Performance and Financial Analysis of a Rotary Drum Longan Dryer

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ABSTRACT

A prototype longan dryer designed for a full capacity of 300 kg longan per batch consisted of a 5 to 25 kW LPG burner, a 0 to 9 m³/min-air blower and a 0 to 1 rpm adjustable speed driving system. The experiments were carried out with forced hot air circulation and conducted with different operating conditions to determine the drying performance. The effects of the drying temperature (80°C to 90°C), airflow rate (2.00 to 5.62 m³/min) and drum rotational speed (0.50 to 1.00 rpm) on fresh longan drying were considered. Higher drying temperature, air flow rate and rotational speed resulted in higher drying performance. With 90°C drying temperature, 4.50 m³/min airflow rate and 0.75 rpm drum rotational speed, the final dried whole longan produce was about 95 kg with average efficiency of 68% and average drying rate of 5.64 kg water evaporated/h. The average specific energy consumption (SEC) was about 3.37MJ/kg of water evaporated. The operating energy cost was 2.70 baht/kg dried produce (1 baht = US$ 0.0227) compared with 4.87 baht/kg of the conventional fixed bed dryer. The quality of the dried whole longan was acceptable to the consumers.

1. INTRODUCTION

A variety of fruits are available in Thailand. Some of these fruits are consumed fresh, while the others are modified or processed such as dried, canned and frozen products. Drying is a popular method for fruit preservation because the process is not complicated.

Longan belongs to the *Sapindaceae* family. It is nearly spherical in shape with the size ranging from 20 mm to 40 mm diameter. When the fruit is ripe, its peel is light brown in color; it has a dark brown seed of approximately 10 mm diameter, which is covered by thick flesh. The fruit flesh is pale white to light pink in color and has sweet taste. However, the size, color and sweetness of the fruit depend on its variety. The favorite varieties in Thailand are E-dor, Chompoo, Biew Khieu and Haew [1].

Longan is an economically valuable fruit in the northern part of Thailand. The most popular longan variety is called E-dor that is about 80% of gross rate. E-dor has good characteristics because it is easy to care, has high yield, high disease resistance, and good quality (thick flesh, sweet, good aroma and small seed). E-dor is harvested in July to September. The longan produced in 1997 was 195,000 tons for the whole country, which valued 2,954 million baht. The export percentage for dried whole longans was about 35.41% and the trend is increasing continually [2].

Fresh whole longan has high moisture content of up to about 300% (d.b), thus, it can be stored only for a short period. Drying can extend its period of preservation. Dried longan flesh is widely consumed as dried fruit, longan juice, cake decoration, and other uses.

Drying is an operation involving simultaneous heat and mass transfer. The physical mechanism of drying hygroscopic porous produce such as whole longan is quite complicated and is not yet well understood. The moisture within the produce moves in the form of a liquid and/or vapor. The liquid movement can be due to surface forces - capillary, moisture concentration differences (liquid diffusion), and diffusion of moisture in the pore surface (surface diffusion). The vapor movement can be due to moisture concentration differences (vapor diffusion) and temperature differences (thermal diffusion). It can also be water and vapor movement due to total pressure differences [3].

The drying behavior of solids can be characterized by measuring the moisture content loss as a function of time. Existing literature [4] has defined a generalized drying curve that includes an induction period, a constant drying rate period and a falling drying rate period. After the induction period, in which the produce is heated to the drying temperature, the produce undergoes a constant drying rate when a film of water is freely available at the drying surface for evaporation into the drying medium. During this period, the rate of heat transfer to the solid and the rate of mass transfer to the air are equal. The surface maintains a constant temperature, in the hot air drying, at the wet-bulb temperature of the drying air. The factors that control the rate of drying during this period are air temperature, airflow rate, total pressure and partial pressure of vapor. The falling drying rate period is inductive of an increased resistance to both heat and mass transfer and occurs when the surface water no longer exists and the water to be evaporated comes from within the structure and must be transported to the surface. In this period, the surface temperature increases above the wet-bulb temperature and the rate of drying is influenced mainly by the factors which control the movement of water within the solid and external factors become less important. The drying rate decreases and the moisture content of produce slowly reaches the equilibrium moisture content corresponding to the relative humidity of the air. The moisture content at which the produce demonstrates a change from constant drying period to falling drying period is called the critical moisture content which is about 8 to 12 hours of drying time for whole longan.

Hot air fixed bed dryers are most widely used for the production of dried whole longans, but they suffer from high heat loss and nonuniform drying. The shape of the dried whole longan is deformed and the quality sometimes is not acceptable (black brown color, poor aroma and nonuniform moisture content) [5]. Usually the drying time for whole longan is about 52 hours [6].

