DRYING CHARACTERISTICS OF TROPICAL GRAINS

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ABSTRACT

Accurate prediction of drying characteristics of grains can offer great help in the design of thermally efficient dryer while maintaining good quality of processed products by supplying appropriate rate of drying air, its temperature as well as its relative humidity. It is also useful in determining the performance of dryers operated by different types of energy sources as solar, biomass, kerosene and other alternative sources.

Infinite slab, cylindrical and sphere models were used to determine the drying constant of rough rice (IR-36), soybean (Orba) and corn (Arjuna) under thin layer condition.

INTRODUCTION

At present, in Indonesia, big harvest usually falls coincidently with the rainy season where solar irradiation is at such a low level so that natural drying might not be sufficient to reduce the moisture content of the harvested grains.

Suharmadi and Sudaryono had conducted an experiment where 100 kg of wet paddy at 24% wb was stored for a period of 18 days (1). They found that 4.2% of the samples were spoiled and damaged.

Artificial drying techniques have been introduced to Indonesia since 1969. However, due to lack of skill and knowledge about drying process, most of the dryer were not operated under the optimal condition (2). Most of these dryers were designed and constructed to meet the drying condition of the grains in the foreign countries where the machines were made.

To design a good dryer, drying characteristics of grains should be known. Accurate prediction of drying characteristics of grains can offer great help in the design of a thermally efficient dryer while maintaining good quality of processed products by supplying appropriate rate of drying air, its temperature as well as its relative humidity. It is also useful in determining the performance of dryer operated by different type of energy sources as solar, biomass, kerosene and other alternative sources.

This paper presents the experimental as well as analytical studies on the drying characteristics of rough rice (variety IR—36), corn (variety Arjuna) and soybean (variety Orba) under thin-layer drying conditions. Several mathematical models were developed and tested with the experimental measurements. Further, the respective drying constants were also determined from the mathematical model applied here in.

THEORETICAL CONSIDERATIONS

Basic Model

The geometry of the grains can be classified into three catagories: slab, cylindrical and sphere. The thin-layer drying model for the three geometries above can be derived from its moisture-balance equation. For the infinite slab model thin-layer drying, the moisture balance can be expressed as follows (3, 4, 5):

$$\frac{\partial M}{\partial t} = D \frac{\partial^2 M}{\partial y^2} \qquad \ldots /1/$$

with Initial condition : M (y,0) = Mo
Boundary condition : M(a,t) = Me

This model can be considered as the general thin-layer drying model which can be applied regardless of the shape of the dried commodity. For infinite cylinder and sphere:

$$\frac{\partial M}{\partial t} = D \left(\frac{\partial^2 M}{\partial r^2} + \frac{c}{r}\frac{\partial M}{\partial r} \right) \qquad \ldots /2/$$

Initial condition : M(r,0) = Mo

Boundary condition : M(R,t) = Me

The coefficient c in the above equation has a value of unity for cylindrical body and 2 for a sphere. The initial and boundary conditions used in both equations are based on the assumptions that the distribution of moisture within the kernel are isotropic with homogeneous initial moisture content, Mo, constant ambient temperature and relative humidity and the surface moisture content suddenly changes to Me, following the imposed ambient condition.

There are many solutions of equation /1/ and /2/ available in order to get the average moisture content.

First, an infinite slab body, the analytical thermal equation developed by Bird *et al.* (3) can be modified and integrated to obtain the average moisture content as expressed below:

$$\frac{\overline{M} - Me}{Mo - Me} = 2 \sum_{n=0}^{\simeq} \frac{(-1)^n}{(n+½)^2 \pi^2} \sin(n+½) \exp(\frac{(n+½)^2 \quad ^2Dt)}{a^2} \ldots /3/$$

Brooker (5) expressed the average moisture content of an infinite cylindrical body as:

$$\frac{\overline{M} - Me}{Mo - Me} = \sum_{n=1}^{\simeq} \frac{4}{\lambda n} \exp(\frac{\lambda n}{4} X_1^2) \qquad \ldots /4/$$

where $X_1 = A/V(\sqrt{Dt})$

For spherical body, Babbit and Illustrulid (6) found the following relationship:

$$\frac{\overline{M} - Me}{Mo - Me} = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp(-n^2 X) \quad /6/$$

where X = Kt

Approximate Model

To lessen the computer time and storage, the authors introduced on approximate model of the form:

$$\frac{\overline{M} - Me}{Mo - Me} = \sum_{n=1}^{\infty} a_n \exp(-bX) \quad /7/$$

where a and b are the parameters of the model

EXPERIMENTAL PROCEDURES

Apparatus in Figure 1 was used for measuring parameters K and Me from Eq./8/, /9/ and /10/. This apparatus was designed and contructed in such a way to enable the authors to produce a certain level of temperature and relative humidity of the air (7).

