. Thompson (1968) presented a schematic diagram of the basic simulation approach:



Theoretical Thin-Layer Drying Equations

The transfer of moisture in capillary porous products such as rice can be described by the following mechanisms (Brooker et al. 1974):

(1) Liquid movement due to surface forces (capillary flow).

(2) Liquid movement due to moisture concentration differences (Liquid diffusion).

(3) Liquid movement due to diffusion of moisture on the pore surface (Surface diffusion).

(4) Vapor movement due to moisture concentration differences (Vapor diffusion).

(5) Vapor movement due to temperature differences (Thermal diffusion).

(6) Water and vapor movement due to total pressure differences (Hydrodynamic flow).

Lykov and his co-workers in the Soviet Union (1966) developed the following model for describing the drying of capillary porous products based on the physical mechanisms listed above:

$$\frac{\partial M}{\partial t} = \nabla^2 K_{11} M + \nabla^2 K_{12} T + \nabla^2 K_{13} P$$

$$\frac{\partial M}{\partial t} = \nabla^2 K_{21} M + \nabla^2 K_{22} T + \nabla^2 K_{23} P$$

$$\frac{\partial M}{\partial t} = \nabla^2 K_{31} M + \nabla^2 K_{32} R + \nabla^2 K_{33} P$$

Where K_{11}, K_{22}, K_{33} are the phenomenological coefficients, the other K values are coupling coefficients.

Neglecting the pressure and temperature gradients in the rice kernel during drying leads to a simplification of Lykov equations. The result becomes (Bakker-Arkema et al. 1974):

$$\frac{\partial M}{\partial t} = \nabla^2 K_{11} M$$

Since moisture flow within a rice kernel usually takes place by diffusion, the above equation is called the diffusion equation and the transfer coefficient K_{11}, the diffusion coefficient D.

Several solutions of the equation have been developed to predict the thin-layer dryer behavior of grain, but due to their stability and accuracy problem in the numerical solution, the Michigan State University grain drying model is based on empirical thin-layer relationships rather than diffusion type equations.

A main objective of this study is to identify a thin-layer equation that predicts satisfactorily the drying behavior of rice. Chancellor's semi-theoretical thin layer equation for rice was chosen (Chancellor, 1967).

Fixed Bed Model

The Michigan State University fixed bed model is applicable to the stationary bed drying of cereal grain and is based on the previous ideas by Schumann (1929), Van Arsdel (1956), and Klapp (1961).

The following assumptions were made in the development of this model (Bakker-Arkema et al. 1974):

(1) No appreciable volume shrinkage occurs during the drying process.

(2) No temperature gradient exists within each grain particle.

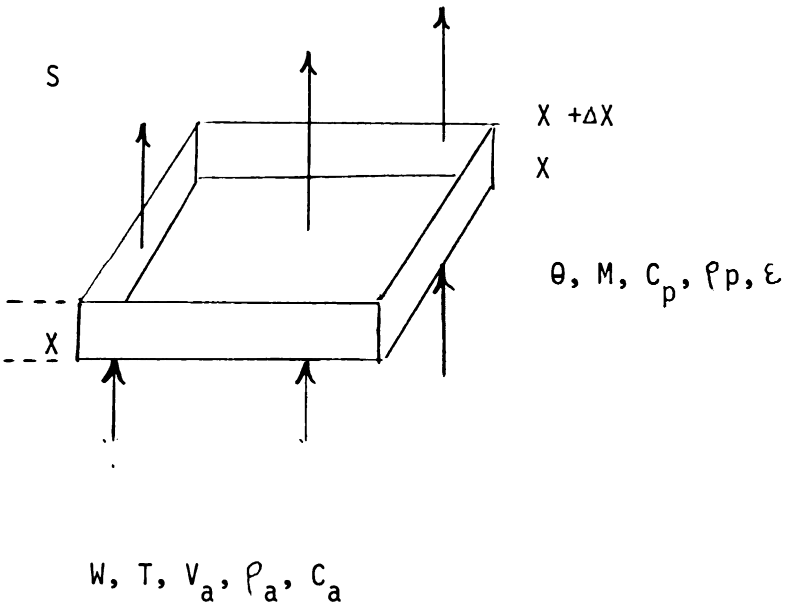
(3) Particle-to-particle heat conduction is negligible.

(4) Airflow is plug type.

(5) Bin walls are adiabatic with negligible heat capacity.

(6) $\partial T / \partial t$ and $\partial H / \partial t$ are negligible compared to $\partial T / \partial X$ and $\partial H / \partial X$.

Energy and mass balances are written on a differential volume (SdX) located at an arbitrary location in the fixed grain bed.



There are four unknowns in this problem : $\overline{M}$ the average grain kernel moisture content, H the Humidity ratio of the air, T the air temperature and θ the kernel temperature. Four balances are made resulting in four equations (Bakker-Arkema et al. 1974):

(1) For the enthalpy of the air:

Energy out = Energy in - Energy transferred by convection

$$(G_aC_a + G_aC_vH) \quad (T + \frac{\partial T}{\partial X} dX) \; Sdt = (G_aC_a + G_aC_aH) \; STdt$$

$$- haSdx(T - \theta)dt$$

or:

$$\frac{\partial T}{\partial X} = \frac{-ha}{G_aC_a + G_aC_vH} (T - \theta)$$

(2) For the enthalpy of product

Energy transferred = Change in internal product energy +

energy for evaporation

$$haSdX \; (T - \theta) = (\rho_pC_p + \rho_pC_wM) \quad SdX \frac{\partial \theta}{\partial t} dt +$$

$$\left[h_{fg} + C_v(T - \theta) \quad G_a \frac{\partial H}{\partial x} dXSdt \right]$$

or:

$$\frac{\partial \theta}{\partial t} = \frac{ha}{\rho \; C_p + \rho_pC_wM} (T - \theta) - \frac{h_{fg} + C_v(T - \theta)}{\rho_pC_p + \rho_pC_wM} G_a \frac{\partial H}{\partial X}$$

(3) For the humidity of air:

$$\rho_pSdX \frac{\partial M}{\partial t} = G_aSHdt - G_aS(H + \frac{\partial H}{\partial X} dX) \; dt$$

or:

$$\frac{\partial H}{\partial X} = \frac{-\rho_p}{G_a} \quad \frac{\partial M}{\partial t}$$

(4) For the moisture content:

$\frac{\partial M}{\partial t}$ = An appropriate thin-layer equation. In this study, Chancellor's thin-layer equation for rice.

Modification of the Michigan State University Model

Though the simulation model can be used for all cereal grains, it was designed for corn. To make a rice version of the model requires changes that will take account for the differences between the two grains. Fortunately the model has that provision (Bakker-Arkema et al., 1974).

The following changes are needed:

[1] A new subroutine for the thin-layer drying of rice. This subroutine called LAYEQ computes the amount of drying that occurs during a discrete time interval. The Chancellor equation provides that prediction. Fig. 1 shows a listing of the LAYEQ subroutine. The solution for this equation is as follows:

(1) Call subroutine CREADY to compute the equilibrium moisture content, moisture ratio and check for absorption. (Fig. 2)

```
SUBROUTINE  LAYEQ                                    CDC 6600 FTN V3.0-P380 OPT=1  12/11/75 .01.00.46.
               SUBROUTINE LAYEQ                                                         LAYEQ        2
         C******                                                                        LAYEQ        3
         C******                                                                        LAYEQ        5
         C******   DESCRIPTION                                                          LAYEQ        6
         C******        SUBROUTINE TO FIND THE MOISTURE CONTENT BASED ON EQUATION       LAYEQ        7
         C******   BY W. J. CHANCELLOR                                                  CHAN         1
         C******                                                                        LAYEQ        9
         C******   USAGE                                                                LAYEQ       10
         C******        USED IN THE FIXED BED AND CROSSFLOW MODELS WITH GRAIN           LAYEQ       11
         C******   TEMPERATURES GREATER THAN 160 F                                      LAYEQ       12
         C******                                                                        LAYEQ       13
               COMMON /MAIN/XMC,TH,RH,DELT,CFM,XMO,KAB                                  LAYEQ       14
               COMMON /NAME/INAME,IPROD                                                 LAYEQ       15
               COMMON/LEL/XXX                                                           CHAN         2
               EXTERNAL CHAN                                                            CHAN         3
               DATA A,B/0.0,15.0/                                                       CHAN         4
               DATA INAME,IPROD/10HCHANCELLOR,10H RICE      /                           CHAN         5
               CALL CREADY(TXMO,DELM,XME,IOOPS,XMR)                                     CHAN         6
               IF(ICOPS-1)1,2,1                                                         CHAN         7
             1 B=200.                                                                   CHAN         8
               A=0.0                                                                    CHAN         9
               XXX=XMR                                                                  CHAN        10
               CALL ZEROIN(A,B,.0001,CHAN)                                              CHAN        11
               TT=(A+B)/2.0+DELT                                                        CHAN        12
               G=-9960.*EXP(-6147./(TH+460.))*TI                                        CHAN        13
               XMP= .735*(EXP(G)+.25*EXP(4.*G)+.1111*EXP(9.*G))                         CHAN        14
               XMC=DELM*XMR+XME                                                         CHAN        15
               RETURN                                                                   CHAN        16
             2 KAB=KAB+1                                                                CHAN        17
               DIV=-.625*PSDB(TH+459.69)**(.466*RH)*RH*RH*RH                            CHAN        18
               XMC=(XMC-XME)*EXP(DIV*DELT)+XME                                          CHAN        19
               RETURN                                                                   CHAN        20
               END                                                                      CHAN        21


                FUNCTION CHAN(TI)                                                        CHAN       22
                COMMON/MAIN/XMC,TH,RH,DELT,CFM,XMO,KAB                                   CHAN       23
                COMMON/LEL/XXX                                                           CHAN       24
                G=-9960.*EXP(-6147./(TH+460.))*TI                                        CHAN       25
                CHAN=XXX-.735*(EXP(G)+.25*EXP(4.*G)+.1111*EXP(9.0*G))                    CHAN       26
                RETURN                                                                   CHAN       27
                END                                                                      CHAN       28
```

Fig. 1 Subroutine LAYEQ.

```
SUBROUTINE  CREADY                                   CDC 6600 FTN V3.0-P380 OPT=1  12/11/75 .01.00.46.      PAGE      1
                SUBROUTINE CREADY (TXMO,DELM,XME,IOOPS,XMR)                                        CHAN       37
                COMMON/MAIN/XMC,TH,RH,DELT,CFM,XMO,KAB                                             CHAN       38
                XME=CMC(RH,TH)                                                                     CHAN       39
                IOOPS=0                                                                            CHAN       40
                IF(XME-XMC)2,1,1                                                                   CHAN       41
              1 IOOPS=1                                                                            CHAN       42
              2 IF(XMO-XMC)3,4,4                                                                   CHAN       43
              3 TXMO=XMC                                                                           CHAN       44
                GO TO 5                                                                            CHAN       45
              4 TXMO=XMO                                                                           CHAN       46
              5 DELM=TXMO-XME                                                                      CHAN       47
                XMR=(XMC-XME)/DELM                                                                 CHAN       48
                RETURN                                                                             CHAN       49
                END                                                                                CHAN       50
```

Fig. 2 Subroutine CREADY

(2) Check absorption flag; if it is not set, compute the equivalent time, add the time increment and compute the new moisture content.

(3) Use the Del-Guidice equation to simulate absorption if the absorption flag is set.

In the drying process, the conditions at a particular position change with each time step. Each set of new conditions specifies a new drying curve. The amount of drying must be transferred to the new curve before solving for moisture content at the end of the current time step. This correction is made by solving the thin-layer equation for time using the current moisture content. This is referred to as the equivalent drying time (Thompson 1967).

The Chancellor equation in its original form cannot be solved for time, so the root finding technique is employed using the subroutine ZEROIN, which is available in the Fortran Psychrometric package (SYCHART).

[2] A function subprogram for the equilibrium moisture content of rice had to be written. Wratten (1969) extrapolated data obtained by Karon and Adam (1949) by the use of the following equation of Strohman and Yoerger (1967):

$$RH = (e^{ae^{bM}} \ln P_s + Ce^{dM})$$

Where:

RH = Relative humidity, decimal.

M = Moisture content, decimal DB.

P_s = Saturation vapor pressure of water, lb per sq. ft

a, b, c, d = Constants

Though the results obtained by this equation are believed to have small errors (Wratten, 1969), values for the constants are not available.

The Henderson equation for predicting equilibrium moisture content of cereal grains is used. Its general form is:

$$1 - P_v/P_{vs} = \exp\ (-aT_{abs}M^b)$$

Where:

M : Equilibrium moisture content, per cent DB.

P_v/P_{vs} : Relative Humidity, decimal.

a, b : Product constants.

Based on data in the book by Brooker et al. (1974), the values for a and b were calculated to be:

$a = 0.3438 \times 10^{-5}$

$b = 2.377$

The change in equilibrium moisture content with respect to relative humidity is more considerable, so for simplification purposes, a and b were assumed to be independent of temperature.

Henderson's equation with constants for rice as discussed above, was used in subroutine CMC to calculate the equilibrium moisture content at each time step. A listing of function subprogram CMC is shown in Figure 3.

[3] Appropriate values for the physical and thermal properties.

Tables 1 and 2 give the values for rice. Table 3 shows a summary of the physical properties of the bed and drying parameters for use in the rice drying model..

The heat of evaporation, h_{fg}, and properties of the air, are assumed to be the same as in the corn drying model.