In this study, a rotational drum type dryer was designed and constructed for whole longan fruit drying. An experimental study has been carried out to determine the effects of the air inlet conditions and the rotational speed on the drying performance. A cost analysis was also performed. A simple model to predict the moisture content and the bed temperature was also presented.

2. THE ROTARY DRUM LONGAN DRYER

2.1 Features of the Rotary Drum Longan Dryer

The dryer is designed for a full capacity of 300 kg whole longan per batch. The unit as shown in Fig. 1 consists of a 5 to 25 kW LPG burner set, a 0 to 9 m^3/min-air blower and a 0 to 1 rpm adjustable drum rotational speed driving system.

Longans are loaded at about 90% of the dryer volume. In each drum revolution, the longans in each layer could roll and change their positions. The LPG burner set generates heat to the air fed by the blower before entering the central core of the drum that is also a perforated closed-end duct. The hot air leaving the central core is forced passing through the longan bed in the dryer uniformly, carries moisture, and leaves the drum shell to the exhaust duct. Some part of the exhaust air could be recirculated and remixed with the fresh air before running in a new cycle. The schematic sketch of the rotary drum longan dryer is shown in Fig. 2.

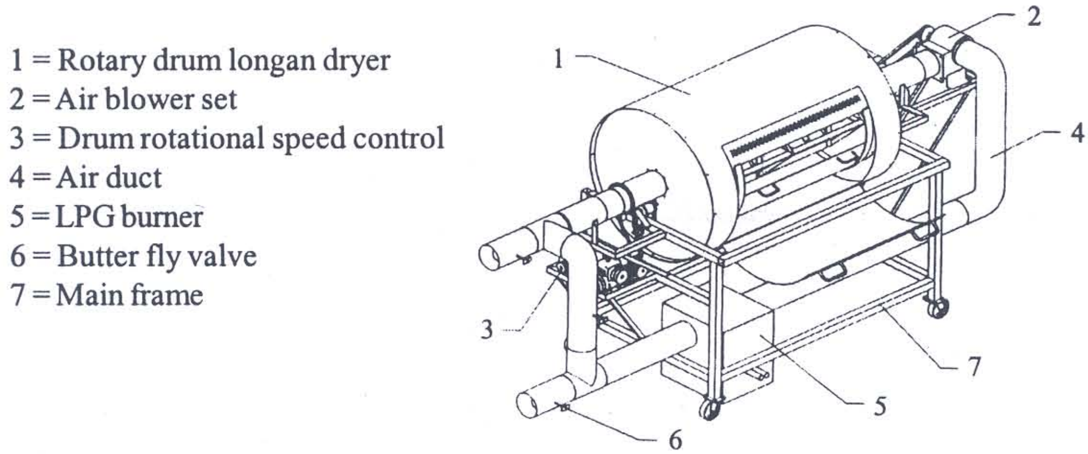

Fig. 1. Isometric view of the rotary drum longan dryer

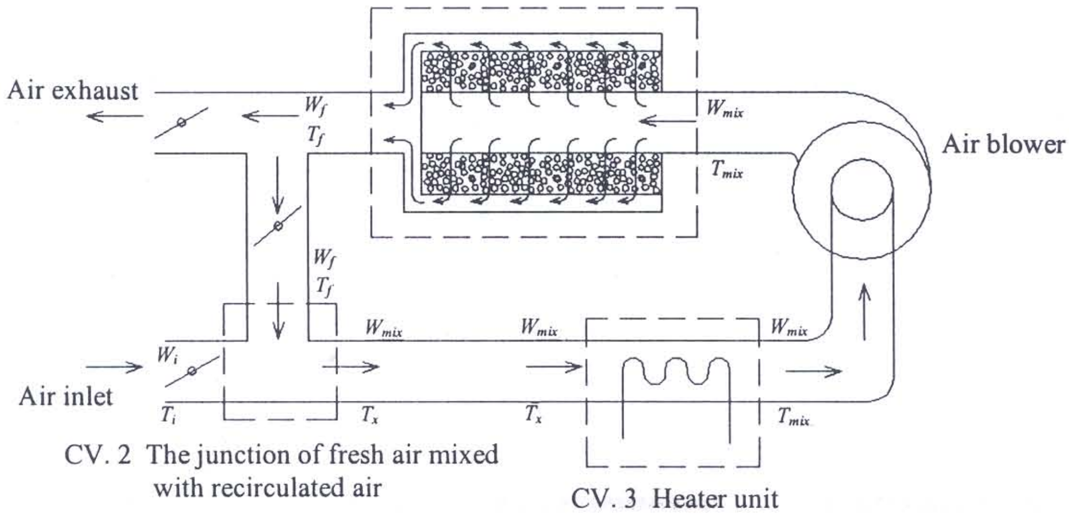

Fig. 2. The schematic sketch of the rotary drum longan dryer

3. MATHEMATICAL MODEL

Deep bed drying refers to heterogeneous drying of products in a deep layer where the drying rate is faster at the inlet of drying air than that at the exhaust end. The bed is assumed to comprise of a stack of thin layers positioned normal to the direction of airflow. The exhaust air condition from a thin layer is treated as the input air condition of the above layer. The change in humidity of the air as it passes through a given layer of product can be estimated from an energy and mass balance for that layer. Since the rotational speed of the drum is rather low, a simplified model for thin layer fixed bed which is based on the mass-energy equation concept has been used to evaluate the drying rate and the bed temperature. Figure 3 shows the element of the longan bed.