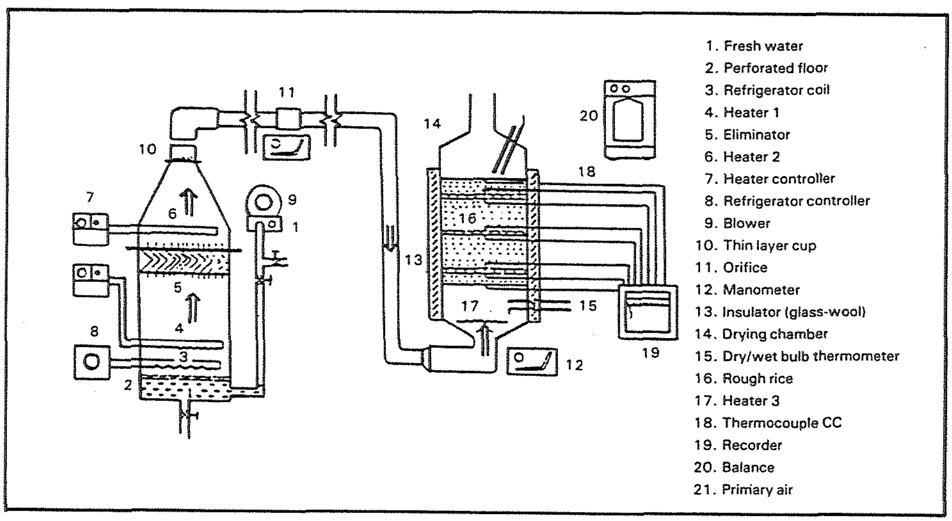

Fig. 1. Schematic experimental apparatus.

Ambient air was passed through a water bath maintained at a certain temperature by manipulated heater no. 4 and refrigerator no. 3. Auxilliary heater no. 6 then are manipulated to get certain value of relative humidity and temperature. For thin layer experiment, thin layer cup was placed on the top of the drying chamber (port A in Fig. 1) and filled with 2 layer grains thick of rough rice and grain thick of corn and soybean, 0.1 m/s of air flow was then passed through thin layer.

Initial moisture content of the grain was measured by vacuum oven method, 100°C vacuum 70 cm Hg for 24 hours. Rough rice sample (IR-36), corn (Arjuna) and soybean (Orba) were obtained from the Bogor Research Institute for Food Crops. Experimental run was designed for 5 temperature levels: 35, 40, 45, 50 and 55°C.

RESULTS AND DISCUSSION

Drying Characteristics

Drying rate vs time

Fig. 2a shows the drying rate of rough rice under constant air flow rate at 0.1 m/s and 3 levels of RH, 19.6%, 31.4% and 52.2% respectively. The figure indicated that all drying process occured in the falling rate period. For these three temperature levels under study, the higher drying rate occured and continued until two hours of drying time.

Drying rate vs moisture content

The constant rate period. In the experiment with corn, a certain period of a likely constant drying rate was observed as indicated in Fig. 2b, it was also found that duration of the constant rate period depended on the drying temperature. The higher the drying temperature, the shorter the constant rate period. Under the drying air temperature of 55°C, the constant rate period was no longer observable. The similar characteristics also appeared during the experiment with soybean. The constant rate period for this commodity appear under the drying temperature between 35°C (Fig. 2c).

In corn drying, constant drying rate occured at moisture content above 30% db while soybean at above 27% db (Fig. 3b), which is against the previous report that its occurence only could be detected at moisture content above 70% wb (4).

The occurence of the constant rate period under the relatively low moisture content as detected above should be tested further to confirm their existence.

The falling rate period. Fig 3a shows the pattern of drying rate versus moisture content of rough rice. The falling rate period was devided into 3 regions. Region I indicated the steepest drying rate, region II where the drying rate decreased gradually and region III where the rate approach to zero.