The specific surface area which is the area of the rice kernel surfaces per unit bed volume is calculated as follows:

$$Sa = \frac{\text{Total surface area of rice}}{\text{Volume of rice}} = \frac{ft^2}{ft^3} = ft^{-1}$$

```
FUNCTION     CMC                                   CDC 6500 FTN V3.0-P380 OPT=1  12/11/75 .01.00.46.       PAGE       1
                FUNCTION CMC(RH,T)                                                                       CHAN       29
                F1=-0.000003438                                                                          CHAN       30
                F2=2.377                                                                                 CHAN       31
                TABS=T+459.69                                                                            CHAN       32
                IF(RH.GE..9999)RH=.9999                                                                  CHAN       33
                CMC=((ALOG(1.-RH)/( F1*TABS))**(1/F2))/100.                                              CHAN       34
                RETURN                                                                                   CHAN       35
                END                                                                                      CHAN       36
```

Fig. 3 Function Subprogram CMC

```
BLOCK DATA                                        CDC 6500 FTN V3.0-P380 OPT=1  12/11/75 .01.00.46.       PAGE      1
                BLOCKDATA                                                                     CHAN        51
                COMMON/PRPRTY/SA,CA,CP,CV,CW,RP,HFG                                           CHAN        52
                COMMON/PRESS/PATM                                                             CHAN        53
                DATA RP,CP,E,SA/47.67,.632,.41,324./                                          CHAN        54
                DATA CV,CW,HFG /.45,1.,1000./                                                 CHAN        55
                DATA CA,PATM/.242,14.3/                                                       CHAN        56
                END                                                                           CHAN        57
```

TABLE 3. PHYSICAL BED AND DRYING AIR PARAMETER VALUES USED IN THE RICE DRYING MODEL

Parameter	Units	Values	References
a	ft	324	Wratten et al. (1970)
C_a	BTU/lbF	0.242	Threlkel (1970)
C_p	BTU/lbF	0.632	Wratten et al. (1970)
h	BTU/hr ft F	same as in corn model	Bakker Arkema et al. (1974)
h_{fg}	BTU/lb	"	"
P_a	lb/ft	"	"
P_p	lb/ft	47.67	Wratten et al. (1970)
C_v	BTU/lbF	0.45	Threlkel (1970)
C_w	BTU/lbF	1.0	"

Area of one grain : 0.0658 in^2 (Wratten, 1968)

Volume of one grain : $1.152 \times 10^{-3}\ \text{in}^3/\text{grain}$

Weight of one grain :

$$1.152 \times 10^{-3}\ \frac{\text{in}^3}{\text{grain}} \times 85.64\ \frac{\text{lb}}{\text{ft}^3} \times \frac{\text{ft}^3}{1728\ \text{in}^3}$$

$$= 5.71 \times 10^{-5}\ \text{lb/grain}$$

85.64 lb/ft^3 = true density of rice (Wratten 1968).

Number of grain per cubic foot:

$$\frac{40.49\ \text{lb/ft}^3}{5.71 \times 10^{-5}\ \text{lb/grain}} = 7.1 \times 10^5\ \text{grain/ft}^3$$

40.49 lb/ft^3 bulk density.

Surface area :

$$7.1 \times 10^5\ \text{grain/ft}^3 \times 0.0658\ \text{in}^2\text{/grain} \times \text{ft}^2\text{/144 in}^2$$

$$= 324\frac{\text{ft}^2}{\text{ft}^3} = 324\ \text{ft}^{-1}$$

RESULTS AND DISCUSSION

The simulation model describing fixed bed drying of rice consists of four equations and four unknowns. The system can be solved simultaneously by numerical integration using finite difference techniques. An expression required for the equilibrium moisture content of rice has been obtained as discussed earlier. A model of the thermodynamic chart for calculating the humidity and other harmodynamic properties of the drying air, to check for possible condensation is also available.

The four subroutines which form the fixed bed rice dryer model are:

(1) The thin-layer rice drying process (Subroutine LAYEQ);

(2) The equilibrium moisture content (Subroutine CREADY, function subprogram CMC);

(3) The dry air-water vapor relationship (SYCHART package); and

(4) The main MSU fixed bed drying model.

The model will need the following input to provide the desired output:

- Initial moisture content, product temperature, drying air temperature, humidity ratio of the air, and airflow rate (First card);
- Depth of bed, number of nodes between printout and depth increment (Second card);
- Maximum drying time, time increment between printout, and final moisture content (Third card).

The relationship between airflow and depth increment is critical in the fixed bed program and has to be observed strictly to insure stability. If the depth increment is too large with respect to airflow, the equation will diverge or oscillate from the true solution. If too small, the solution requires excessive computer time.

After the rice drying model had been operated properly, a number of runs were made to simulate the drying behavior as described by the thin-layer equation and the equilibrium moisture content equation.

Drying parameters were also investigated using as standard run:

28.2 per cent moisture content, DB (=24% wb)
100 deg. F, drying air temperature

30 CFM per sq. ft. air flow rate

1 ft., bed depth

A complete listing of the output is provided in Figure 4. To test the accuracy of the Chancellor's equation, data obtained from the computer output were plotted against experimental results for the same drying condition.

Figure 5 shows that the fixed bed rice drying simulation model agrees very well with the experimental curve by Soemangat and Esmay for the H_2O removed. It should be noted that the Chancellor thin-layer equation and the Soemangat data were developed from the same variety of rice.

In Figure 2 are plotted drying rate data for IR.8 rice obtained experimentally by Kachru (1970) and calculated by the thin-layer Chancellor equation. A fairly good fit results. The properties for IR.8 variety of rice have not been determined. The values calculated from the equilibrium moisture content equation and the experimental data are plotted in Figure 7. The good fit is due to the fact that both were developed from data obtained by Hogan and Karn (1955).

Typical results of deep bed drying are presented in Figure 8 for a 1 ft bed depth. The lowest curve, representing the bottom of the bed is a typical thin-layer curve, but the curves above this

```
                           M I C H I G A N   S T A T E   U N I V E R S I T Y
                  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 T
                        F I X E D   B E D   D R Y E R   M O D E L
                                         U S I N G   T H E
                           CHANCELLOR THINLAYER EQUATION FOR RICE




                                       INPUT PROPERTIES AND CONDITIONS


R TEMP(DEG F)     PROD TEMP(DEG F)    REL HUM(DECIMAL)     ABS HUM(LB/LB)     DB MC(DECIMAL)    EQUIL MC(DECIMAL)  AIR FLOW RATE(CFM)
 100.0000             40.0000              .1202               .0050              .2820              .0585             30.0000
                                                                                                                   127.7069(LB/HR)

     HEAT CAPACITIES(BTU/LB):                AIR              PRODUCT          WATER VAPOR        WATER LIQUID
                                             .2420             .6320              .4500              1.0000


            H T COEF CONV       ATMOS PRESS        LAT HEAT EVAP     BULK DENS DRY PROD    SPEC SURF AREA
              7.4284              14.3000            1000.0000           47.6700             324.0000




                                             PROGRAM CONTROLS


                SIMULATE A DEPTH OF  1.00 FT BY INCREMENTS OF  .0250 FT PRINTING EVERY  .10 FT
                FOR A TOTAL TIME OF 15.00 HR PRINTING EVERY 1.00 HR
                OR UNTIL THE AVERAGE MC FALLS BELOW .130000
```

Fig. 4 Listing of a sample output

```
DEPTH          .00     .10     .20     .30     .40     .50     .60     .70     .80     .90    1.00

     TIME =   .03                            PERCENT CONDENSATION = 20.00             PERCENT ABSORPTION =   .00
     AVERAGE MC = .2804                 ENERGY INPUT =   19.61         H2O REMOVED =     .08                BTU/LBH2O =  252.88

AIR TEMP  100.000  80.000  80.000  80.000  80.000  80.000  80.000  80.000  80.000  81.343  81.834
PROD TEMP 90.000  80.000  80.000  80.000  80.000  80.000  80.000  80.000  80.000  78.734  78.279
MC DB       .280    .280    .280    .280    .280    .280    .280    .280    .280    .281    .282
REL HUM   .12016  .33762  .44120  .54129  .63819  .73212  .82326  .91177  .99778 1.00000 1.00000
ABS HUM   .00500  .00753  .00988  .01217  .01440  .01657  .01870  .02077  .02280  .02392  .02432

     TIME =  1.02                            PERCENT CONDENSATION =   .59             PERCENT ABSORPTION =   .37
     AVERAGE MC = .2569                 ENERGY INPUT =  634.75         H2O REMOVED =    1.20                BTU/LBH2O =  531.11

AIR TEMP  100.000  93.732  87.794  82.348  77.460  73.199  69.634  66.559  62.848  62.193  62.500
PROD TEMP 98.385  93.702  87.764  82.319  77.434  73.175  69.583  66.540  62.829  62.193  62.503
MC DB       .227    .236    .245    .251    .256    .260    .264    .266    .268    .269    .269
REL HUM   .12016  .18791  .27197  .37112  .48275  .60188  .72142  .83620  .97213  .99136  .98245
ABS HUM   .00500  .00647  .00780  .00896  .00995  .01077  .01144  .01196  .01222  .01218  .01220

     TIME =  2.02                            PERCENT CONDENSATION =   .29             PERCENT ABSORPTION =  1.09
     AVERAGE MC = .2370                 ENERGY INPUT = 1258.42         H2O REMOVED =    2.14                BTU/LBH2O =  586.70

AIR TEMP  100.000  95.717  91.362  87.070  82.938  79.034  75.419  72.151  69.275  66.847  65.000
PROD TEMP 98.923  95.696  91.340  87.048  82.916  79.012  75.399  72.132  69.258  66.833  64.989
MC DB       .194    .204    .215    .224    .232    .240    .246    .252    .257    .262    .266
REL HUM   .12016  .16447  .21896  .28404  .35960  .44499  .53849  .63716  .73686  .83182  .91140
ABS HUM   .00500  .00602  .00702  .00796  .00885  .00965  .01038  .01101  .01156  .01201  .01235

     TIME =  3.01                            PERCENT CONDENSATION =   .19             PERCENT ABSORPTION =   .71
     AVERAGE MC = .2182                 ENERGY INPUT = 1879.12         H2O REMOVED =    3.04                BTU/LBH2O =  617.65

AIR TEMP  100.000  96.795  93.445  90.024  86.590  83.203  79.916  76.772  73.802  71.043  68.575
PROD TEMP 99.202  96.780  93.428  90.006  86.572  83.184  79.898  76.754  73.785  71.027  68.560
MC DB       .171    .183    .192    .202    .211    .220    .228    .235    .242    .249    .256
REL HUM   .12016  .15254  .19168  .23812  .29243  .35494  .42523  .50308  .58753  .67698  .76720
ABS HUM   .00500  .00577  .00655  .00732  .00808  .00880  .00949  .01014  .01073  .01128  .01176
```

PERCENT ABSORPTION -

```
    TIME =  5.02                                 PERCENT CONDENSATION =   .11                PERCENT ABSORPTION =   .42
    AVERAGE MC = .1858              ENERGY INPUT = 3129.14         H2O REMOVED =    4.59              BTU/LBH2O =  682.11

AIR TEMP  100.000   97.706  95.301  92.809  90.421  87.998  85.519  83.009  80.489  77.972  75.491
PROD TEMP 99.428   97.695  95.289  92.796  90.409  87.985  85.506  82.996  80.475  77.957  75.476
MC DB       .139    .147    .157    .167    .177    .136    .194    .203    .212    .220    .229
REL HUM    .12016  .14143  .16645  .19556  .22798  .26493  .30710  .35489  .40872  .46908  .53582
ABS HUM    .00500  .00550  .00601  .00655  .00709  .00765  .00820  .00875  .00929  .00983  .01035

    TIME =  6.01                                 PERCENT CONDENSATION =   .09                PERCENT ABSORPTION =   .34
    AVERAGE MC = .1724              ENERGY INPUT = 3746.71         H2O REMOVED =    5.22              BTU/LBH2O =  717.28

AIR TEMP  100.000   98.031  95.956  93.794  91.562  89.352  87.182  84.965  82.701  80.409  78.104
PROD TEMP 99.513   98.021  95.946  93.784  91.551  89.341  87.171  84.953  82.688  80.396  78.091
MC DB       .127    .135    .145    .154    .163    .172    .181    .189    .198    .207    .215
REL HUM    .12016  .13799  .15882  .18290  .21052  .24144  .27578  .31460  .35848  .40786  .46307
ABS HUM    .00500  .00541  .00585  .00631  .00679  .00727  .00776  .00825  .00875  .00925  .00974

    TIME =  7.01                                 PERCENT CONDENSATION =   .08                PERCENT ABSORPTION =   .29
    AVERAGE MC = .1604              ENERGY INPUT = 4372.25         H2O REMOVED =    5.80              BTU/LBH2O =  754.46

AIR TEMP  100.000   98.284  96.468  94.568  92.596  90.563  88.478  86.505  84.478  82.402  80.285
PROD TEMP 99.573   98.275  96.459  94.558  92.586  90.552  88.467  86.495  84.467  82.390  80.273
MC DB       .117    .124    .133    .142    .151    .160    .168    .177    .185    .194    .202
REL HUM    .12016  .13533  .15297  .17326  .19643  .22276  .25254  .28476  .32108  .36199  .40793
ABS HUM    .00500  .00535  .00573  .00612  .00654  .00696  .00740  .00784  .00829  .00875  .00921

    TIME =  4.01                                 PERCENT CONDENSATION =   .14                PERCENT ABSORPTION =   .53
    AVERAGE MC = .2011              ENERGY INPUT = 2501.80         H2O REMOVED =    3.86              BTU/LBH2O =  648.54

AIR TEMP  100.000   97.253  94.483  91.748  88.936  86.087  83.229  80.392  77.608  74.891  72.295
PROD TEMP 99.313   97.240  94.469  91.734  88.921  86.072  83.214  80.377  77.593  74.875  72.280
MC DB.      .153    .162    .173    .183    .193    .202    .210    .219    .227    .235    .243
REL HUM    .12016  .14627  .17682  .21192  .25277  .29973  .35329  .41375  .48115  .55564  .63596
ABS HUM    .00500  .00561  .00623  .00687  .00751  .00815  .00877  .00938  .00996  .01052  .01105
```