3.1 Heat and Mass Transfer Equations

The following assumptions incorporated in the rotary drum longan dryer model are:

- Drying air temperature and flow rate is uniform within the longan layer,
- Heat of evaporation is far greater than sensible heat of the longan,

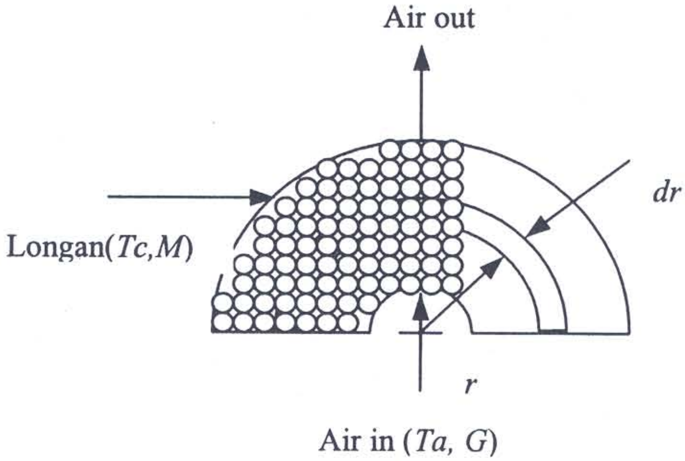

Fig. 3. Element of the longan bed

- $\partial T / \partial t$ and $\partial H / \partial t$ are negligible compared to $\partial T / \partial r$ and $\partial H / \partial r$,
- There is no heat loss by the system,
- Temperature of the longan and air are slightly different and could be negligible, and
- Shrinkage of longan bed is negligible.

The heat balance equations to compute the temperatures and humidity of air in the bed, and the moisture content in the longan bed could be derived as follows:

- Energy balance for air:

$$GC_a \frac{\partial T_a}{\partial r} = -h_v (T_a - T_c) \tag{1}$$

- Energy balance for longan:

$$k(M - M_{eq}) L \rho_c = h_v (T_a - T_c) \tag{2}$$

- Mass balance between longan and air:

$$G \frac{\partial H}{\partial r} = k(M - M_{eq}) \rho_c \tag{3}$$

- Drying rate for thin layer longan:

$$\frac{\partial M}{\partial t} = -k(M - M_{eq}) \tag{4}$$

From Eqs. (1) and (2):

$$GCa \frac{\partial T_a}{\partial r} = -k(M - M_{eq}) L \rho_c \tag{5}$$

which can be written in finite difference form as:

$$T_{a(r+1),t} - T_{r,t} = -\frac{k\, L\rho_c}{GC_a}(M_{r,t} - M_{eq})\Delta r \tag{6}$$

Similarly, Eqn. (3) can be rewritten as:

$$H_{(r+1),t} - H_{r,t} = \frac{k\ \rho_c}{G}(M_{r,t} - M_{eq})\Delta r \tag{7}$$

With the value of moisture content, $M_{r,t}$ of the r^{th} layer, the values of the temperature and the humidity of air leaving the layer can be evaluated.

k is drying constant which could be experimentally found as 0.04 s^{-1} and 0.08 s^{-1} for constant drying rate and falling drying rate periods, respectively.