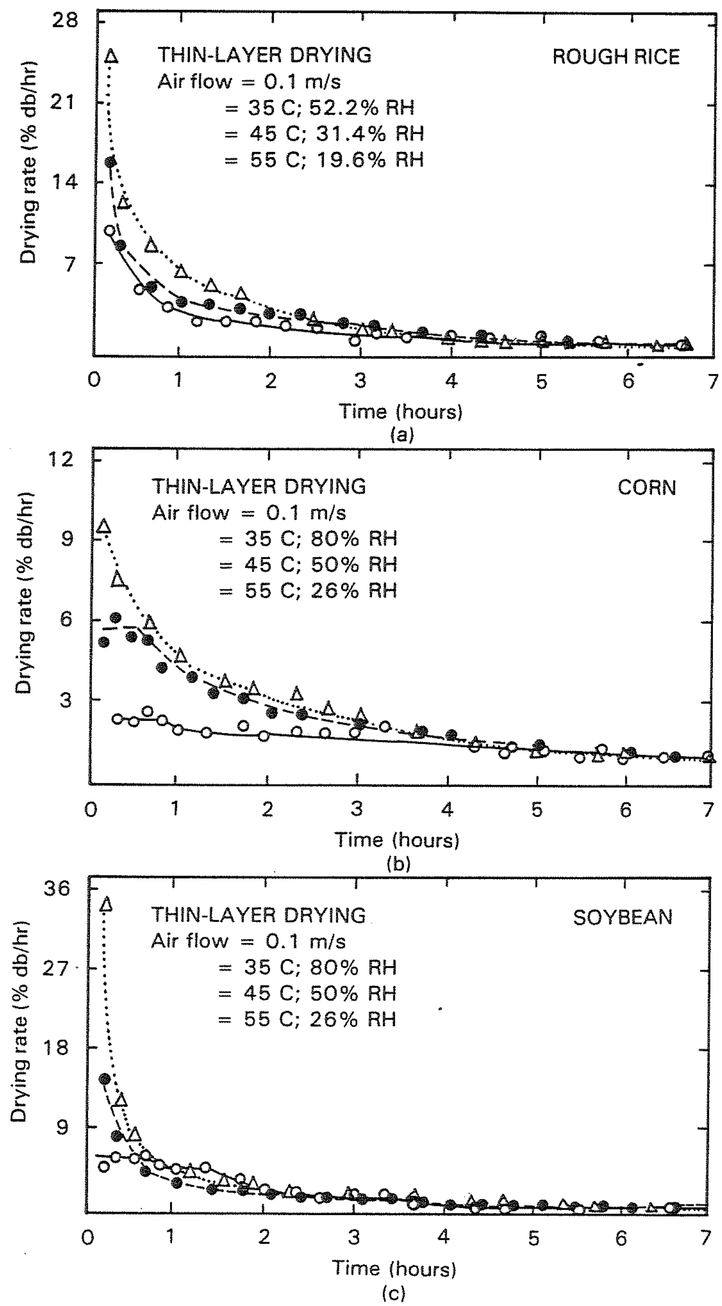

Fig. 2. Drying rate vs drying time of rough rice, corn and soybean under 25°C, 45°C and 55°C drying temperature.

