KW: Simulation; Rice; Dryers; Temperature; Energy 1730

class: Energy

RERIC International Energy Journal: Vol. 12; No. 1, June 1990 p.41-51

Simulation of Deep Bed Rough Rice Drying under Tropical Conditions

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ABSTRACT

A fixed-bed dryer was designed and constructed and drying experiments with fixed beds of rough rice were carried out under various tropical conditions of drying air and using rough rice of various initial moisture contents. The air temperature and moisture content of rough rice at various levels within the beds were measured periodically.

A computer program based on energy and mass balances was developed to simulate the deep-bed drying process. Experimental data from the dryer were compared with the results from this program. The results showed that the simulated drying rates and drying air temperature between the layers were slightly higher than those experimentally observed. The greatest difference between the simulated and experimental values was found in the top layer of the deep bed. However, there was good agreement with respect to the shapes of the moisture and temperature profiles.

INTRODUCTION

Deep bed drying refers to the heterogeneous drying of grain in a deep layer (more than 20 cm deep) where drying is faster at the inlet end of the dryer than at the exhaust end (Noomhorm, 1986). The deep layer is assumed to comprise of a stack of thin grain layers positioned normal to the direction of air flow. The exhaust air conditions from a lower thin layer are treated as the input air conditions of the layer above it (Fig. 1). The change in humidity of the air as it passes through a given layer of grain can be estimated by writing a mass balance for that layer. Any moisture lost by the grain will be picked up by the air. The change in temperature of the air as it passes through a given layer of grain can be estimated by writing an energy balance for that layer.

If the increments of depth and time are sufficiently small, then the conditions of the air will change only slightly as it passes through each layer. By using a mathematical and computer simulation, the moisture and temperature profile in a deep-bed grain drying process can be predicted. The sum of the change in each layer comprising the grain column gives the overall drying picture of the grain bulk.

The Objectives of the Study

To simulate and experimentally verify the deep bed drying of rough rice under tropical conditions.

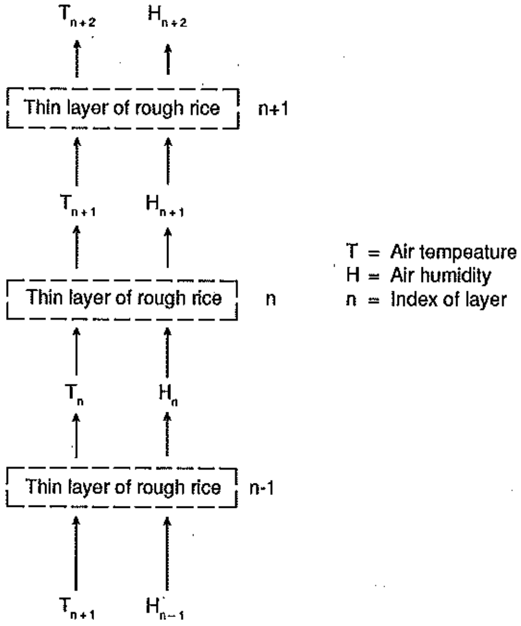

Fig. 1. Schematic diagram of basic simulation approach.

MATERIALS AND METHODS

The apparatus used in the deep bed drying experiment consists of two major parts: the air conditioning unit and the deep bed drying unit. The air conditioning unit is used to deliver a specified quantity of air to the drying section at constant conditions of temperature and relative humidity. The air conditioning unit is connected to the deep bed drying bin. The bin was fabricated from steel plate. The inside dimensions of this bin are 0.30 m x 0.30 m and 0.60 m high. The bottom of this bin is fitted with steel net and wire mesh to hold the grain. The column of grain in this bin consisted of 6 layers of rice each being 5 cm deep. A series of 4 mm diameter holes was drilled through the side of the bin and thermocouple probes were inserted in the holes (Fig. 2) to sense and record the temperature of the layers; the thermocouple probes were connected to a data logger. The temperature measurement was accurate to ±1°C. An additional set of holes of 2 cm diameter were also drilled to withdraw some samples from each layer to determine the weight and average moisture content by the standard oven method (16 hours at 130°C). A Oertling digital balance with an accuracy of 0.005 g was used for the weighing system.