From Eqn. (4), the moisture content M_r after time lapse Δt is calculated as:

$$M_{r,(t+1)} - M_{r,t} = -k(M_{r,t} - M_{eq})\Delta t \tag{8}$$

The equilibrium moisture content (M_{eq}) was calculated from modified Smith's model [1] as:

$$M_{eq} = [9.704 - 10.638\ln(1-\phi)]/100 \tag{9}$$

ϕ is the air relative humidity which is given by:

$$\phi = \frac{P_v}{P_{vs}} = \frac{101.325H}{(0.622P_{vs} + HP_{vs})} \tag{10}$$

(P_{vs}) is the saturating vapor pressure of water which was calculated by Wilheim [7]:

$$\ln(P_{vs}) = -\frac{7511.52}{T_{abs}} + 89.63121 + 0.023998970T_{abs} - 1.1654551x10^{-5}T^2{}_{abs}$$
$$-1.2810336x10^{-8}T^3{}_{abs} + 2.0998405x10^{-11}T^4{}_{abs} - 12.150799\ln(T_{abs}),$$

$$273.16\,K < T_{abs} < 393.16\,K \tag{11}$$

H is the humidity ratio given by:

$$H = \frac{0.622\phi P_{vs}}{(P_v - \phi P_{vs})} \tag{12}$$

With the initial moisture content, the air properties and the drying temperature, the moisture content of the longan and the air temperature and the humidity ratio leaving the bed could be calculated. The calculation steps are shown in Fig. 4.

3.2 Drying Experiments

Samples of E-dor longans with initial moisture content of about 2.20 to 2.80 (dry basis decimal) were dried to 0.15 to 0.25 (dry basis decimal). The experiments were carried out to determine the effect of inlet air temperature (80°C to 90°C), airflow rate (2.00 to 5.62 m^3/min) and drum rotational speed (0.50 to 1 rpm) on the drying performance. The average ambient temperature was 25°C to 32°C and 50% to 70% relative humidity. The fresh whole longan of 285 kg to 300 kg is dried continuously for 54 hours. The size of the longan body is spherical with 1.94 mm to 2.20 mm diameter.

3.3 Determination of Moisture Content During Drying

The longan samples could be taken out from a manhole and water losses were measured by weighing the sample. The dry matter of the samples was evaluated by drying the samples in the