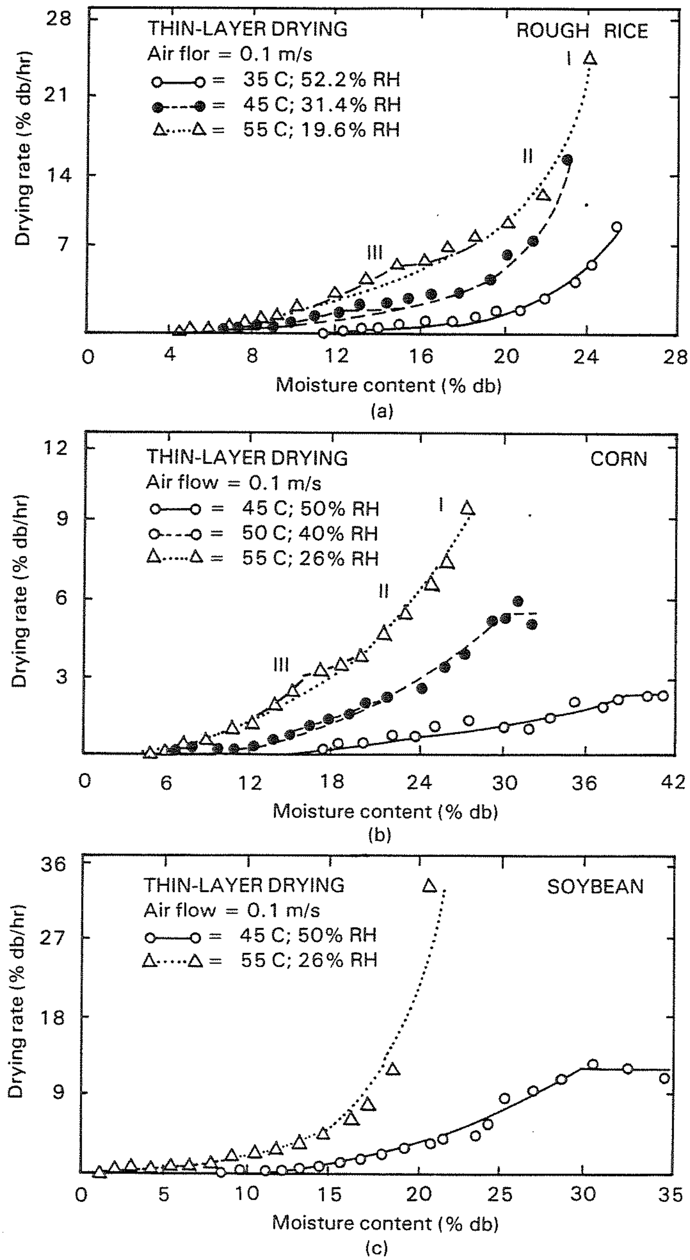

Fig. 3. Predicted change of moisture content using ISTLD, ICTLD and sphere model for thin - layer - drying of rough rice, corn and soybean.

The region III could only be seen clearly when drying with temperature at of 55°C. This characteristics were also detected similarly in corn drying experiment 55°C (Fig. 3b). The shift from one region to another varied according to the level of the drying temperature. The higher the drying temperature, the smaller the moisture content at which the shift in drying rate took place. In Fig. 3a, region III occured at moisture content ± 15 and ± 12% db respectively for the two levels of temperature of 45 a and 55°C. For corn, region III occured at moisture content of ± 15% db under 55°C drying temperature.

Determination of the Form of the Approximate Model

Infinite-slab-thin-layer drying model

Using n = 25 and range of Dt/a^2 from 0 to 10 in Eq. /3/ and n = 2 for Eq. /7/ the authors obtained the approximated model for infinite slab as:

$$\frac{\overline{M} - Me}{Mo - Me} = 0.177293 \exp(-36.5655X) + 0.81585 \exp(-2.47511X) \quad /8/$$

X is equal to Kt where K is a function of diffusivity and geometry of the body to replace the infinite series $(-(n+1/2)^2 \pi^2 D/a^2)$ in Eq. /3/. Equation /8/ is a modification of the slab model of Henderson (8) to represent the movement of moisture within a body during the falling rate period (9). This model has a standard deviation of 0.000467 from the exact solution. Hence forth Eq. /8/ will be called the Infinite-Slab-Thin-Layer Drying model (ISTLD model).

Approximate-infinite-cylindrical-model thin layer drying

The final expression for the approximate Infinite-Cylindrical-Thin Layer-Drying Model is given by.

$$\frac{\overline{M} - Me}{Mo - Me} = \begin{cases} 1 + 0.0265907X^{1.0185} + 0.024801X^{2.41975} - 1.1275X^{0.5} & (0 \leqslant X \leqslant .64) \\ 0.691547\exp(-1.445766X) + 0.134633\exp(-7.617876X) & (X > .64) \end{cases} \quad /9/$$

Where $X = (A^2/V^2 D)t = Kt = X_1^2$

Equation /9/ is called the approximate Infinite-Cylindrical-Thin-Layer Drying model (ICTLD model) and has a standard deviation of 0.000808 from its analytical solution (Eq. /4/).

4.2.3. *Approximate-Sphere-Thin-Layer Drying Model.*

Approximate model for sphere is expressed simply as (5):

$$\frac{\overline{M} - Me}{Mo - Me} = \begin{cases} 1 - 1.077522733\sqrt{X} + 0.303935509X (0 \leqslant X \leqslant 0.9) \\ 0.6679481(-X) + 0.1562563\exp(-4.02587X)\ (X > 0.9) \end{cases} \qquad /10/$$

Determination of Parameters in the Approximate Model.