PERCENT ABSORPTION

```
     TIME =  8.00                                 PERCENT CONDENSATION =    .07                PERCENT ABSORPTION =   .25
     AVERAGE MC = .1499                   ENERGY INPUT = 4930.80          H2O REMOVED =   6.30                    BTU/LBH2O =  792.40

 AIR TEMP  100.000   98.488   96.879   95.188   93.424   91.597   89.714   87.781   85.902   84.011   82.078
 PROD TEMP 99.625    98.481   96.872   95.180   93.415   91.588   89.704   87.771   85.892   84.001   82.067
 MC DB        .109     .115     .124     .132     .141     .149     .157     .165     .174     .182     .191
 REL HUM    .12016   .13321   .14835   .16573   .18553   .20797   .23329   .26177   .29286   .32740   .36609
 ABS HUM    .00500   .00530   .00562   .00597   .00633   .00671   .00710   .00750   .00791   .00833   .00876

     TIME =  9.01                                 PERCENT CONDENSATION =    .06                PERCENT ABSORPTION =   .22
     AVERAGE MC = .1403                   ENERGY INPUT = 5619.14          H2O REMOVED =   6.75                    BTU/LBH2O =  831.91

 AIR TEMP  100.000   98.661   97.228   95.714   94.129   92.478   90.770   89.008   87.196   85.379   83.615
.PROD TEMP 99.669    98.655   97.222   95.707   94.121   92.470   90.761   88.998   87.186   85.369   83.605
 MC DB        .102     .108     .116     .123     .131     .139     .147     .155     .163     .171     .179
 REL HUM    .12016   .13144   .14452   .15952   .17659   .19589   .21763   .24205   .26943   .29974   .33263
 ABS HUM    .00500   .00525   .00553   .00584   .00616   .00649   .00684   .00721   .00758   .00796   .00836

     TIME = 10.01                                 PERCENT CONDENSATION =    .05                PERCENT ABSORPTION =   .20
     AVERAGE MC = .1318                   ENERGY INPUT = 6242.29          H2O REMOVED =   7.16                    BTU/LBH2O =  871.89

 AIR TEMP  100.000   98.808   97.522   96.158   94.722   93.223   91.664   90.050   88.383   86.666   84.904
 PROD TEMP 99.706    98.802   97.516   96.151   94.715   93.215   91.656   90.041   88.375   86.657   84.894
 MC DB        .095     .101     .108     .116     .123     .131     .138     .146     .153     .161     .169
 REL HUM    .12016   .12997   .14138   .15445   .16930   .18608   .20495   .22613   .24985   .27640   .30606
 ABS HUM    .00500   .00522   .00546   .00573   .00601   .00631   .00662   .00695   .00729   .00765   .00801

     TIME = 10.25                                 PERCENT CONDENSATION =    .05                PERCENT ABSORPTION =   .19
     AVERAGE MC = .1298                   ENERGY INPUT = 6397.36          H2O REMOVED =   7.25                    BTU/LBH2O =  881.96

 AIR TEMP  100.000   98.842   97.590   96.259   94.857   93.392   91.867   90.286   88.654   86.969   85.238
 PROD TEMP 99.715    98.836   97.584   96.252   94.851   93.384   91.859   90.278   88.645   86.961   85.229
 MC DB        .094     .100     .107     .114     .121     .129     .136     .143     .151     .159     .167
 REL HUM    .12016   .12964   .14067   .15331   .16768   .18393   .20215   .22262   .24553   .27118   .29982
 ABS HUM    .00500   .00521   .00545   .00570   .00598   .00627   .00657   .00690   .00723   .00757   .00793
```

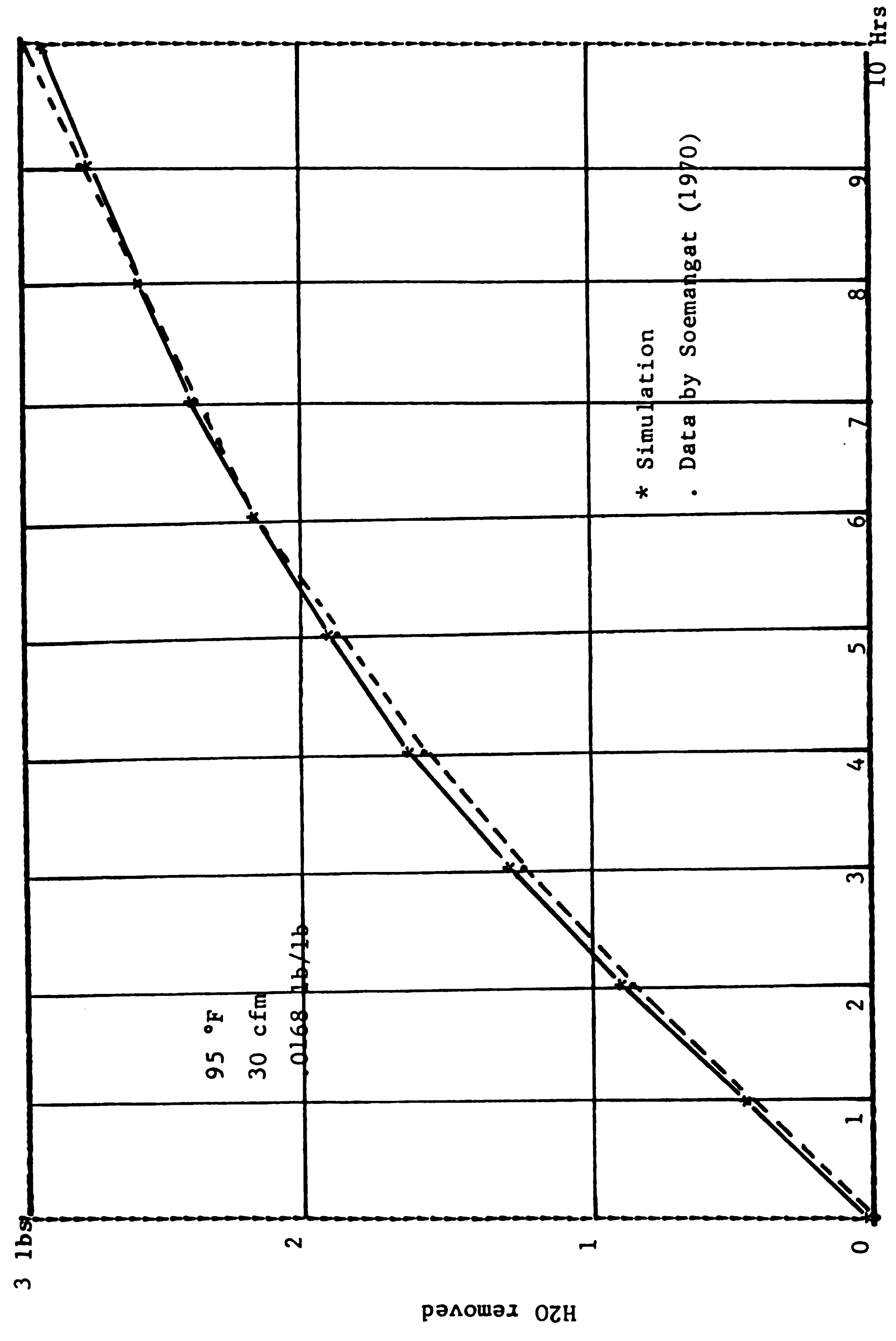


Fig 5. Result of simulation vs experimental data for drying of 1 ft of short grain rice.

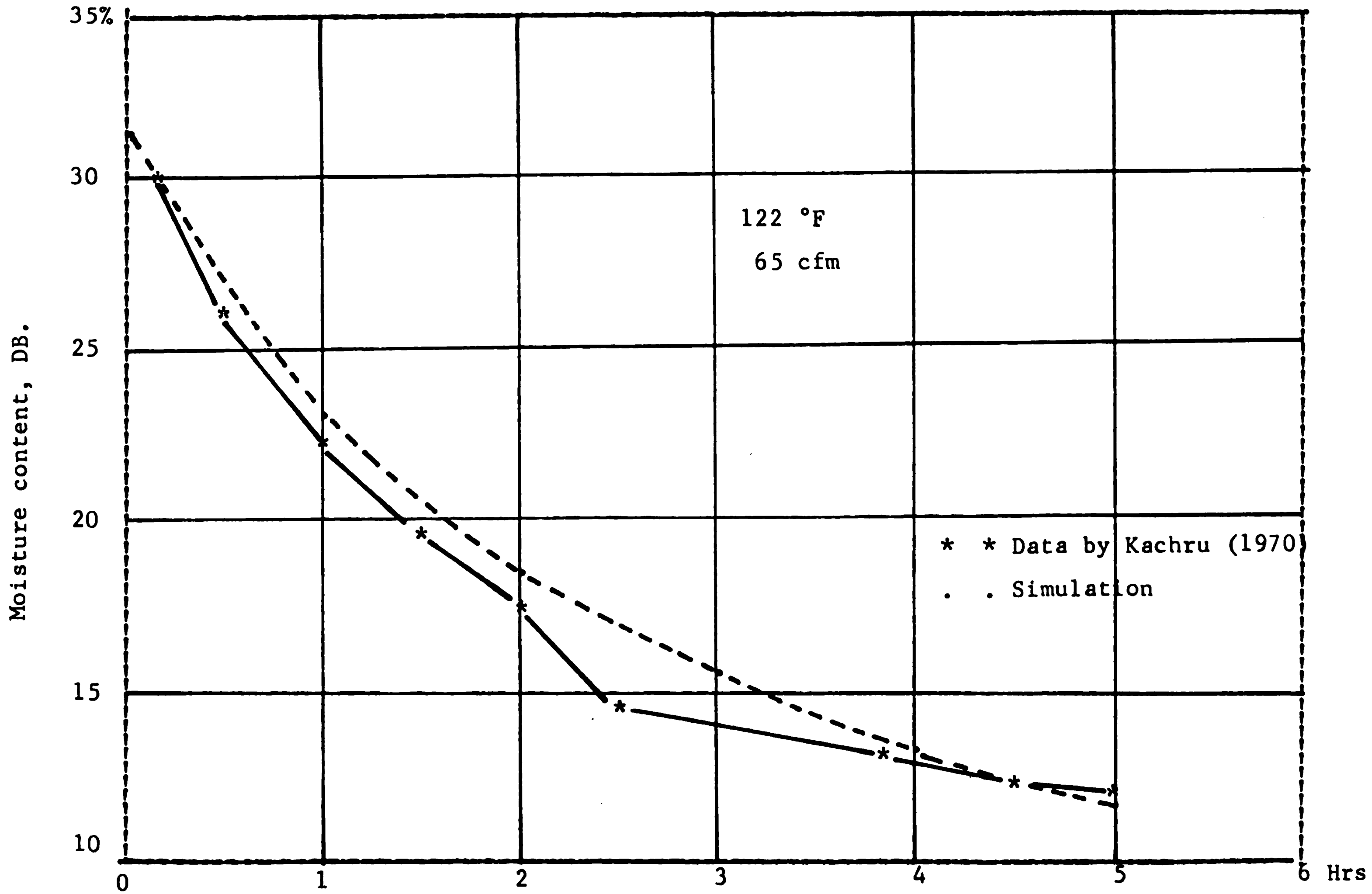


Fig 6. Result of simulation vs experimental data of a thin layer drying of IR 8 rice.

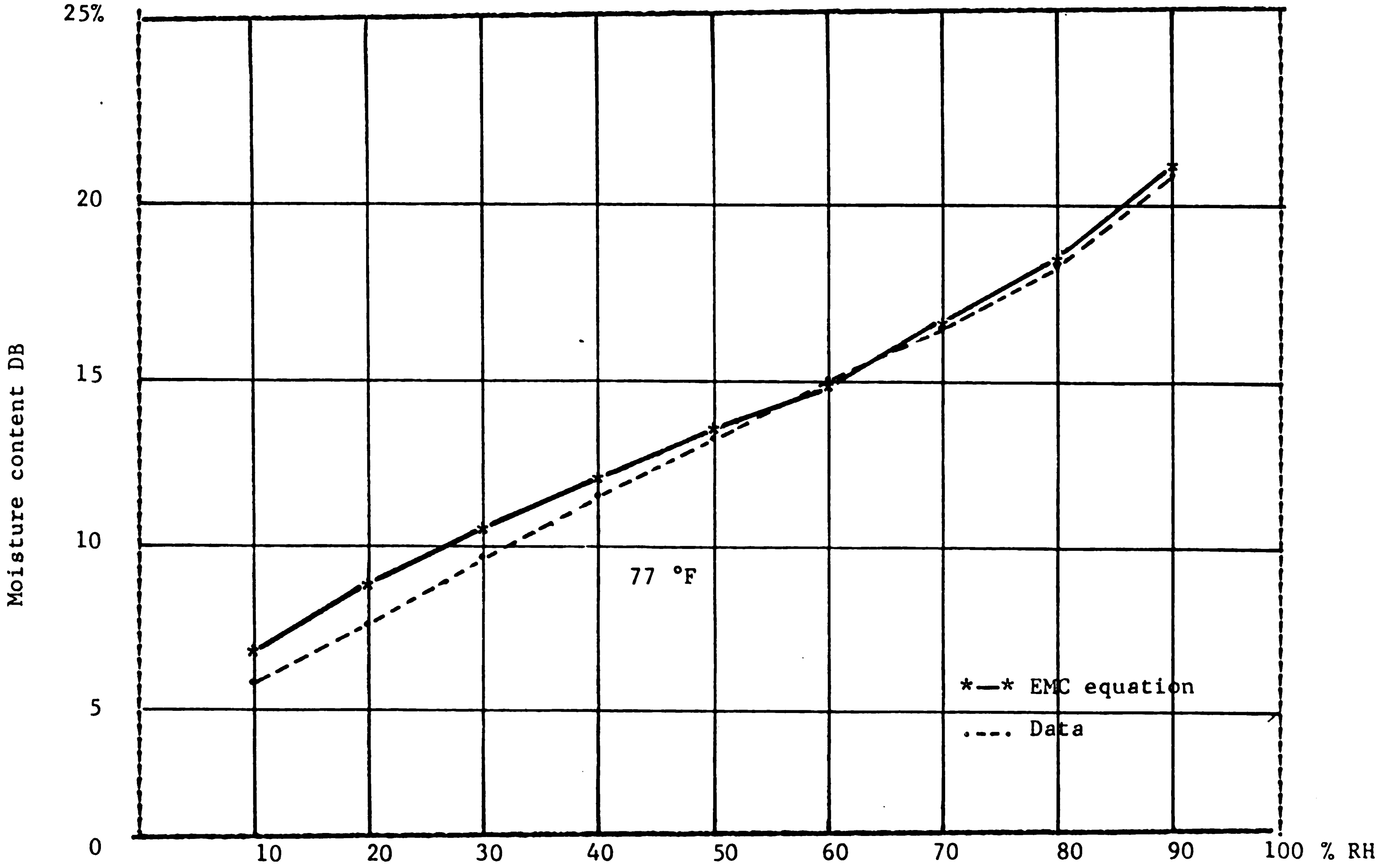


Fig 7. Equilibrium moisture content equation vs data.