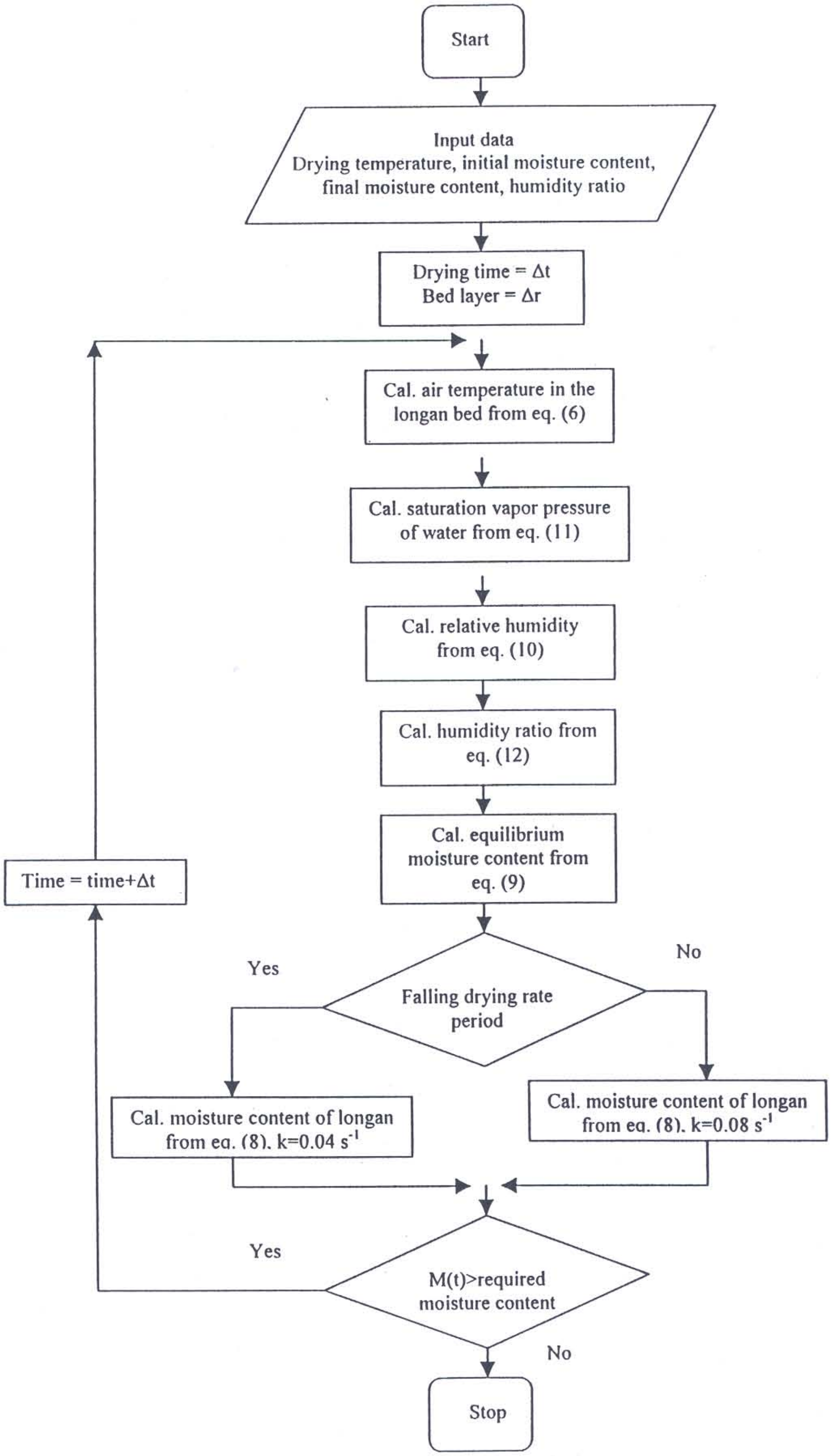

Fig. 4. Flowchart of the longan drying simulation

ventilation air oven at 103±1°C for 72 hours. Inside the bed, the air temperature at three different positions in the airflow direction and at the drying chamber air inlet and outlet were recorded. The wet bulb of air temperatures at the inlet and the outlet of the dryer were also measured.

4. RESULTS AND DISCUSSION

4.1 Drying Behavior of the Whole Longan in the Rotary Drum Longan Dryer

From Fig. 5, it is found that the moisture content decreases when the time lapses. For the first 6 to 8 hours, the moisture content decreases nearly steadily which means that the process is in a constant drying rate zone. After that, the moisture content decreases quickly in the falling drying rate region. The moisture content goes to the near equilibrium state at after about 30 hours. Higher drying air temperature results in higher rate of moisture removal.

Figure 6 shows the effect of air flow rate on drying performance. Higher air flow rate (5.6 m^3/min) gives better heat and mass transfer than the lower rate (2.00 m^3/min), therefore the moisture could be reduced quicker. From the figure, it can be seen that even the initial moisture content is rather high for the previous case, the rate of moisture reduction is still higher and the moisture content is less than the latter case after about 12 hours.

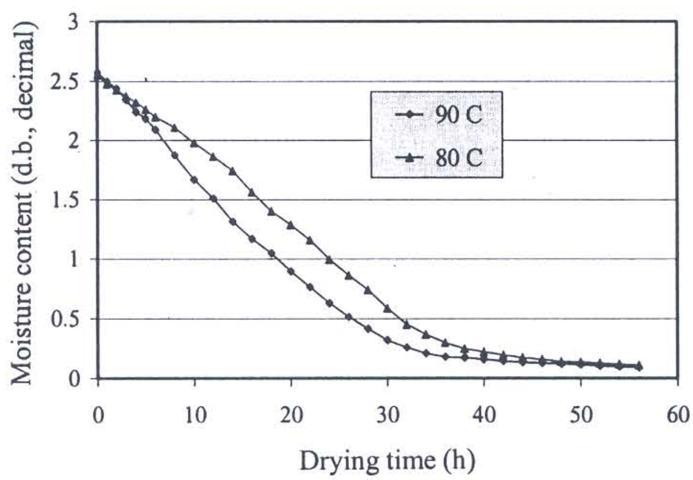

Fig. 5. Effect of air temperature on the drying curve of whole longan at airflow rate of 4.5 m^3/min, relative humidity of 70% and the drum rotational speed of 1 rpm.