Rough rice, RD7 (from 20 kg to 30 kg) was conditioned to the desired moisture content as follows. The grain was divided into small batches of 2 kg. Each batch was sprayed and mixed with a calculated amount of distilled water to bring the moisture content up approximately to the desired value. After thorough mixing, the grain was stored in plastic containers at about 5°C for at least 14 days.

Before the start of each drying run, a sample was removed from the refrigerator and placed on the floor of the laboratory to bring the temperature of the rough rice to room temperature. A part of this sample was used in the deep bed drying test and the remainder was used to check its initial moisture content by the standard oven method. The air conditioning unit was also run at

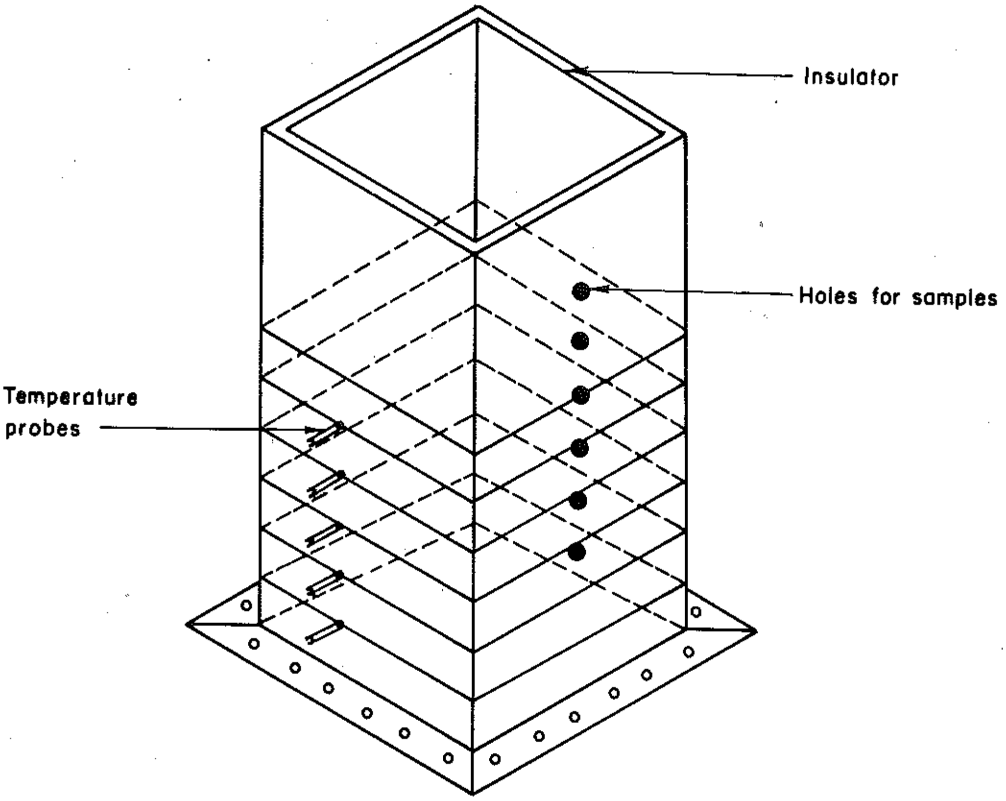

Fig. 2. Schematic diagram of the deep bed drying bin.

the desired conditions of drying air before each experiment begun so that the temperature, relative humidity and air velocity could become stabilized.

After stabilization, the bin was filled with prepared rough rice. The air temperature was measured at various locations in the bin. A data logger was used to continuously record the temperature at each layer during drying. Rough rice samples for the determination of moisture content by the standard oven method were drawn from each layer at the end of the drying time. Each drying run took 6 hours.