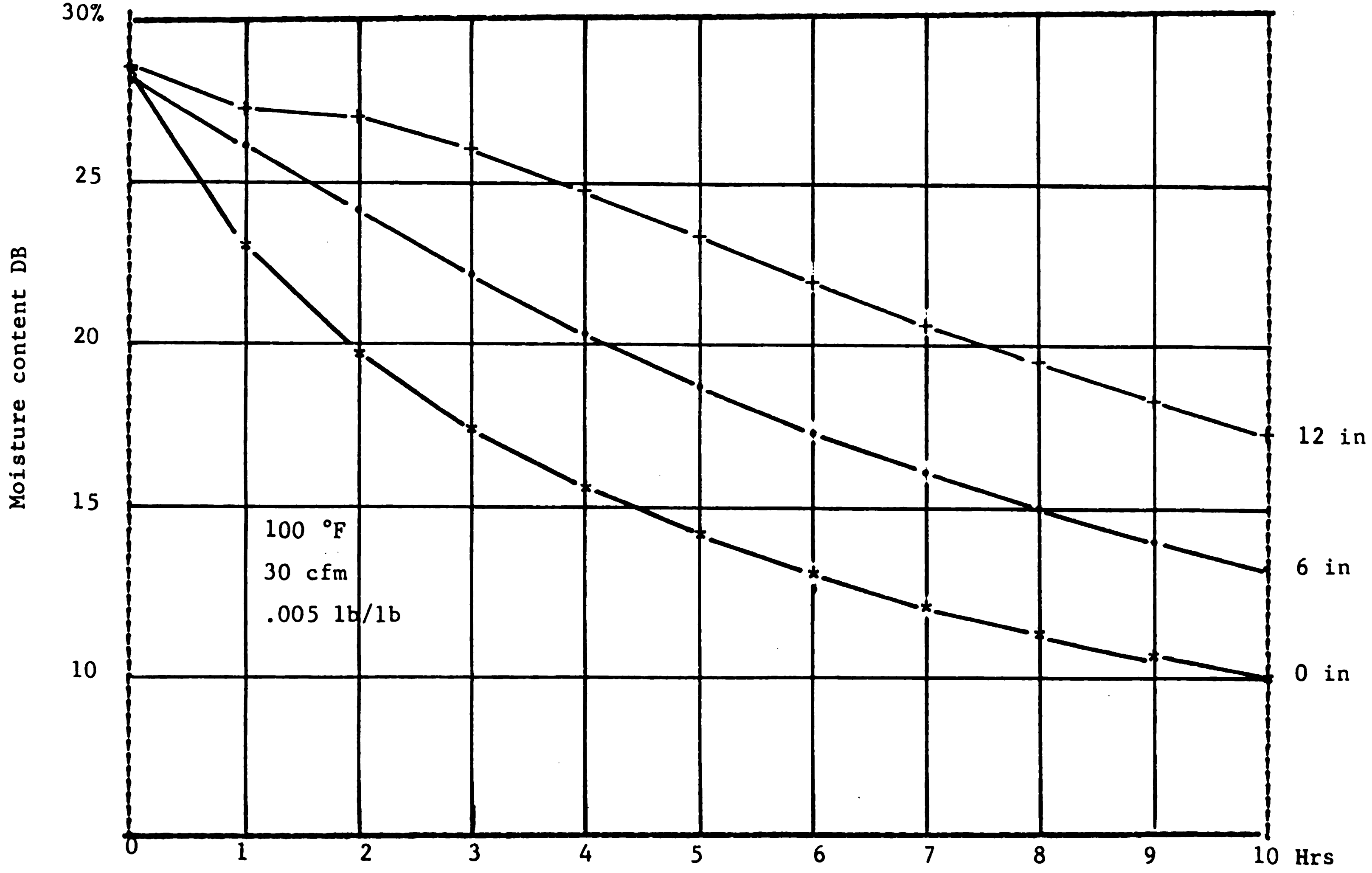


Fig 8. Drying rate in a fixed rice bed at three locations.

exhibit quite distinctive characteristics. It is interesting to note that 2 hours of drying (1 ft bed) have passed before any decrease in moisture takes place in the upper layers. However, it does not mean no drying in the bed occurs since the average moisture content of the grain bed decreases steadily.

Effect of time on moisture content, product temperature and absolute humidity distribution in the bed are shown from Figures 9 through 11.

The complex nature of relative humidity of the drying air in the bed is investigated in Figure 12 (1 ft bed depth). It can be seen that the relative humidity in the bottom of the bed is that of the inlet air while in the upper layers, the relative humidity stays constant for a certain period of time before decreasing.

Figures 13 to Figure 15 show the effect of drying air temperature on drying rate (average moisture content), on moisture content distribution and on rice temperature within the bed.

The effects of airflow on drying rate, on moisture content and on grain temperature are shown in Figures 16 to 18.

The results of the effect of inlet air humidity are plotted on Figure 19; it is clear that higher humidity decreases drying rate.

Figures 20, 21, and 22 investigate the characteristics of a 2 ft bed depth. It can be seen that at higher bed depths drying is more

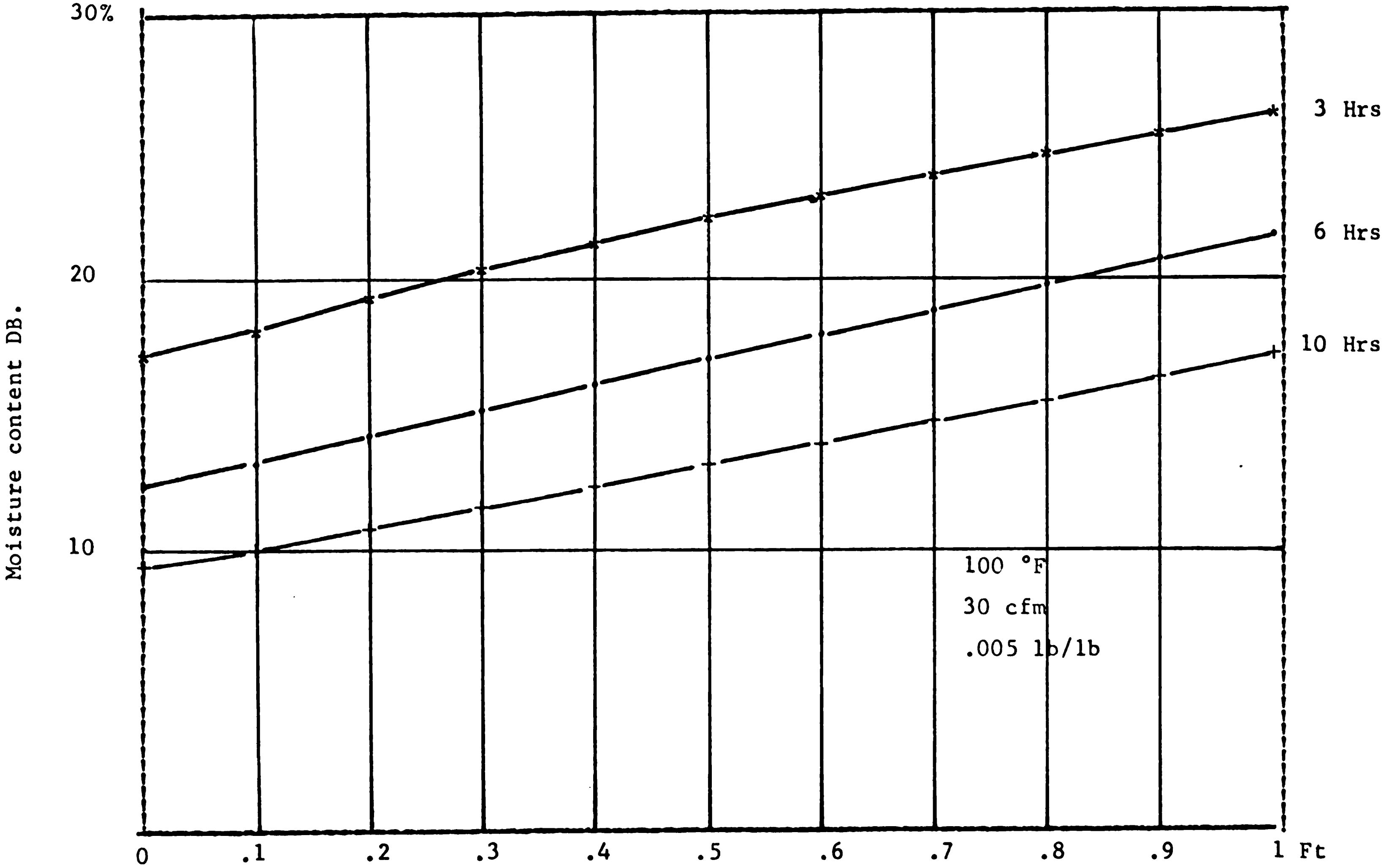


Fig 9. Moisture content vs depth at three time intervals.

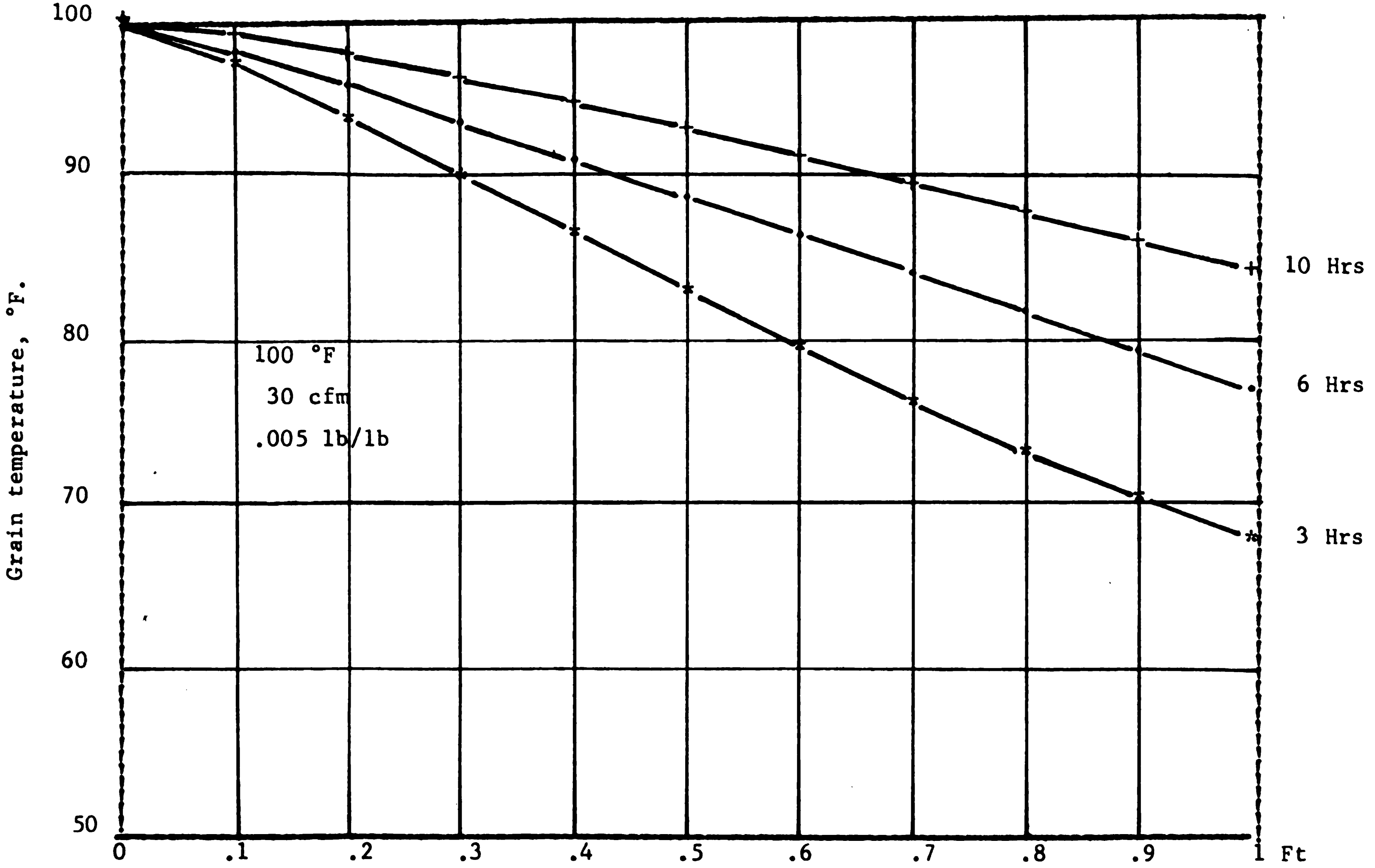


Fig 10. Grain temperature vs depth at three time intervals during fixed bed drying of rice.

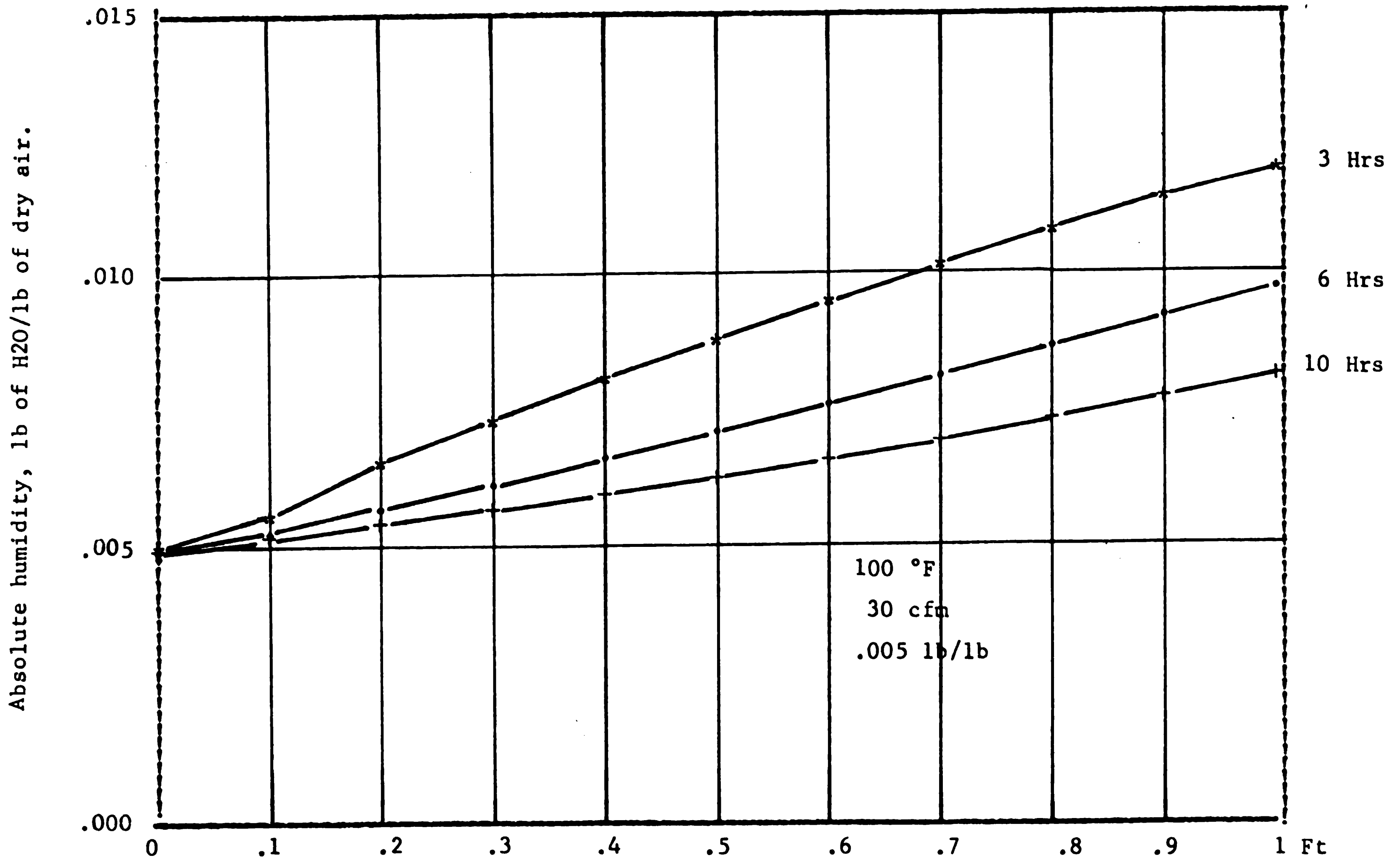


Fig 11. Absolute humidity vs depth at three time intervals during fixed bed drying of rice.