The drying constant K and Me

In general the approximate-thin-layer-drying-model in equations /8/, /9/ and /10/ can be arranged as:

$$M = Me + (Mo - Me)\ \Psi(K.t) \ldots\ldots\ldots\ldots\ldots\ldots \quad /11/$$

where $\Psi(K.t)$ can be expressed interms of the ISTLD, ICTLD or sphere models. To determine the average moisture content in Eq. /11/ there are two parameters must be known, namely the drying constant K and equilibrium moisture content, Me. The value of Me was determined experimentally while the drying constant K was determined by means of the non linear least square method.

Parameters K and Me in Eq. /11/ are combined non linearly. This equation can be linearly through introducing the aproximation:

$$f_i(K + \Delta K, M + \Delta Me) = f_i(K, Me) + \Delta K \frac{\partial f_i(K,Me)}{\partial K} + \Delta Me \frac{\partial f_i(K,Me)}{\partial Me} \ldots\ldots\ldots\ldots \quad /12/$$

Applying condition of minimum least square method onto Eq. /12/ as:

$$\frac{\partial (Y_i - f_i(K + \Delta K, Me + \Delta Me))}{\partial K} = \frac{\partial (Y_i - f_i(K + \Delta K, Me + \Delta Me))}{Me} = 0 \quad /13/$$

where Y_i = experimental data,

we get two simultaneous equations as:

$$\Delta K \sum^{\eta} \left(\frac{\partial f_i(K,Me)}{\partial K}\right)^2 + \Delta Me \sum^{\eta} \left(\frac{\partial f_i(K,Me)}{\partial K} \frac{\partial f_i(K,Me)}{\partial Me}\right) = \sum^{\eta} (Y_i - f_i(K,Me)) \frac{\partial f_i(K,Me)}{\partial K} \quad /14/$$

$$\Delta K \sum^{\eta} \left(\frac{\partial f_i(K,Me)}{\partial K} \frac{\partial f_i(K,Me)}{\partial Me}\right) + \Delta Me \sum^{\eta} \left(\frac{\partial f_i(K,Me)}{\partial Me}\right)^2 = \sum^{\eta} (Y_i - f_i(K,Me)) \frac{\partial f_i(K,Me)}{\partial Me} \quad /15/$$

If initial value of K and Me are known, the value of Δ K and Δ Me can-be calculated from Eq. /14/ and /15/. Initial value of K and Me are guessed arbitrary close to its true value. If Δ K and Δ Me are close to zero it means the guessing value of K and Me are closely equal to its exact value. If Δ K and Δ Me still quite large, get the new value of K and Me by adding Δ K and Δ Me and the above procedure are repeated.

The K value for rough rice

In general, rough rice in Indonesia belongs to the Indica group which has a slender body. Therefore, in this study, for the IR-36 variety, the ISTLD and ICTLD model was used and the respective values of K and Me were determined. In addition to this the application of a sphere model was also studied here for comparison. Using the three models mentioned above for rough rice, the authors obtained the K value expressed in terms of absolute temperature:

$$K_{slab} = \exp(6.7731 - \frac{4078.95}{T}) \quad /16/$$

$$K_{cyl} = \exp(8.2159 - \frac{4444.89}{T}) \quad /17/$$

$$K_{sp} = \exp(12.5132 - \frac{5619.5}{T}) \quad /18/$$

K_{slab}, K_{cyl} and K_{sp} referred to K derived from the ISTLD, ICLTD and sphere model respectively.

The K value for corn and soybean

Sine the shape of corn kernel and soybean are generally round and flat, the drying characteristics of thin layer drying was predicted by ISTLD and sphere model. The K value obtained was expressed in the following form:

Corn: $$K_{slab} = \exp(1.9281 - \frac{2803.35}{T}) \quad /19/$$

$$K_{sphere} = \exp(7.5529 - \frac{4505,10}{T}) \quad /20/$$

Soybean: $$K_{slab} = \exp(0.0484 - \frac{1963.79}{T}) \quad /21/$$

$$K_{sphere} = \exp(0.6422 - \frac{1996.47}{T}) \quad /22/$$

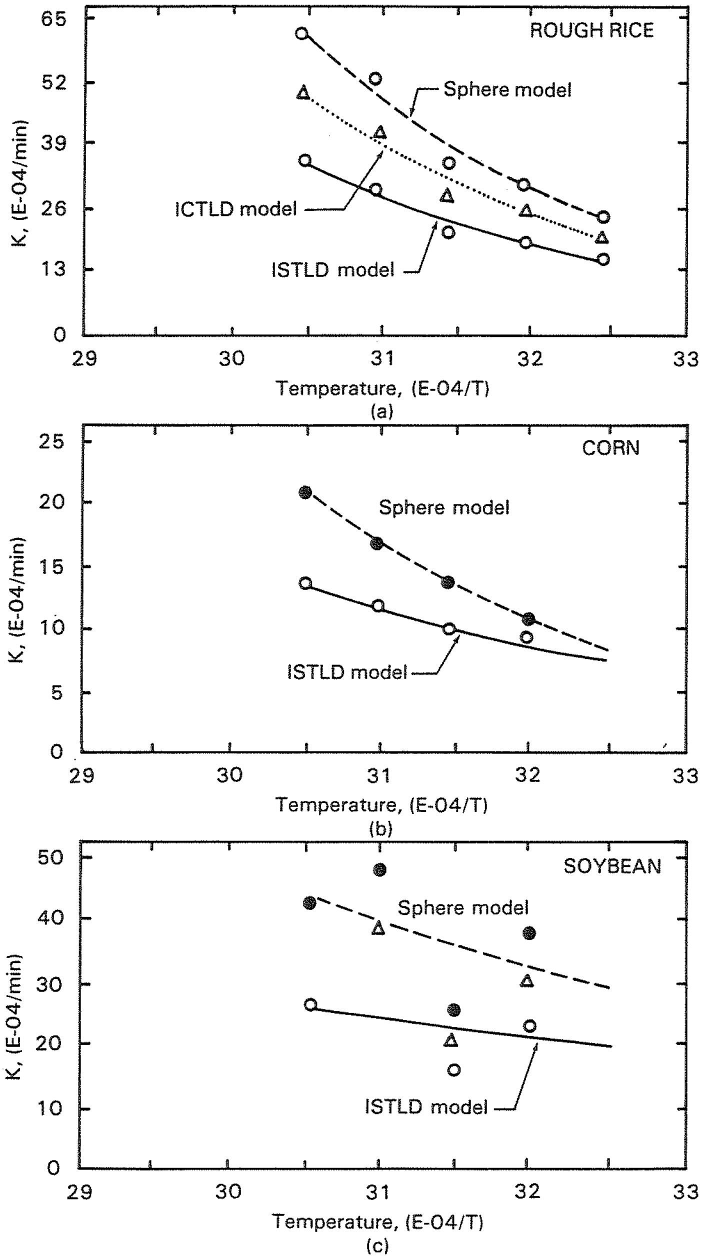

Fig. 4. Value of the drying constant of rough rice, corn and soybean as a function of the absolute temperature.