The deep bed drying experiments were conducted under various inlet air conditions and using rough rice of various initial moisture contents. Data from the experiment were recorded and compared with the output from the computer simulation.

DEVELOPMENT OF DEEP BED DRYING MODEL

Drying air at temperature, T (°C) and absolute humidity, W_o (kg water per kg dry air) is passed through a thin layer of rough rice at moisture content, M (percent moisture) and temperature, T_g (°C) for a drying time interval, Δt. During this interval, ΔM percent moisture is evaporated from the rough rice into the air, increasing its absolute humidity to $W_o + \Delta W$. During drying, the temperature of the drying air is decreased, ΔT, in proportion to the temperature increase of the rough rice, ΔT_g, and the evaporative cooling accompanying the moisture evaporation. The amount of drying performed is calculated by a thin-layer drying equation with constants dependent on the drying air temperature, relative humidity and initial moisture content of rough rice. Complete heat balances were used to calculate the final air temperature and grain temperature consistent with the evaporative cooling accompanying the moisture evaporation and with the initial temperature of the drying air and the grain. Figure 3 shows the simulation approach. Thompson (1968) appears to have presented the most complete empirical deep bed analysis to be developed for a digital computer solution and as his method requires little computer time, it has been applied to the present research.

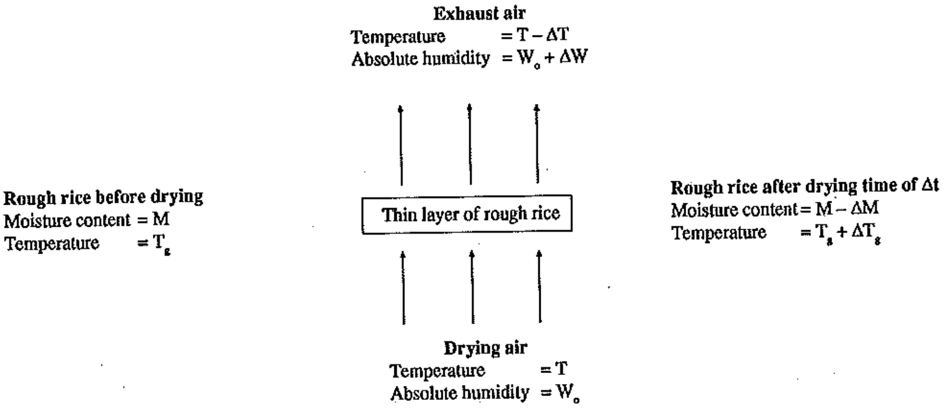

Fig. 3. Schematic diagram of deep bed simulation approach.

The equilibrium conditions of the air and grain after passing air through the grain bed for any interval of time is established by the following energy balance equations between grain and air:

$$C_a T_o + W_o (2502.3 + C_v T_o) + C\,T_{go} = C_a T_e + W_o (2502.3 + C_v T_e) + C\,T_e \tag{1}$$

where the subscript *o* refers to the original and subscript *e* to the equilibrium value of the air temperature, *T*, grain temperature, T_g, and absolute humidity, *W*, and C_a is the specific heat of dry air, (kJ/(kg °C)), C_v is the specific heat of water vapor, (kJ/(kg °C)) and *C* is the specific heat of the rough rice derived by Laithong (1987) multiplied by the grain to air ratio, equals $(1.292 + 0.042M)(R)$; *R* is found by dividing the weight of rough rice in a layer by the weight of air passing through that layer in the time increment Δt.

$$T_e = [(C_a + C_v W_o)\,T_o + C\,T_{go}]/(C_a + C_v W_o + C) \tag{2}$$

The final moisture content of the thin layer at time *o* (at the end of the time increment) is determined from the thin-layer drying equation derived by Wongwises (1989).