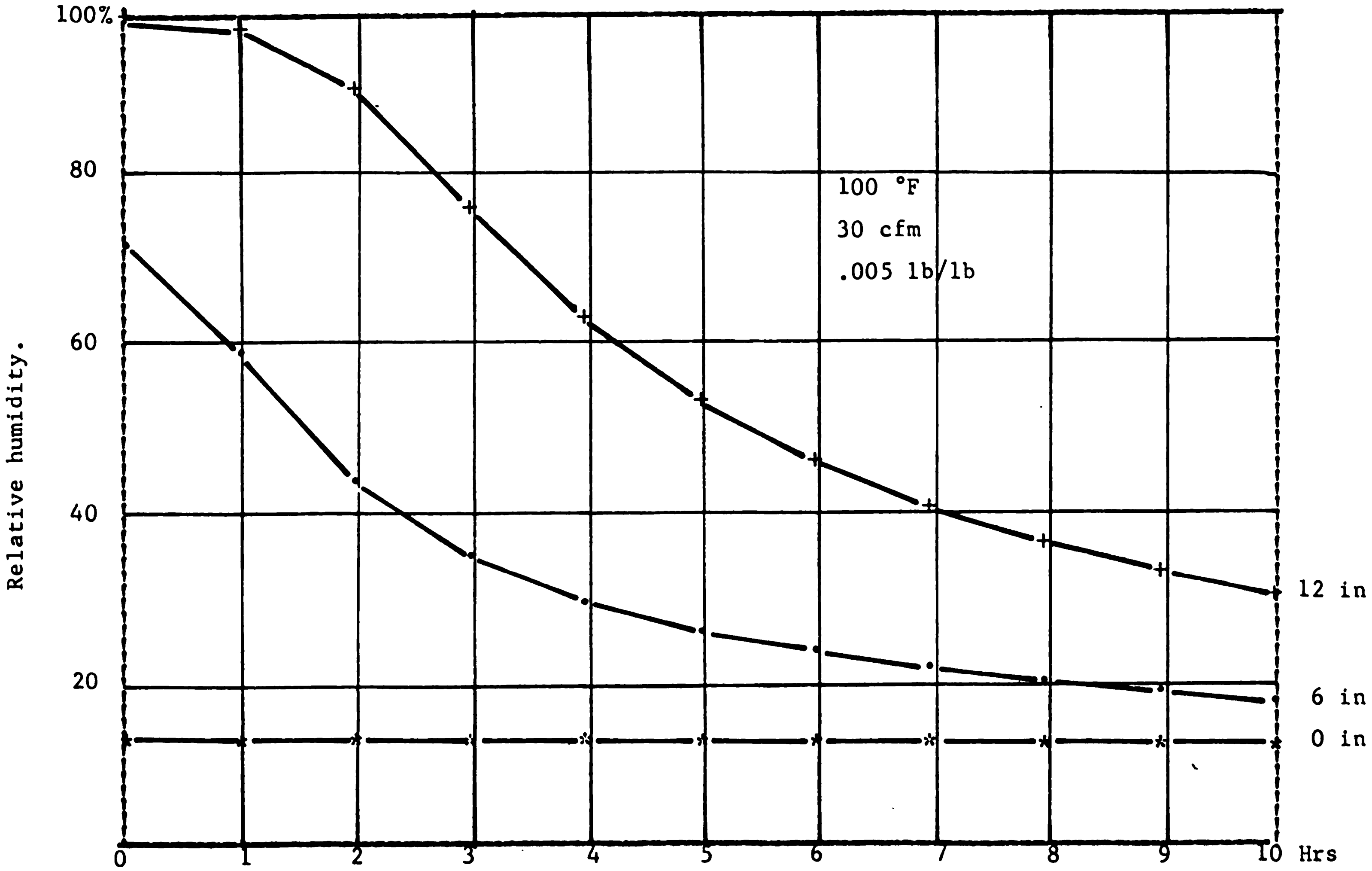


Fig 12. Relative humidity vs time at three locations during fixed bed drying of rice.

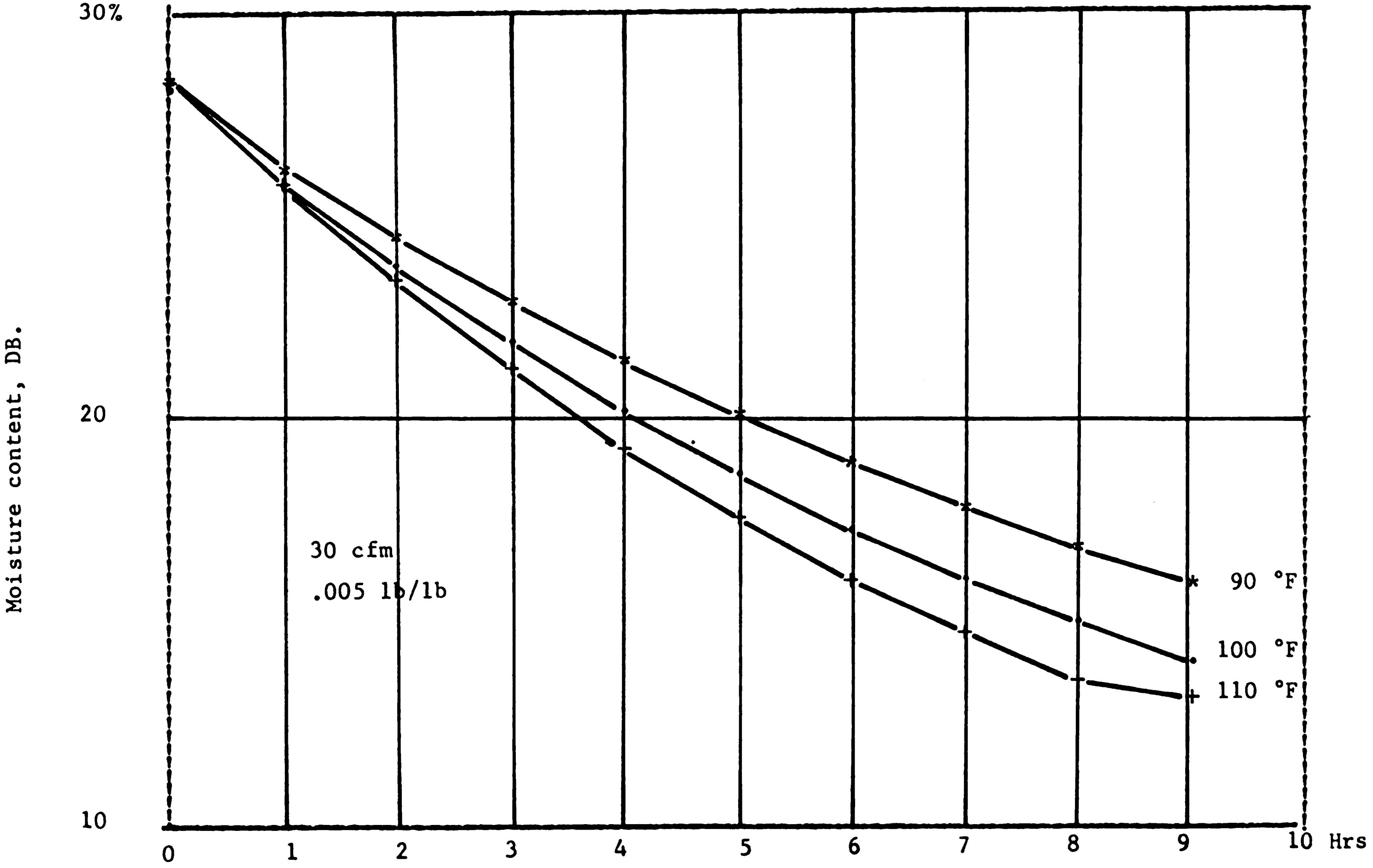


Fig 13. Effect of temperature on drying rate of a fixed bed of rice.

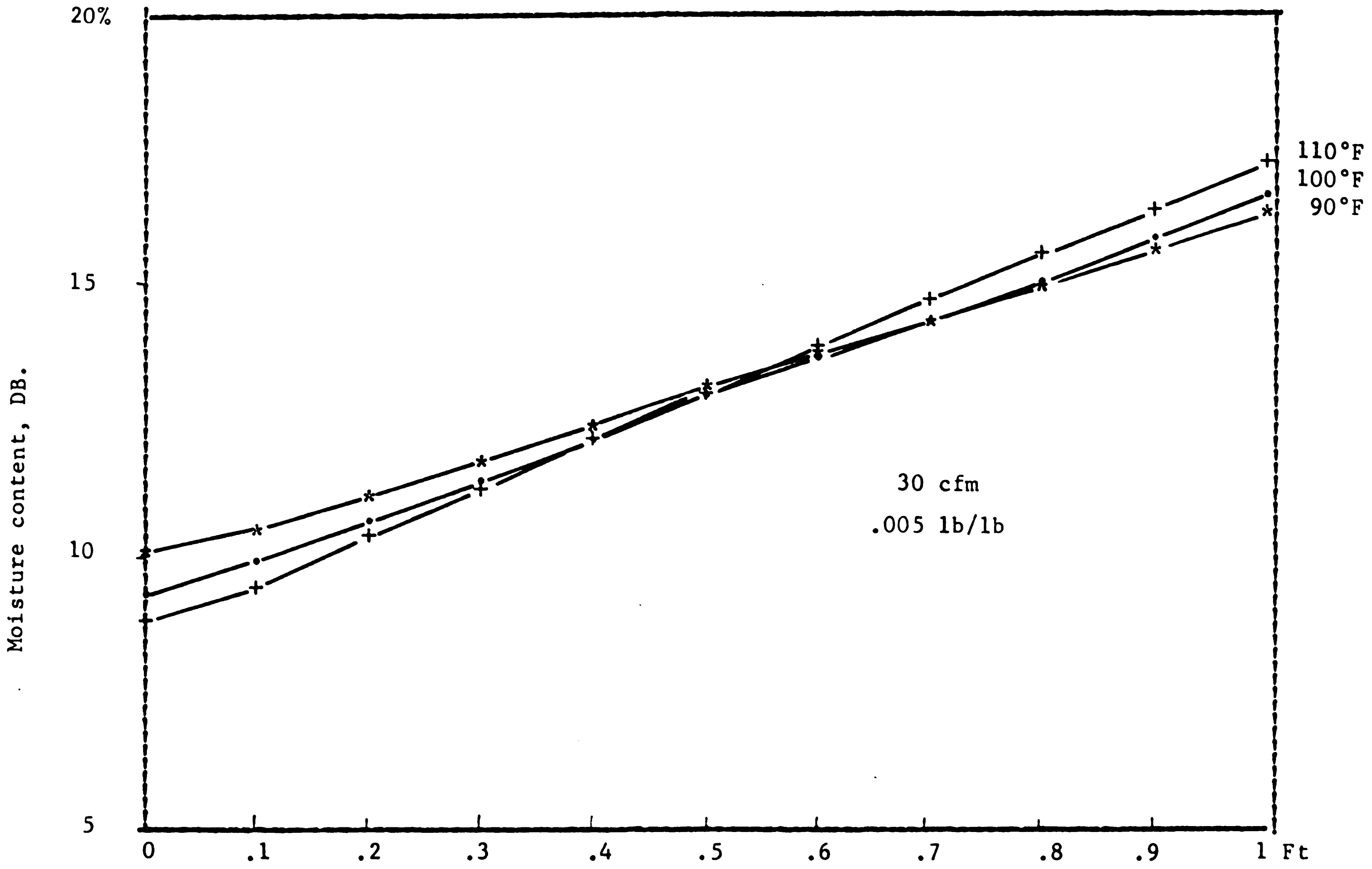


Fig 14. Effect of temperature on moisture gradient during drying of a fixed bed of rice, when MC_{av} first drops below 13%.

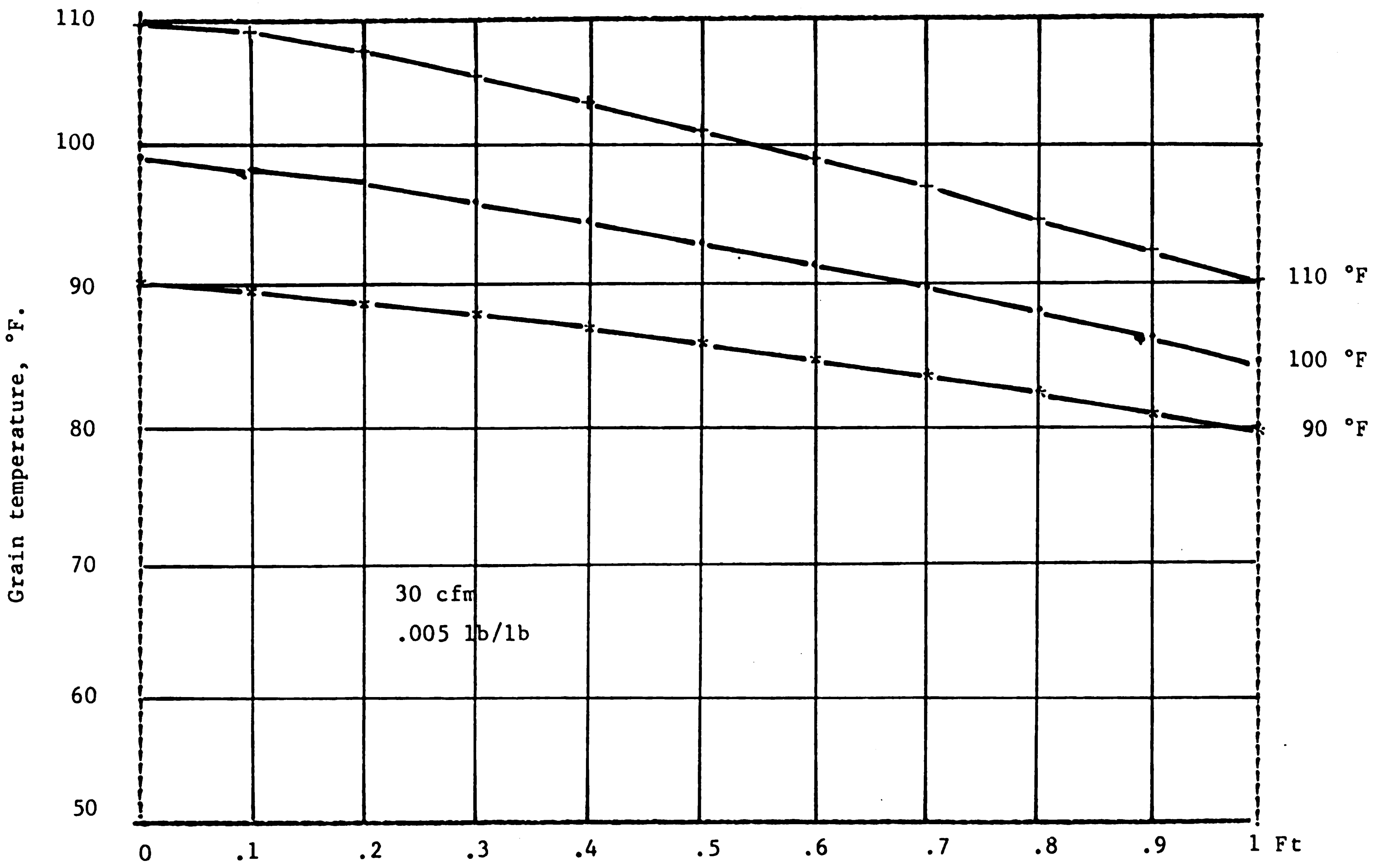


Fig 15. Grain temperature vs depth at three inlet air temperature, when MC_{av} first drops below 13%.