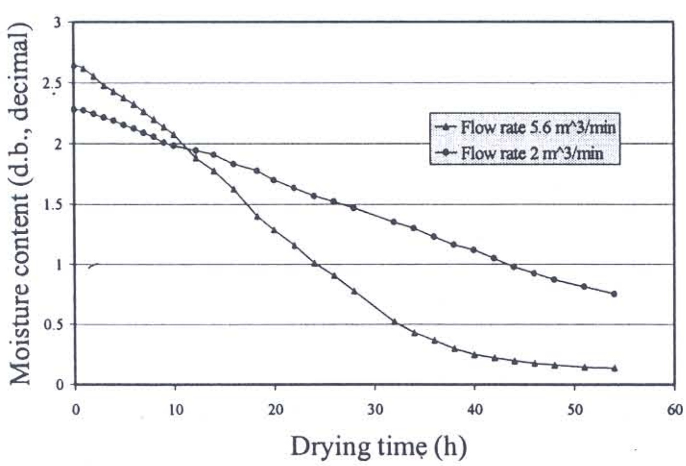

Fig. 6. Effect of airflow rate on the drying curve of whole longan at air temperature of 80°C, relative humidity of 70 % and the drum rotational speed of 1 rpm.

Figure 7 shows the effect of the drum rotational speed on the average moisture content of the whole longan bed during drying. It is found that increase of the drum rotational speed within a range of 0.50 to 0.75 rpm, allows the whole longan body to be in contact with air easily thus increasing the drying rate. However, as the speed is increased above 1 rpm the advantage is not significant. Moreover, if the speed is too high, there is mechanical damage to the skin of the fruit. Therefore, the rotational speed should not be over 1 rpm.

Figure 8 shows the specific energy consumption (SEC) which is used to remove water in the whole longan. For low moisture content, the removal of moisture is rather difficult, therefore, SEC increases with the decrease of whole longan moisture content. Moreover, it is found that the drying temperature has little effect on the specific energy consumption (SEC) at high moisture content of 0.15 to 3.00 (d.b., decimal) but at low moisture content, higher drying temperature such as at 90°C consumes more specific energy consumption (SEC) than that at 80°C. Therefore, at lower moisture content, lower drying temperature is recommended.

Figures 9, 10 and 11 show the simulation results of the whole longan drying, the air temperature and the humidity ratio distributions in the longan bed compared with the experimental results. The simulation results are consistent with the experimental results.

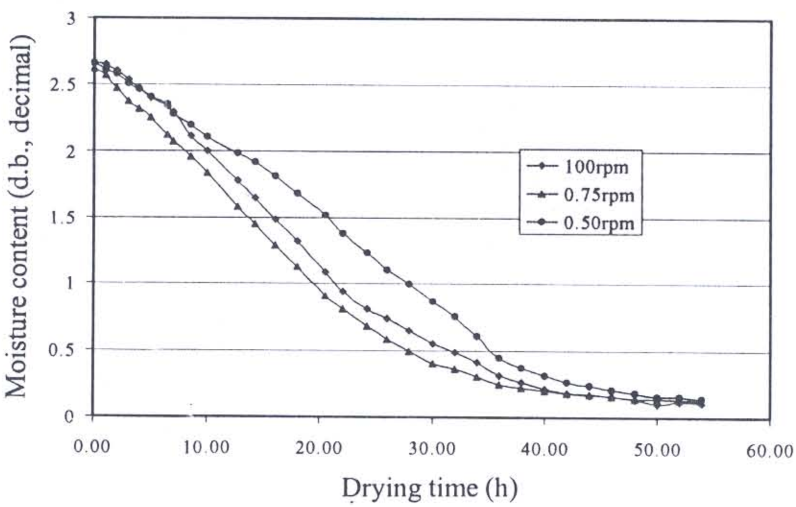

Fig. 7. Effect of the drum rotational speed on the drying curve of whole longan at air temperature of 80°C, relative humidity of 70% and airflow rate of 4.5 m³/min.

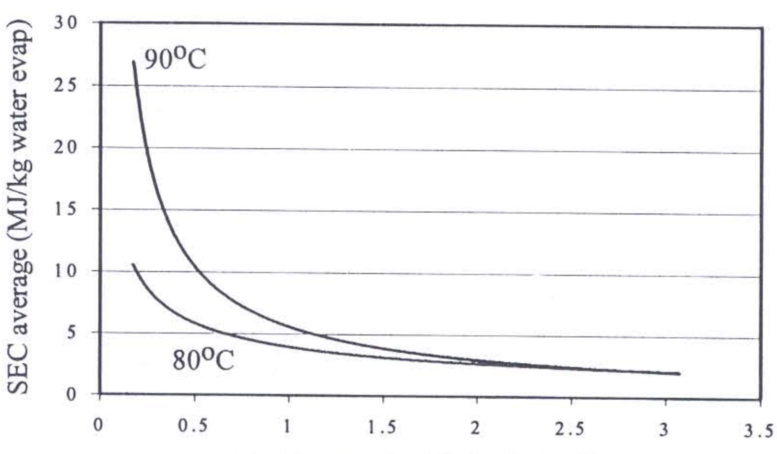

Fig. 8. Effect of average specific energy consumption (SEC) on moisture content at different drying temperature of 80°C and 90°C relative humidity of 70% and the drum rotational speed of 1 rpm.