$$M = (\exp(-Kt^N))\,(M_i - M_e) + M_e \tag{3}$$

where

$$K = \exp(-1.79 - 0.3711H^{1/2} + 0.0153TM_i - 0.84T + 11.0581TM_i^{-1}) \tag{4}$$

$$N = -9.1210 + 3.855 \times 10^{-5}H^2 - 0.3735M_i + 3.8746M_i^{1/2} \tag{5}$$

$$M_e = \left[\frac{-\ln(1 - H/100)}{4.723 \times 10^{-6} \times T_{abs}}\right]^{1/2.386} \tag{6}$$

where
T = drying air temperature (°C)
H = drying air relative humidity (%)
T_{abs} = drying air absolute temperature (°K)
M_i = initial moisture content of rough rice (% (d.b.))
M_e = equilibrium moisture content of rough rice (%(d.b.)).

After the final average moisture in the layer is found, the following equation is used to determine the average absolute humidity of the air leaving the layer over the time Δt:

$$W_f = W_o + \Delta W \tag{7}$$

and

$$\Delta W = (M - M_f)\mathrm{R} \tag{8}$$

where R is the mass of the grain per mass of air furnished during Δt.

The average exhaust air temperature, T_f, of the air leaving the layer over the time Δt is found by another heat balance that considers the evaporation of the water removed in Δt:

$$C_aT_e + W_o(2502.3 + C_vT_e) + CT_{ge} + C_w\,\Delta W\,T_{ge} = C_aT_f + W_f(2502.3 + C_vT_f) + CT_f + \Delta L\Delta W \tag{9}$$

where $T_e = T_{ge}$ from equation (2). The left side of the equation is the heat content of the water that was evaporated, and the last term in the equation is the heat of vaporization required to evaporate moisture from the rice above that required to evaporate the same amount of free water. Solving this equation for the unknown final air temperature:

$$T_f = \frac{(C_a + C_vW_o)T_e - \Delta W(2502.3 + \Delta L - C_wT_{ge}) + CT_{ge}}{C_a + W_fC_v + C} \tag{10}$$

It is possible that the above equations will yield W_f and T_f values that result in relative humidities of above 100 percent. Since this is not feasible it is necessary to simulate condensation of the excess water from the air into the rough rice. This is accomplished by a method of finding the zero of unknown functions developed by Thompson and Pert (1966).

The deep bed drying simulation was developed in the computer program. A simplified flow chart is presented in Fig. 4. Comparison of experimental and predicted moisture removal rates are described below.