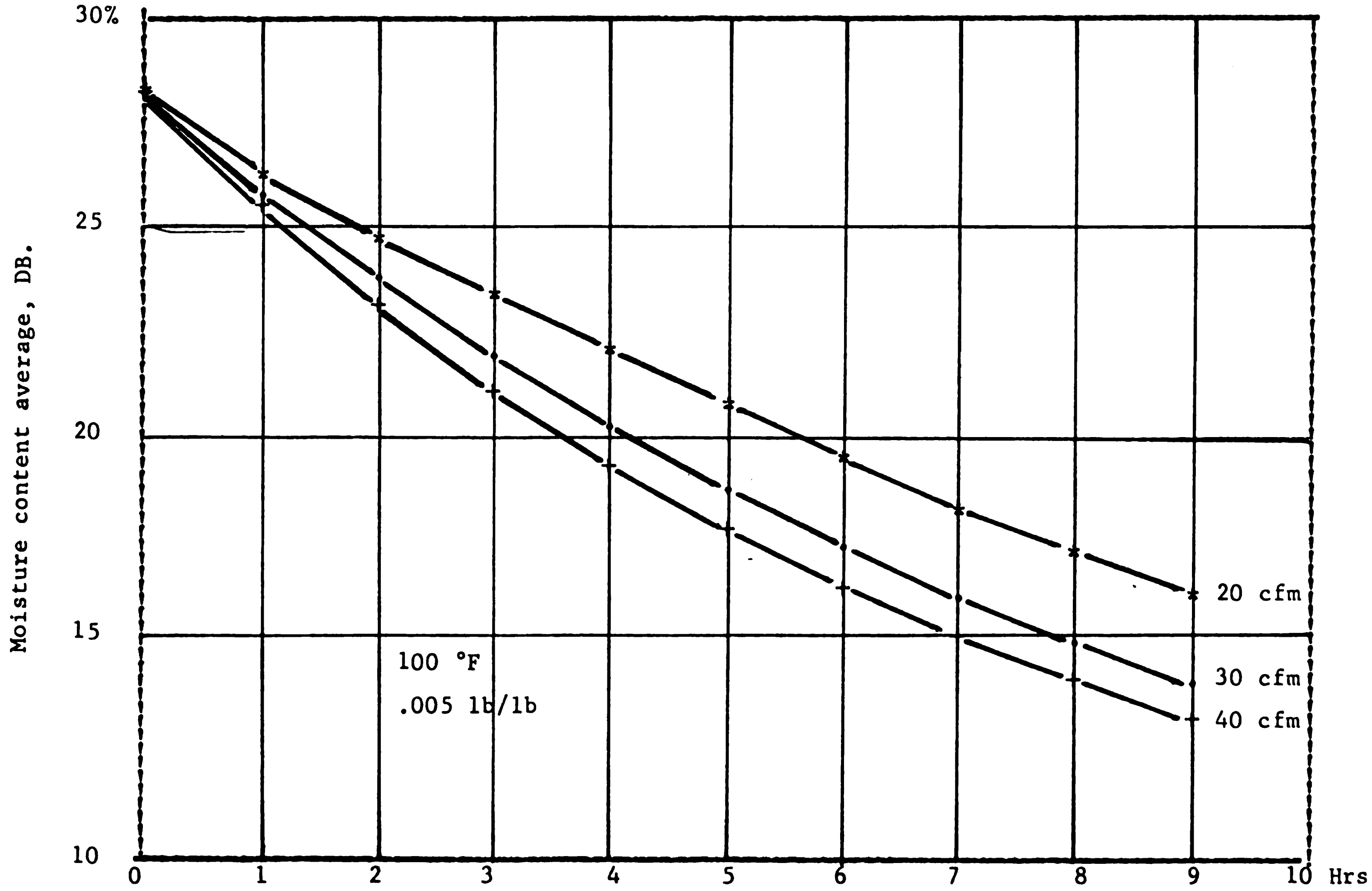


Fig 16. Effect of airflow on drying rate of a fixed bed of rice.

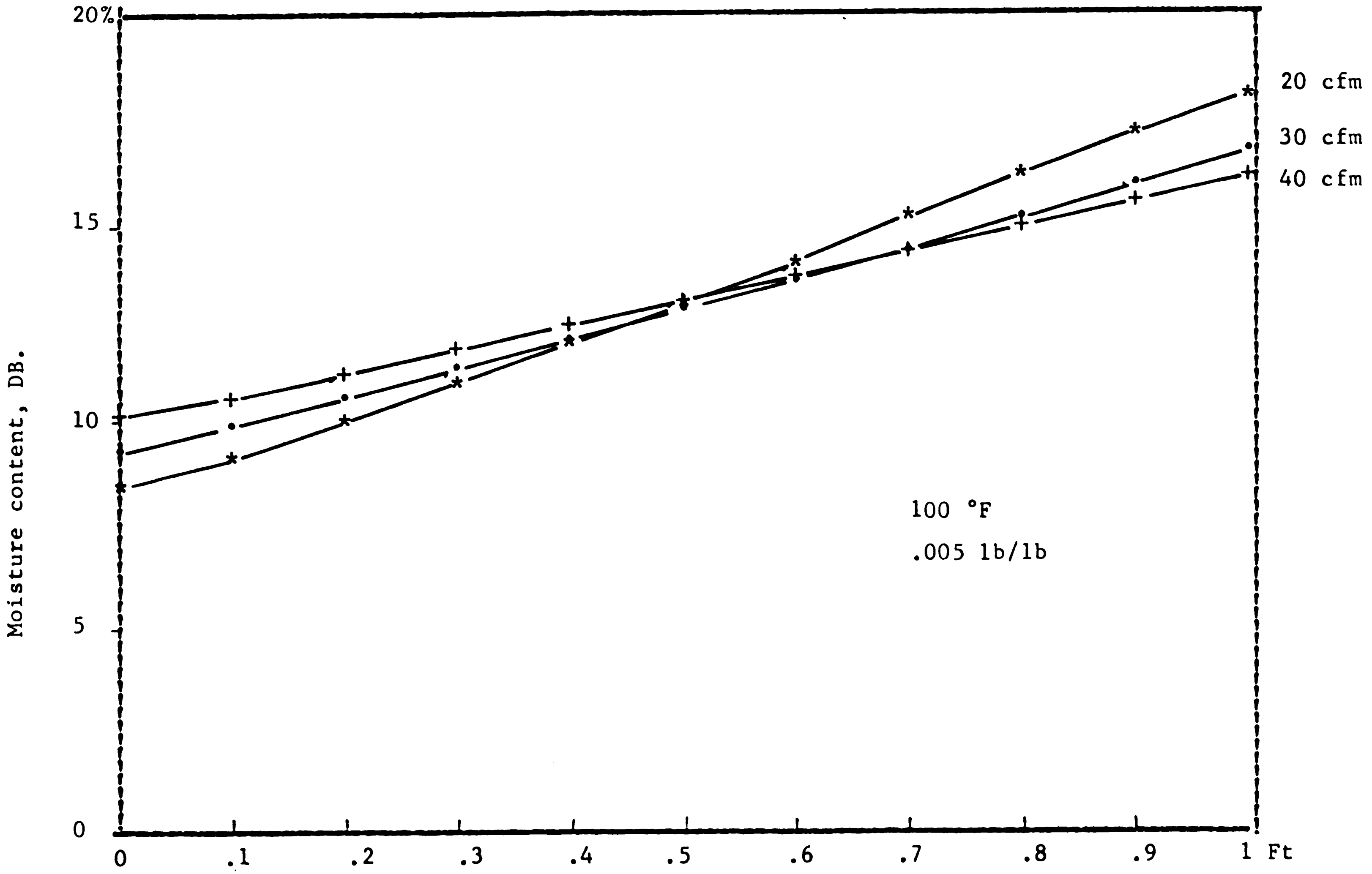


Fig 17. Effect of airflow on moisture gradient during drying of a fixed bed of rice, when MC_{av} first drops below 13%.

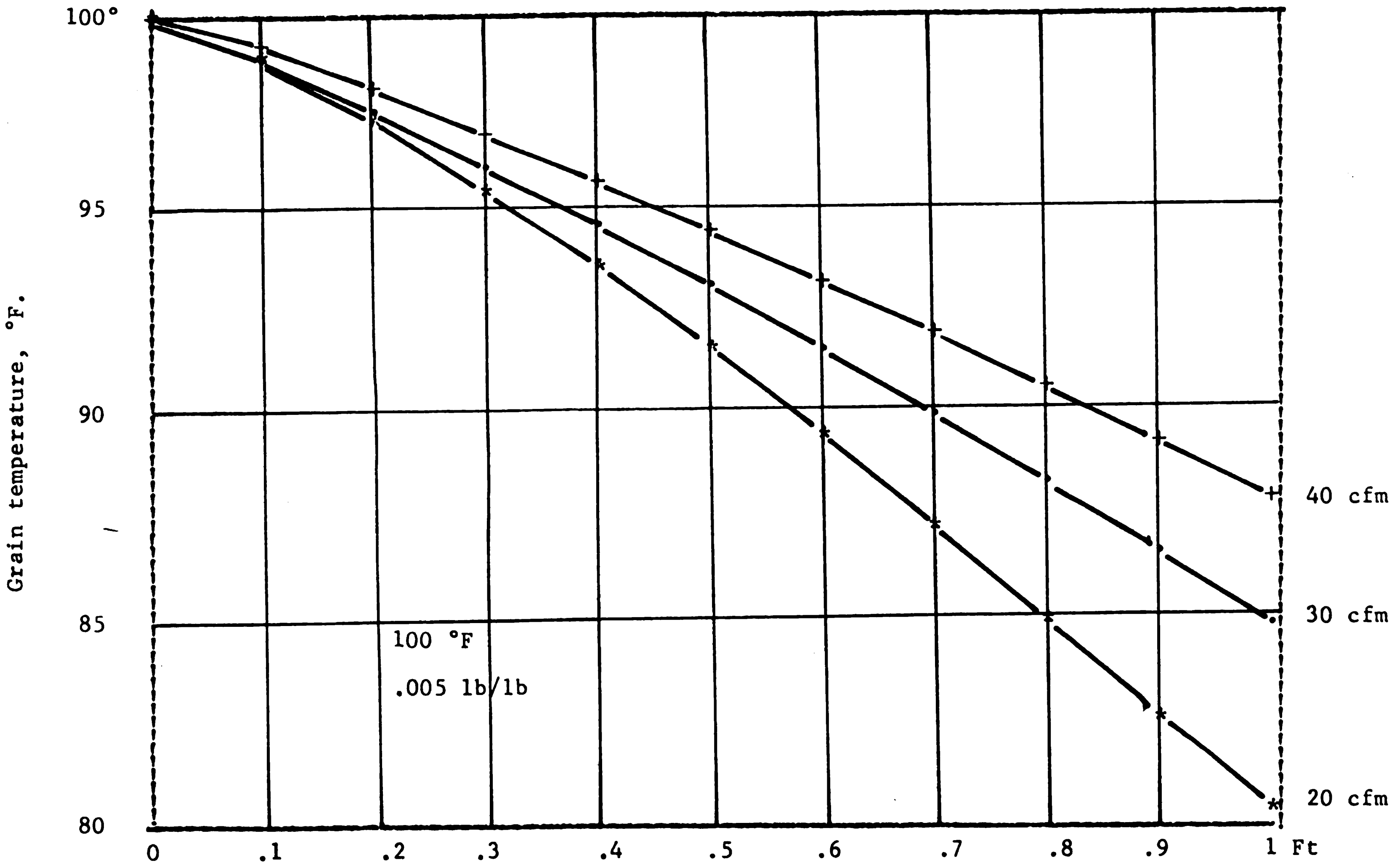


Fig 18. Grain temperature vs depth at three airflow rate, when MC_{av} first drops below 13%.