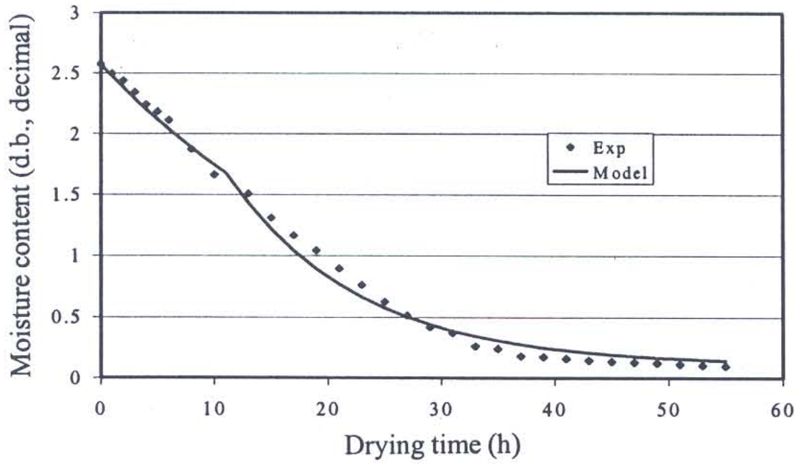

Fig. 9. Comparison of the drying curves, from mathematical model and experimental data, of whole longan at drying air temperature of 90°C, airflow rate of 4.5 m³/min, relative humidity of 70% and drum rotational speed of 0.75 rpm

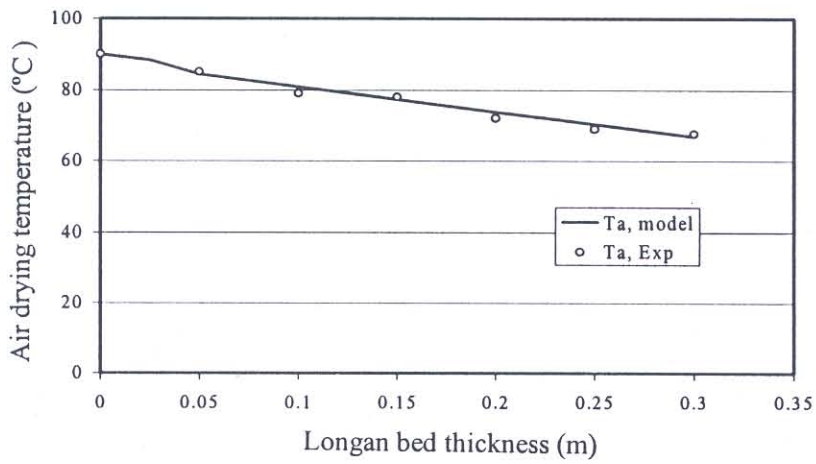

Fig. 10. Comparison of the air temperature distribution in the longan bed as a function of the bed thickness at drying air temperature of 90°C, airflow rate of 4.5 m³/min, relative humidity of 70% and drum rotational speed of 0.75 rpm.

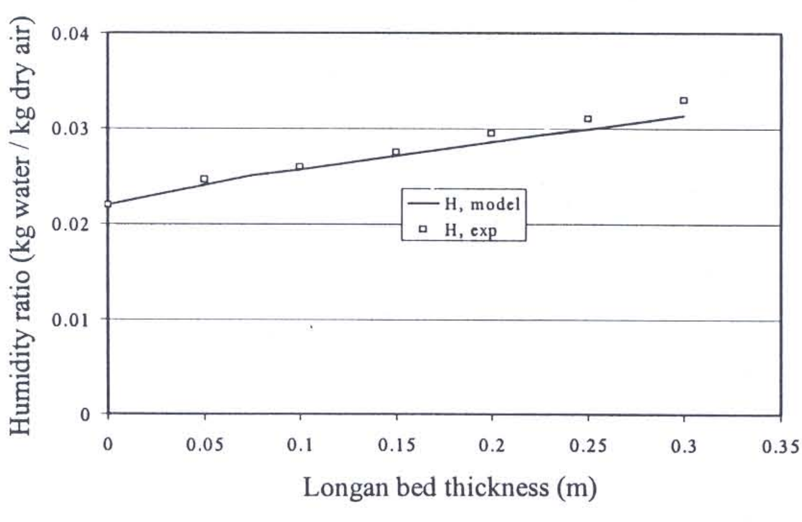

Fig. 11. Comparison of the humidity ratio distribution in the longan bed as a function of bed thickness at drying air temperature of 90°C, airflow rate of 4.5 m³/min, relative humidity of 70% and drum rotational speed of 0.75 rpm