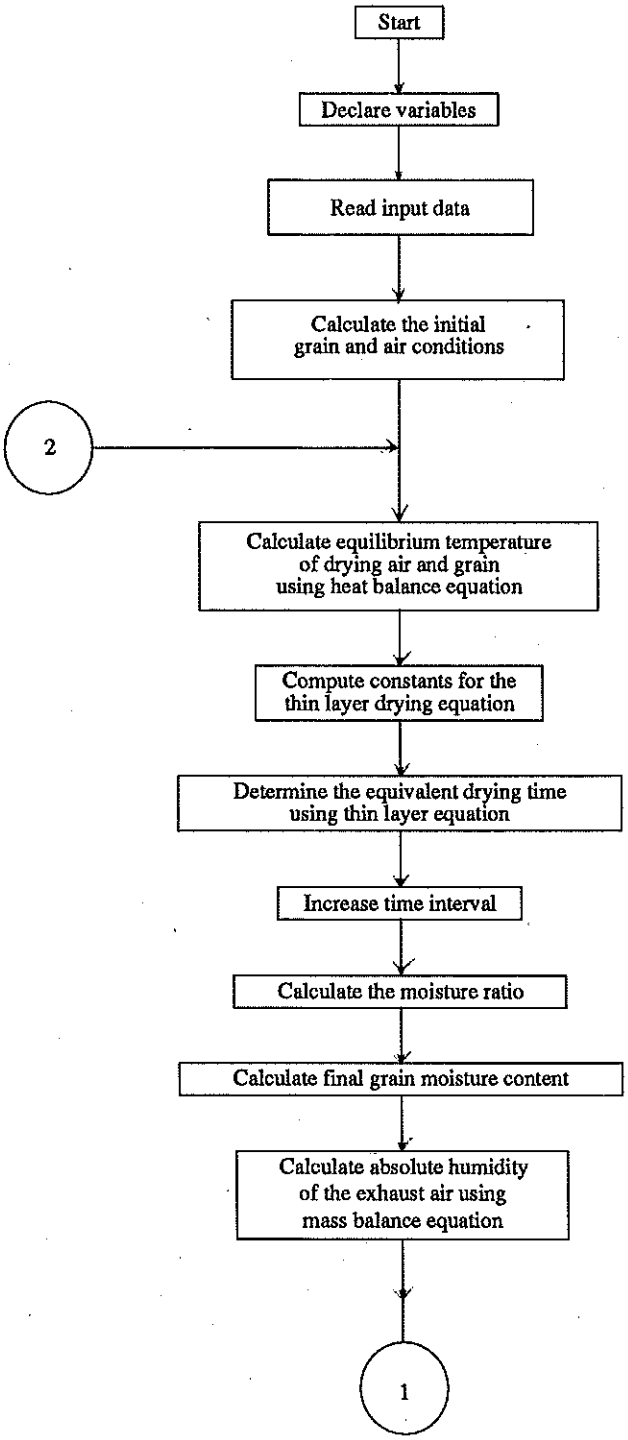

Fig. 4. Flow chart of deep bed simulation program.