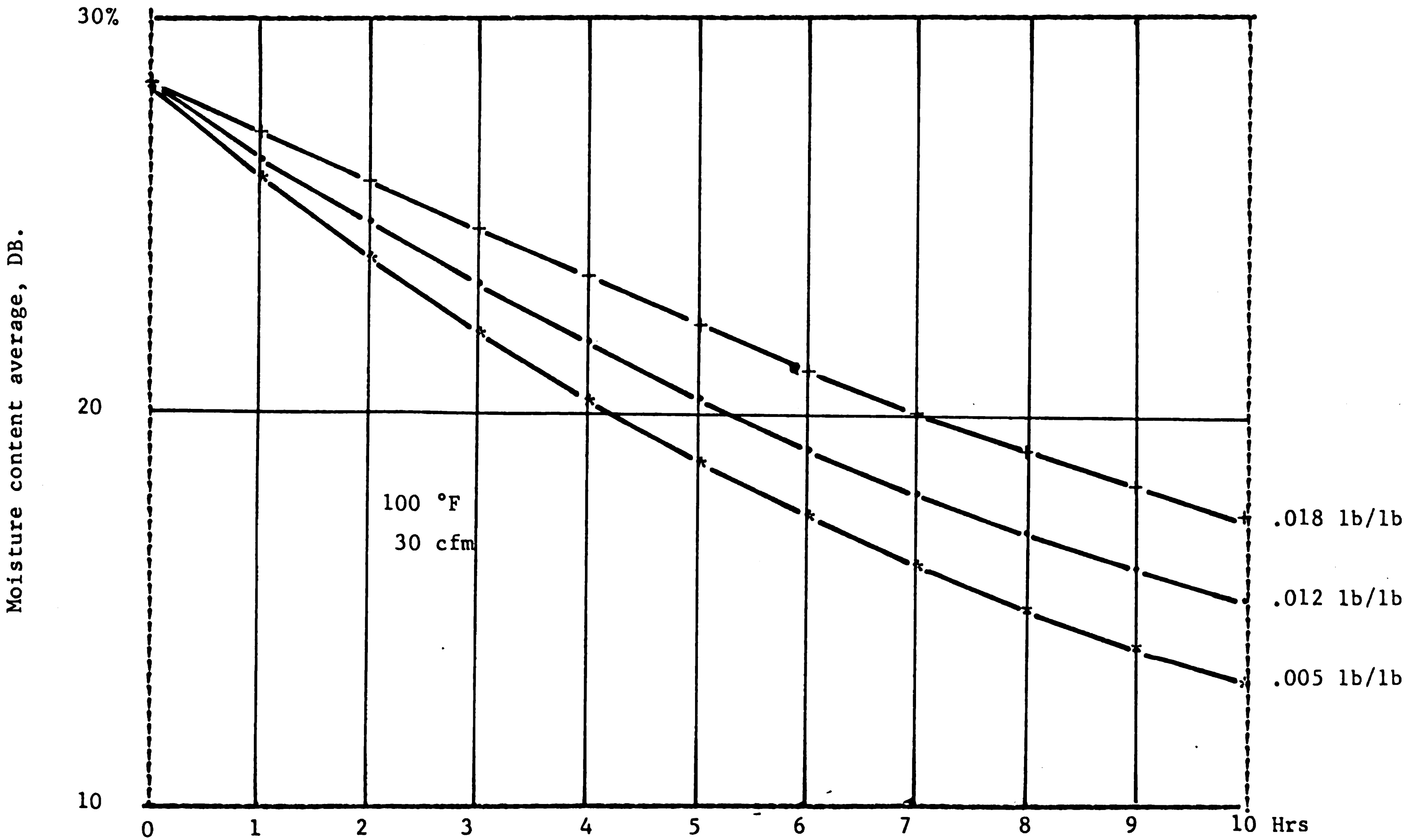


Fig 19. Effect of absolute humidity on drying rate of a fixed bed of rice.

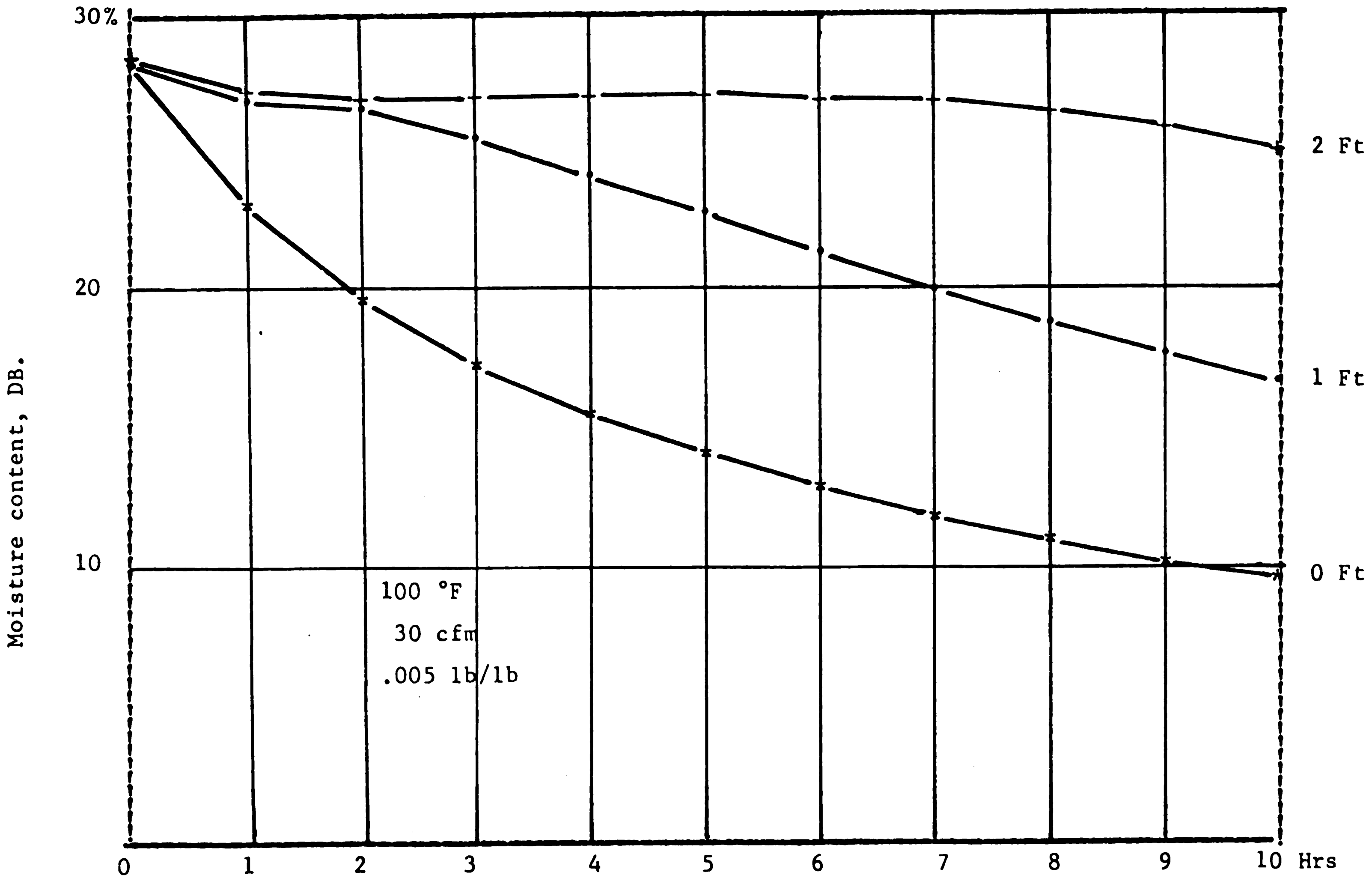


Fig 20. Drying rate in a 2 ft rice depth bed at three locations.

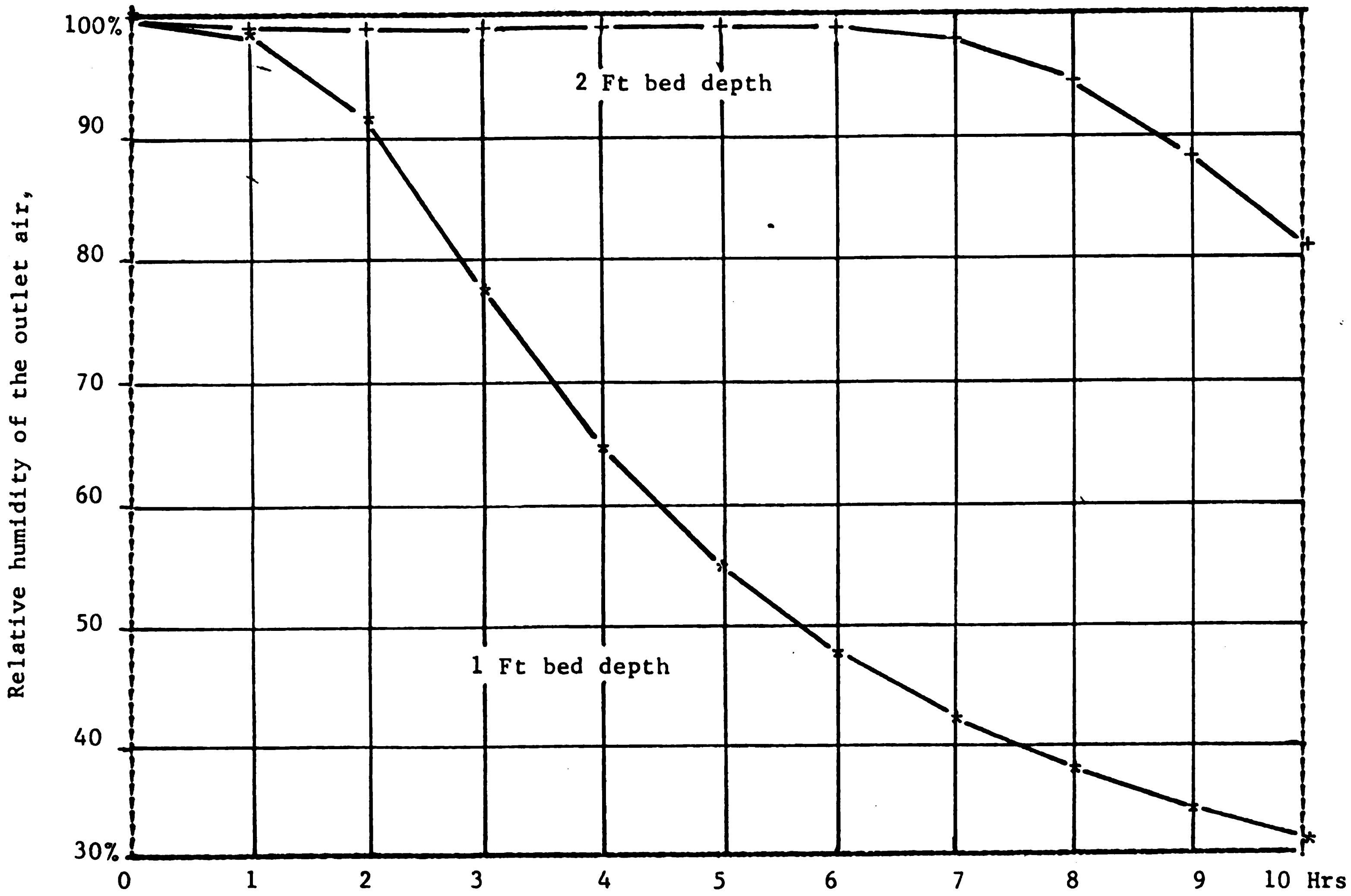


Fig 21. Effect of bed depth on drying efficiency.

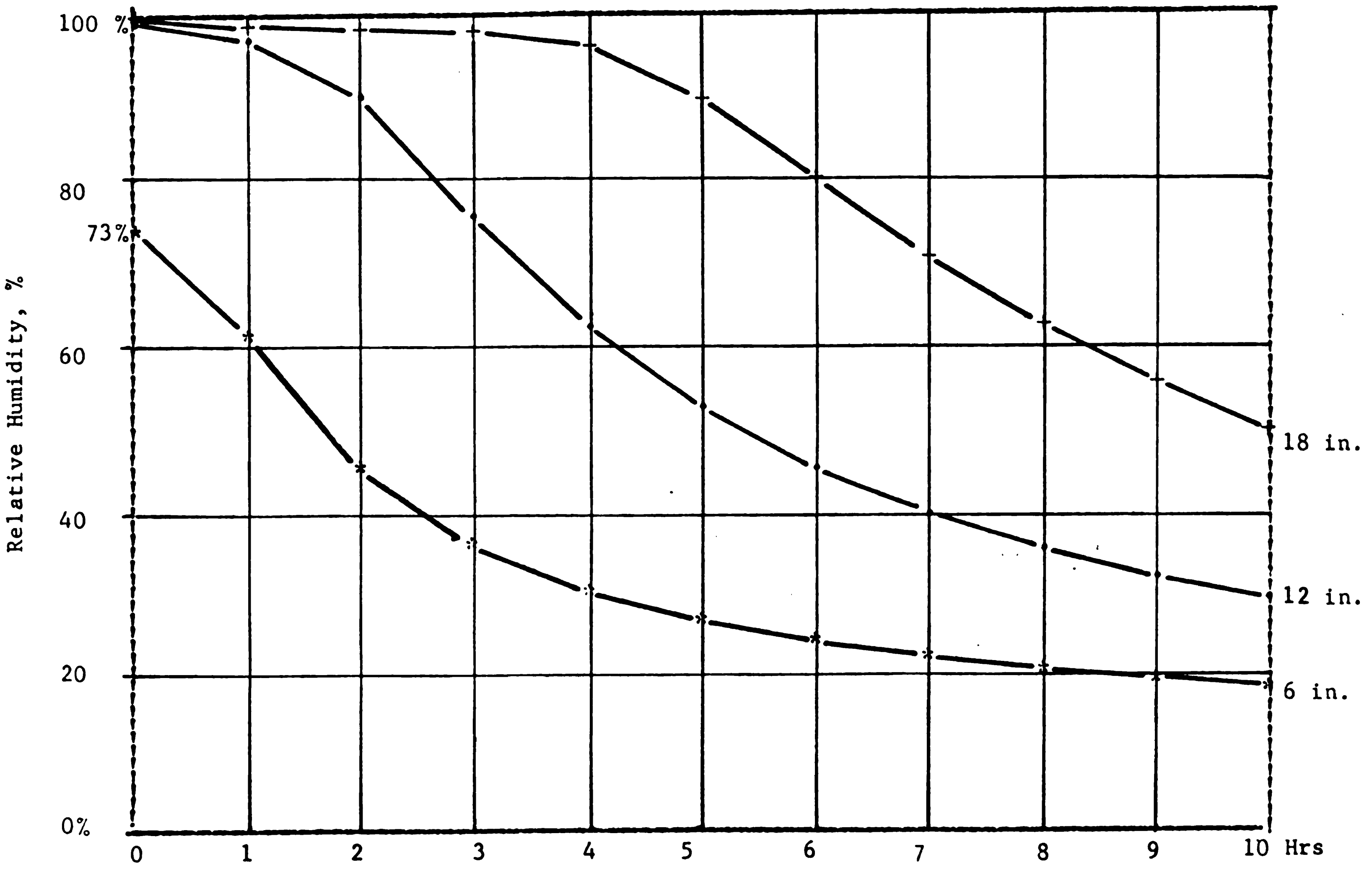


Fig 22. Relative Humidity of air in a 2Ft grain bed.

efficient. Since the relative humidity of the outlet air is higher, more water is removed from the grain.

A number of observations can be made:

(1) An increase in the drying air temperature, increases the drying rate of a rice bed (Figure 13).

(2) The average moisture content decrease of a fixed bed of rice is constant for a certain period of time (Figure 13).

(3) The bottom layer of a fixed bed of rice overdries at high inlet air temperature (Figure 13).