4.2 Drying Efficiency and Financial Analysis of the Rotary Drum Longan Dryer

Drying efficiency results of the rotary drum longan dryer are shown in Table 1. The required final moisture content of each is about 0.25 (d.b, decimal) [8]. From experimental data, the average efficiency is 68% in 34 hours of drying time at 90°C of drying air temperature, 4.5 m^3/min of airflow rate and 0.75 rpm of drum rotational speed.

The efficiency of the rotary drum longan dryer is higher than the fixed bed longan dryer by 26.45%.

Table 2 shows financial analysis comparison between the rotary drum longan dryer (RLD) and the fixed bed whole longan dryer (FLD). It is found that the energy cost (fuel and electrical power) and the average labor cost of the rotary drum longan dryer are lower than the fixed bed dryer which are 2.17 and 1.75 baht per kg-dried produce, respectively. This is because the fixed bed dryer needs labor to turn over the longan bed every 12 hours of drying time.

Table 1 Summary of Experimental Data of Whole Longan Drying

Condition of produce	
Whole longan size (grade)	B
Average initial moisture content (%d.b)	257
Average final moisture content (%d.b)	25
Initial weight (kg)	295.3
Final weight (kg)	103.39
Moisture removed (kg)	191.90
Drying condition	
Average temperature (°C)	90
Air flow rate (m^3/min)	4.50
Rotary speed (rpm)	0.75
Average electrical power (kW)	0.568
Average fuel consumption (kg_{gas}/h)	0.367
Drying time (h)	34
Performance of a rotary drum longan dryer	
Drying $rate_{avg}$ (kg water evap/h)	5.64
Average specific energy consumption -	
-$(SEC)_{avg}$ (MJ/kg water evap)	3.37
Average efficiency (%)	68.61

Table 2 Comparison of Financial and Performance for Dryers (for Thailand, 2002)

Description	RLD	FLD
First cost or capital cost (baht)	35,000	45,000
Energy cost (baht/kg-dried produce)	2.70	4.87
Average labor cost (baht/kg-dried produce)	1.00	2.75
Average efficiency (%)	68.61	42.16

Fixed bed data (FLD) from Naramitrangsee, *et al.* [5]

5. CONCLUSIONS

At higher drying temperature, the airflow rate gives higher drying rate. However, at low moisture content, low drying temperature is recommended for low specific energy consumption. Higher drum rotational speed also increases the performance of the dryer but when the speed is too high, the advantage is not significant and there is mechanical damage to the skin of the fruit. The rotational speed should not be over 1 rpm.

Since the rotational speed is quite low, a simplified model of thin layer fixed bed could be used to evaluate the drying rate and the bed temperatures.

The drying efficiency of the rotary drum longan dryer is very high compared with the normal fixed bed dryer. The energy and the labor costs are cheaper significantly.

The quality of dried whole longan by the rotary drum longan dryer is very good and acceptable by consumers and the dryness of dried whole longan is more uniform than those dried by fixed bed dryer. The drying time of the rotary drum longan dryer is shorter than the fixed bed dryer.

6. ACKNOWLEDGEMENTS

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7. NOMENCLATURE

H	=	humidity ratio of drying air, kg of water / kg of dry air
ϕ	=	relative humidity of air
P_v	=	working pressure
P_{vs}	=	saturation vapor pressure of water
C_a, C_c	=	specific heat constant of air and product respectively, J/kg-K
L	=	specific latent heat (enthalpy of evaporation), J/kg.
k	=	drying constant in thin layer drying, s^{-1}.
G	=	superficial mass velocity (mass flow rate per unit area of bed), kg/m^2s
h_v	=	volumetric heat transfer coefficient, $W/m^3\,^{\circ}C$
M	=	moisture content of product (d.b), kg of water/kg of dry matter
M_{in}	=	initial moisture content of product, kg of water/kg of dry matter
M_{eq}	=	equilibrium moisture content of product (d.b), kg of water/kg of dry matter
T_{abs}	=	absolute temperature, K
T_a, T_c	=	temperature of air and product, $^{\circ}C$
t	=	time, h
ρ_c	=	bulk density of product, kg/m^3
r	=	thickness of bed, m

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