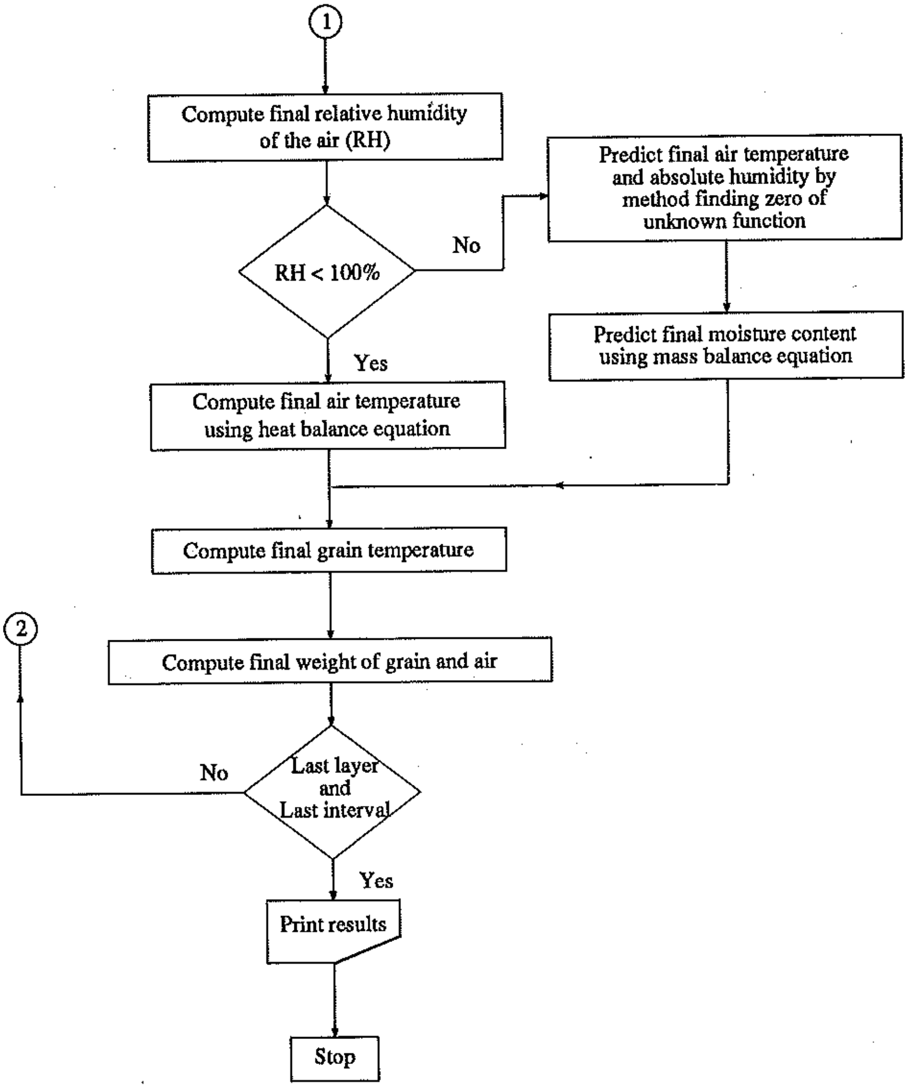

Fig. 4. (Cont.) Flow chart of deep bed simulation program.

RESULTS AND DISCUSSION

The deep bed drying experiments were conducted with rough rice (RD7) to verify prediction. The apparatus used in this experiment was as explained earlier. The experiments were conducted under various inlet air conditions and using rough rice of various initial moisture contents. Air temperature was determined at various points in the bed, namely 0.025 m, 0.075 m, 0.125 m, 0.175 m, 0.225 m and 0.275 m from the air inlet. The moisture content of rough rice in each layer were checked at the end of the drying time. All experimental data from the dryer were compared with the simulated results. A large number of graphs can be drawn from the output of the simulation but because of space limitation, only typical results are shown.

The typical results of the deep bed drying are presented graphically in Figs. 5 through 8. Figures 5 and 6 show the average moisture content vs drying time plot. The moisture content of rough rice at the bottom layers of the dryer used in the experiments dropped quickly as expected from the drying rate of a thin layer of rough rice and approached the equilibrium values (10.88 % (d.b.) and 14.94 % (d.b.)). As shown in Fig. 5, during the first half hour of drying, the moisture content at the level 0.275 m from the bottom remained approximately at the initial values and

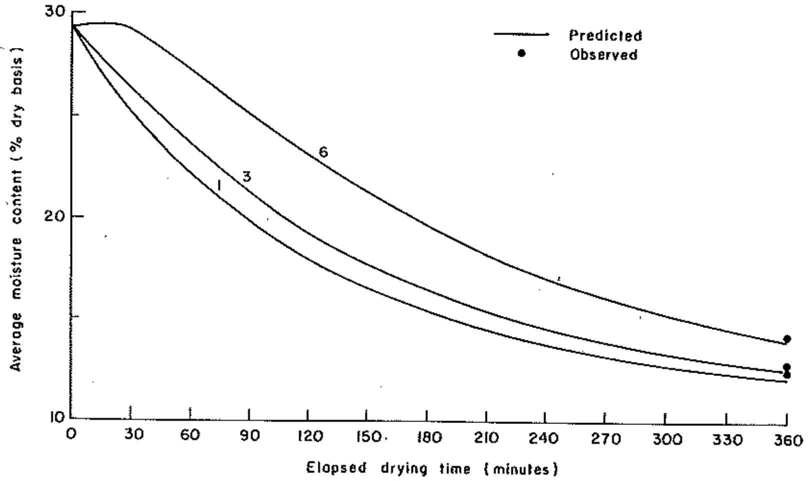

Fig. 5. Plot of average moisture content against time, at various layers in a deep bed of rough rice being dried with heated air. ($T = 44$ °C, $H = 36\%$, $M_i = 29.32$ % D.B., Air flow rate = 0.43 $m^3/sec.\ m^2$)