(4) An increase in the airflow rate increases the drying rate (Figure 16).

(5) At higher inlet air temperature (same airflow) or lower airflow (same temperature) the moisture gradient in the bed is higher (Figures 14 and 17).

(6) Relative humidity of the outlet air increases and grain temperature decreases as the depth of bed increases (Figures 12, 21, and 22).

(7) The drying rate decreases as inlet humidity increases (Figure 20).

(8) The effect of specific surface area on drying rate is small (Table 4).

Figure 23 shows the grain temperature distribution within a fixed bed of rice after various drying periods. Figure 24 shows the temperature and relative humidity profile of the drying air in the grain bed. The rice temperature and moisture content distribution are shown in Figure 25.

It would be difficult and time consuming to obtain data required to plot Figures 23 through 25 from physical experiments. A large number of tests would have to be conducted to obtain the necessary data. Simulation, on the other hand, furnishes this information rapidly and at little cost. Of course, simulation results can only be trusted if the mathematical models represent the physical system satisfactorily.

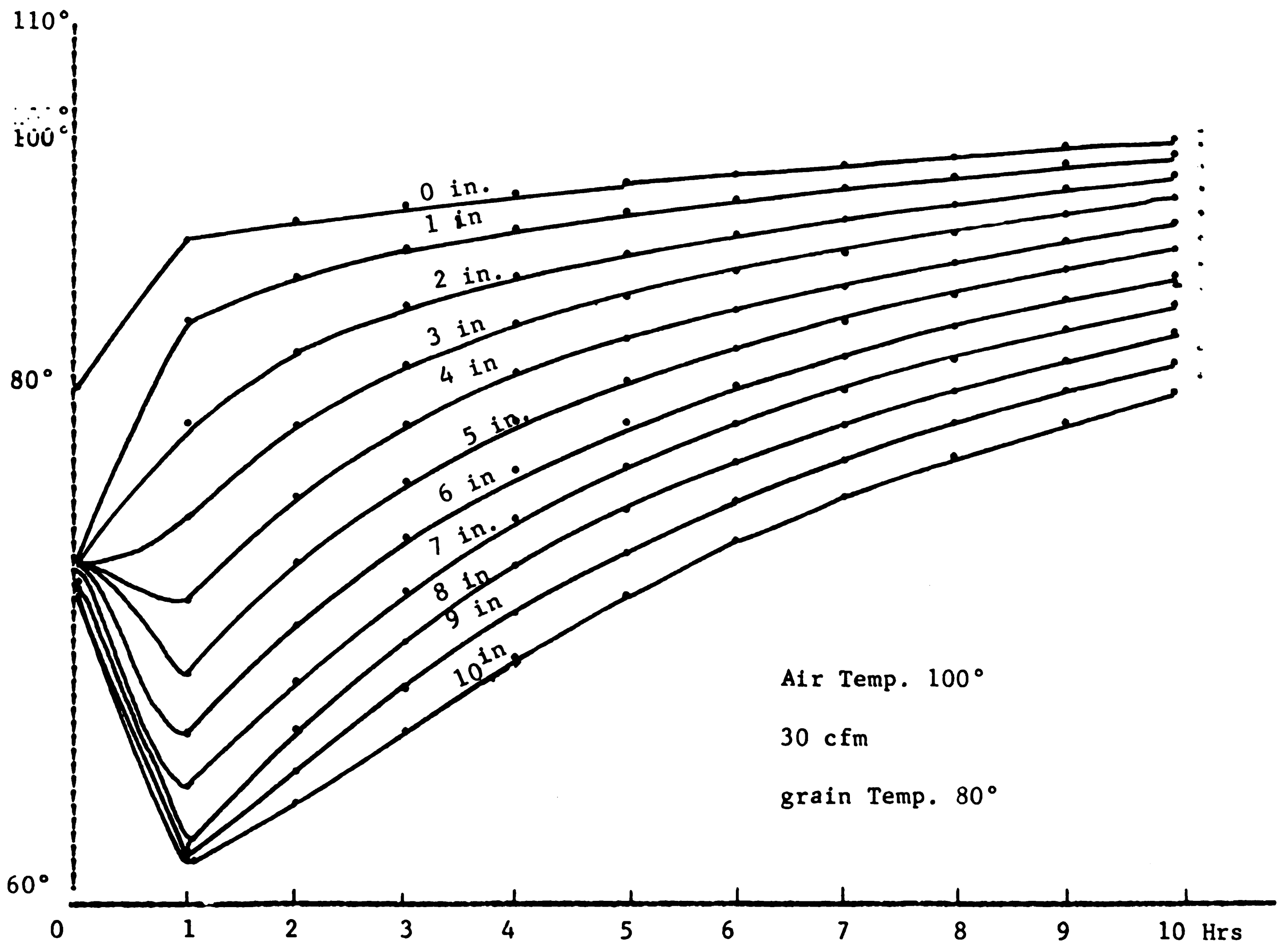


Fig 23. Grain temperature distribution within a fixed bed of rice after various drying periods.

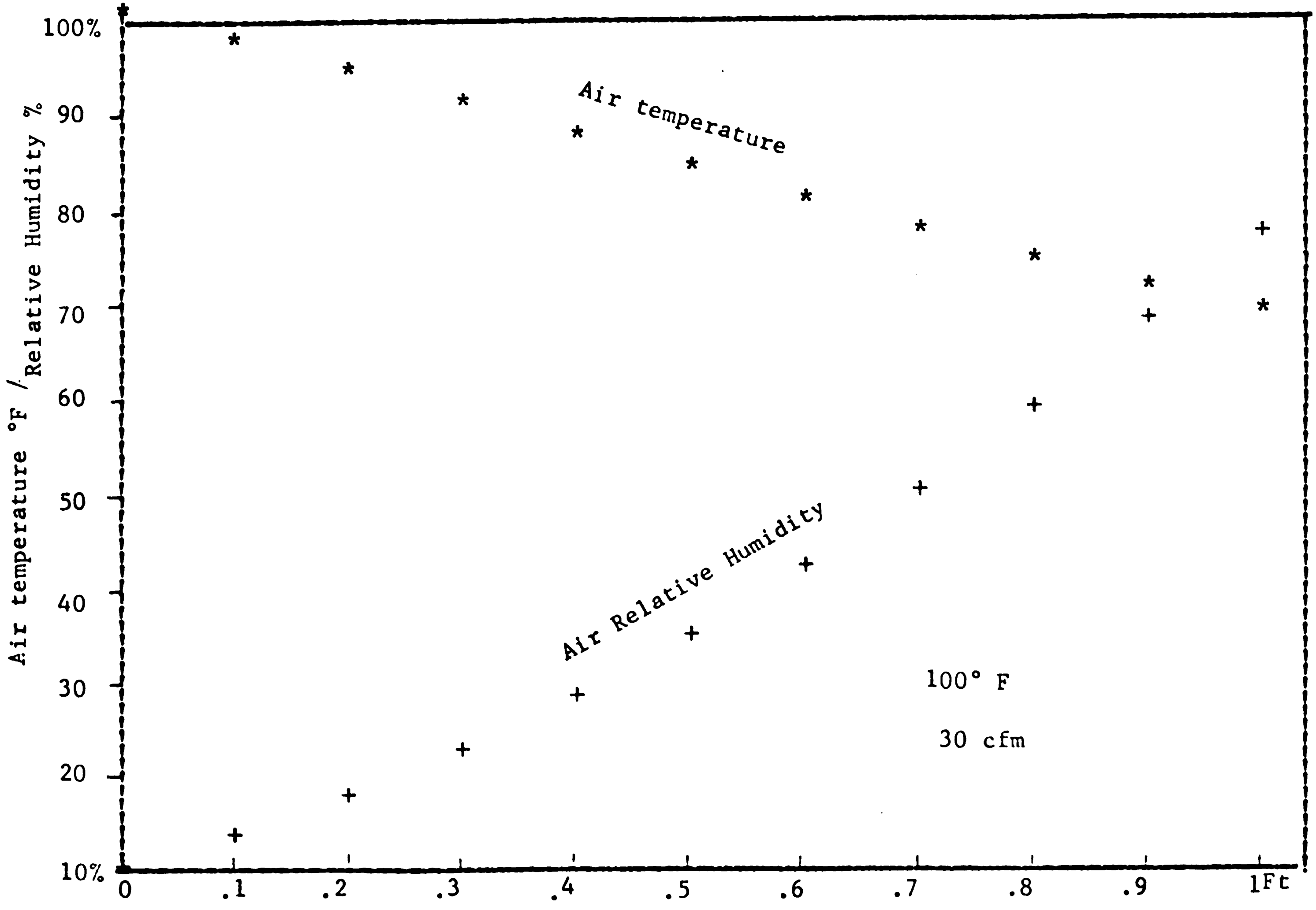


Fig 24. Properties of drying air in a grain bed., after 6 hours.

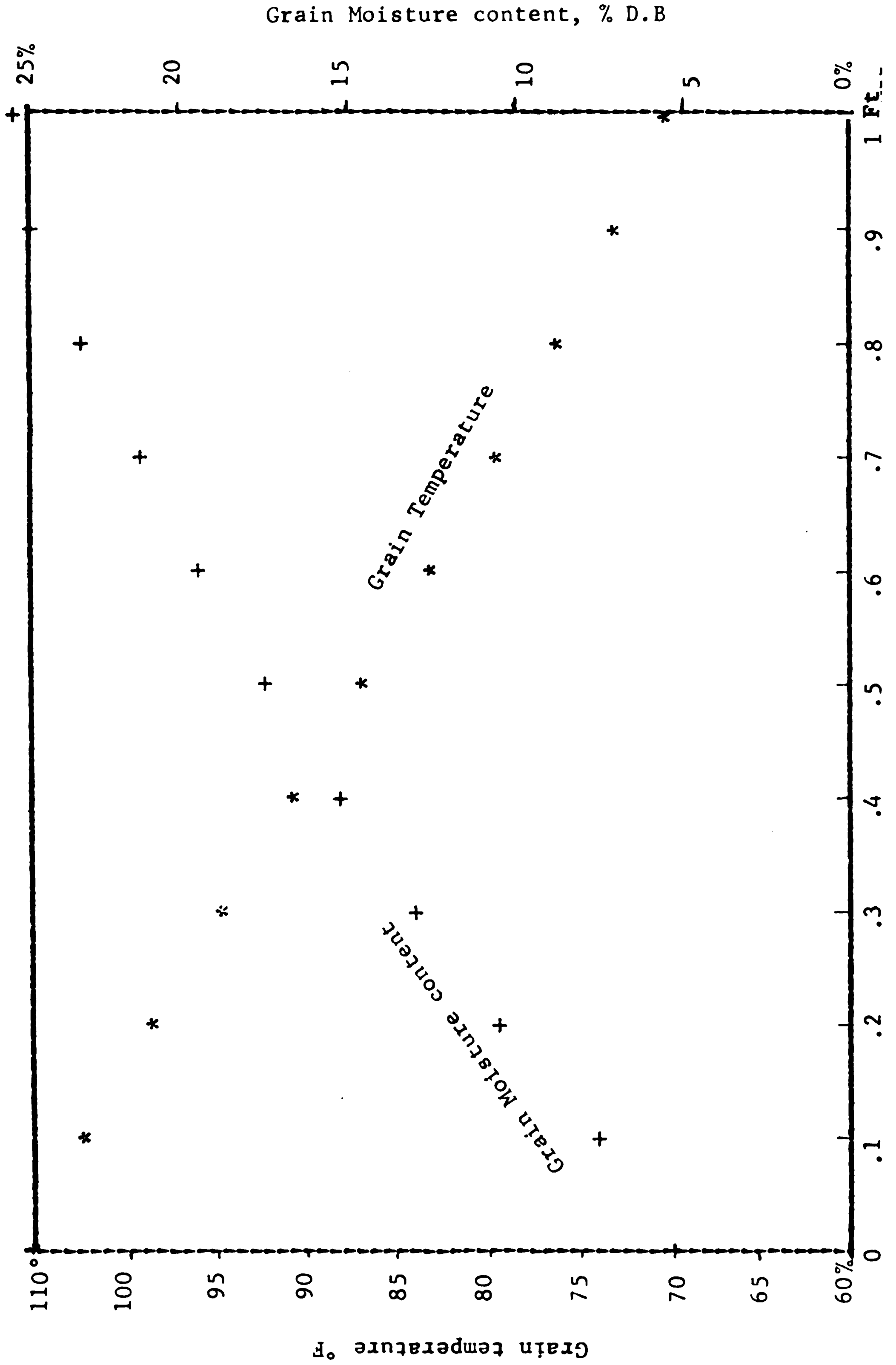


Fig 25. Properties of rice in the drying bed.

TABLE 4. EFFECT OF SPECIFIC SURFACE AREA[1]

Time	Sa=324 ft^{-1}		Sa=400 ft-1	
Hrs	MC %	RH %	MC %	RH %
0	28.0	82.3	28.0	82.3
1	26.4	72.1	26.4	72.3
2	24.6	53.8	24.6	53.9
3	22.8	42.5	22.8	42.5
4	21.0	35.3	21.0	35.3
5	19.4	30.7	19.5	30.7
6	18.1	27.5	18.1	27.5
7	16.8	15.2	16.8	23.2
8	15.7	23.3	15.7	23.3
9	14.7	21.7	14.7	21.7
10	13.8	20.4	13.8	20.4

[1] Temperature: 100°F; bed depth: 1 ft; absolute humidity: .005 lb/lb.

CONCLUSIONS

The rice drying model used in this study is capable of predicting the performance of a fixed bed rice dryer. The accuracy of the results obtained is questionable because of unverified input values for: 1) the rice thin-layer equation, 2) the rice equilibrium moisture content equation at relative humidity higher than 90 per cent, and 3) the physical and thermal properties of rice.

Although the exact prediction for a fixed bed rice dryer by the modified MSU simulation model may at present not be possible, the procedure is valid and a comparative performance study on parameter sensitivity can be made with confidence. It is to be emphasized that throughout this work, the methodology, not the numerical results, is of primary importance.

The substantial saving in time and cost thus justifies the use of simulation in rice dryer design.

SUGGESTIONS FOR FURTHER STUDY

1. In this study the two constants for the equilibrium moisture content equation is evaluated as a function of relative humidity only. For better accuracy, an equation which incorporates both relative humidity and temperature should be developed.

2. Better physical parameters for rice and a more accurate rice drying equation should be developed.

3. Other models such as the MSU concurrent flow and counterflow models should be applied to rice.

4. Apply the newly developed USOLAR model (Bakker-Arkema and Roth 1975) to fixed bed rice drying simulation. The saving in computer time and core memory will be considerable.

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