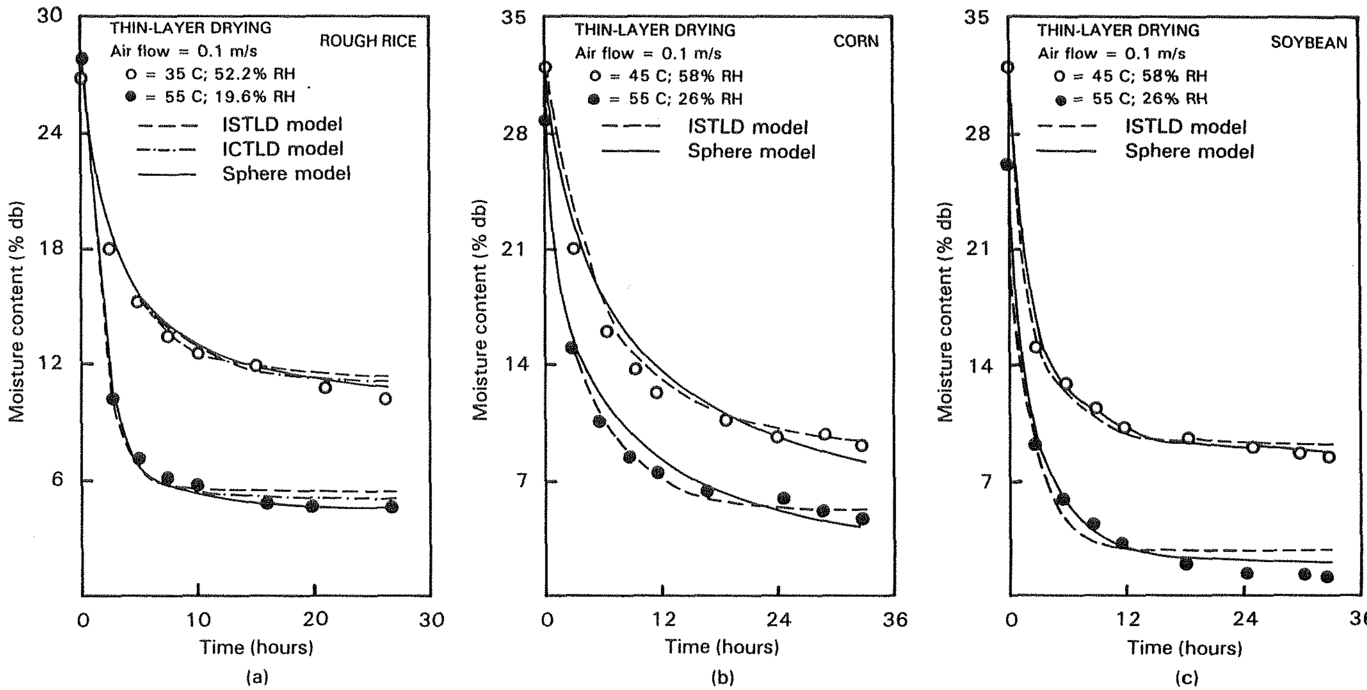

Fig. 5. Predicted change of moisture content using ISTLD, ICTLD and sphere model for thin-layer-drying of rough rice, corn and soybean.

Effect of temperature on K

The curve of K as a function of absolute temperature (I/T) for each grain can be seen Fig. 4. The value of K for ISTLD model was the smallest among the three models.

Fig. 5 shows the comparison of the predicted change in moisture content of grain under thin layer drying condition. For IR-36, the ISTLD, ICTLD and sphere model predicted the moisture content closely with the experimental data. These models shows in agreement with the data within 6 hours of drying time and tend to deviate in large time.

Table 1. Deviation of moisture content as predicted from the theorical model.

Grain	Drying temperature	Average Standard deviation for experimental data		
		ISTLD	ICTLD	Sphere
Rough rice (IR-36)	35	0.14636	0.31619	0.47368
	55	0.39172	0.46301	0.61289
Corn	45	0.68838	—	1.23785
	55	0.54120	—	1.00281
Soybean	45	0.56648	—	0.16461
	55	1.1051	—	0.5214

For corn and soybean, the ISTLD model were found to be more accurate than the sphere model (Fig. 5b, c) and when compared interms of the standard deviation as shown in table 1, the ISTLD model proved to be best representing the experimental data.

In some experimental runs, i.e. soybean drying under 45°C and 50°C, the standard deviation of the sphere model was smaller than the ISTLD model. This fact can explain partially the authors postulate about the need to improve the drying model according to the shape of the dried commodity.

CONCLUSIONS

1. Constant rate period was detected at moisture content 36% and 27% for corn and soybean and the level was found affected by the drying temperature.
2. Thin layer models derived here was also valid in predicting the moisture change both with the constant and falling rate period.
3. Infinite slab, infinite cylinder and sphere thin-layer drying model was found valid for flat, slender or round body.

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LIST OF SYMBOLS

A	=	surface area of the grains, cm^2
a	=	half thickness of symetrical slab body, cm
c	=	constant in Equation /2/, -
D	=	diffusivity, cm^2/min
K	=	drying constant, min^{-1}
M	=	moisture content at time being, % db
Mo	=	initial moisture content, % db
Me	=	equillibrium moisture content, % db
R	=	radius of cylinder or sphere body, cm
r	=	distance from centre of cylinder or sphere body to a specific point, cm
T	=	absolute temperature, °K
t	=	time, min
V	=	volume of the grain, cm^3
X	=	dimensionless time in Eq. /6/, /7/, /8/, /9/ and /10/
X_1	=	dimensionless time in Eq. /4/
y	=	distance from centre of symetrical slab body to a specific point, cm
Y_i	=	the i^{th} of experimental data
λ	=	positive roots of the zeroth order Bessel function of the first kind, -

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