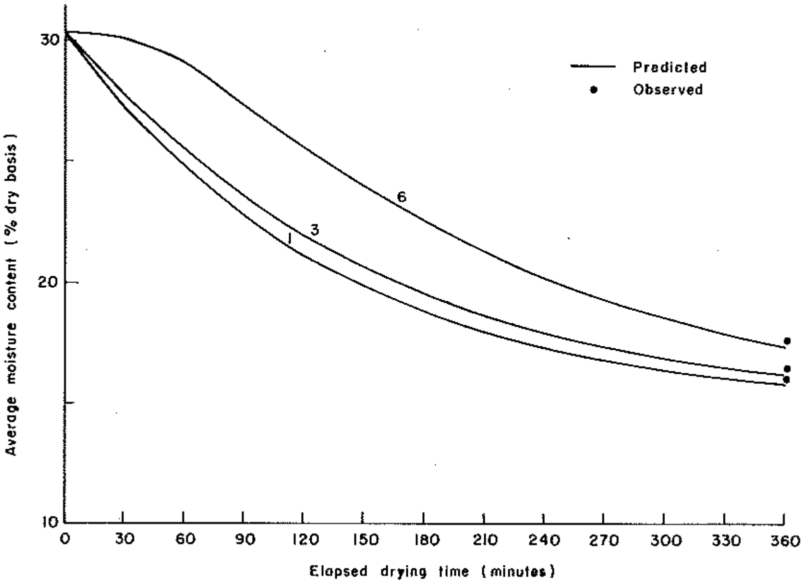

Fig. 6. Plot of average moisture content against time, at various layers in a deep bed of rough rice being dried with heated air. ($T = 33$ °C, $H = 60$ %, $M_i = 30.36$ % D.B., Air flow rate = 0.62 $m^3/sec.\ m^2$)

started to dry approximately forty minutes later. Similarly, as shown in Fig. 6, at the same level the drying starts one hour later. The moisture content at each level shown in Fig. 5 decreased faster than the moisture content at each level shown in Fig. 6. The samples used in the experiments were allowed to warm at room temperature to avoid condensation during drying, so moisture absorption of the grain at any part of the bed was not observed. Predicted values of moisture content for first, third and sixth layers at the end of the drying times were found to be lower than the observed values.

Typical drying air temperature-time profiles at various levels in the dryer used in the experiments are presented in Figs. 7 and 8. The figures also show that air temperature in the grain bed

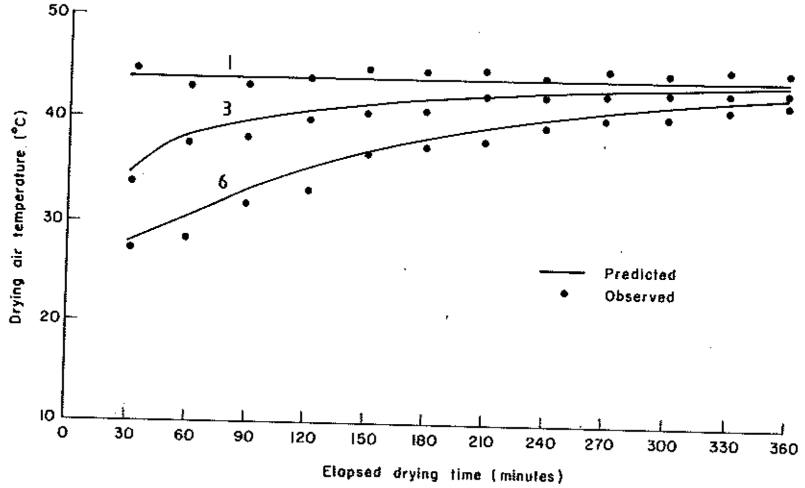

Fig. 7. Plot of drying air temperature against time, at various layers in a deep bed of rough rice being dried with heated air. (T = 44 °C, H = 36 %, M_i = 29.32 % D.B., Air flow rate = 0.43 m^3/sec.m^2)

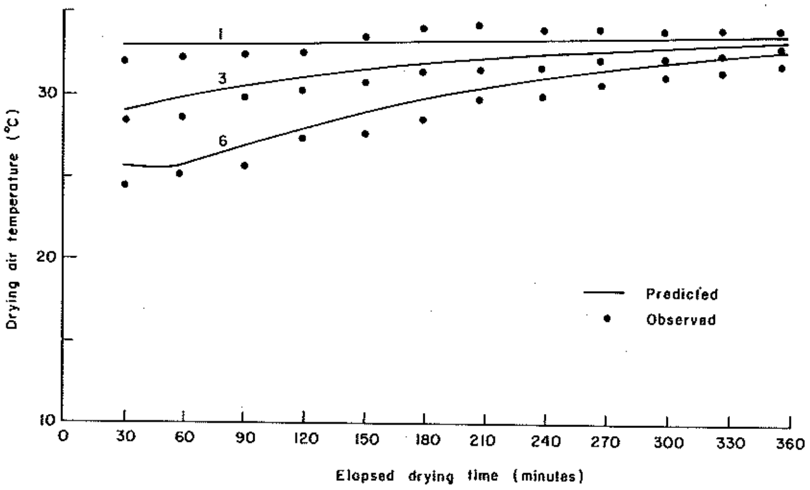

Fig. 8. Plot of drying air temperature against time, at various layers in a deep bed of rough rice being dried with heated air. (T = 33 °C, H = 60%, M_i = 30.36% D.B., Air flow rate = 0.62 m^3/sec. m^2)

rose quickly during the first two hours of drying. After this time they continued to rise and approached the inlet air temperature. Observed temperatures of air between layers were found to be lower than the predicted values.

The difference between the observed and predicted values might be caused by a variation of drying air temperature. The analytical description also assumed a perfectly insulated container. When the drying air temperature dropped, the potential for drying was reduced so the high predicted temperature in the rough rice layers appears to agree with the higher drying rate. However, the shape of the air temperature and moisture content profile of both predicted and observed had a good agreement.

CONCLUSION

Drying experiments with fixed beds of rough rice (RD7) were carried out using various inlet air conditions and rough rice of various initial moisture contents. The drying air temperature and moisture content of rough rice at various levels within the beds were measured periodically. A computer program based on energy and mass balances was developed to simulate the deep-bed drying. Experimental data from the dryer were compared with the results from this program. The results showed that the simulated drying rates and drying air temperature between the layers were slightly higher than those experimentally observed. The greatest difference between the simulated and experimental values was found in the top of the deep bed. However, there was a good agreement with respect to the shapes of the moisture and temperature profiles. The developed simulation can be used to determine the effect of a change of parameter on the drying performance; in addition, it can be used to promote more efficient use of existing dryers and to help with the design of new dryers.

ACKNOWLEDGEMENTS

The author wishes to acknowledge the faculty and staff of the Department of Mechanical Engineering, Chulalongkorn University and King Mongkut's Institute of Technology Thonburi for their generous assistance during his work.

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LIST OF SYMBOLS

C = specific heat of rough rice multiplied by the grain to air ratio, kJ/(kg °C)
C_a = specific heat of dry air, kJ/(kg °C)
C_v = specific heat of water vapor, kJ/(kg °C)
C_w = specific heat of liquid water, kJ/(kg °C)
H = relative humidity of drying air, percent
ΔL = latent heat of water vapor in rough rice in excess of that of free water, kJ/kg
M = average moisture content of rough rice, percent dry basis
R = the weight of rough rice in a layer by the weight of air passing through that layer in the time increment Δt
T = drying air temperature, °C
T_{abs} = absolute temperature of drying air, °K
T_g = grain temperature, °C
t = drying time, minute
W = absolute humidity of drying air, kg of water/kg of air

Subscripts

e	equilibrium
f	final
i,o	initial