Drying Strategy of a Rotary Drum Longan Dryer

C. Thararux * and T. Kiatsiriroat **

* The Joint Graduate School of Energy and Environment
King Mongkut's University of Technology Thonburi
Bangkok 10140

** Department of Mechanical Engineering
Chiang Mai University, Chiang Mai 50200
THAILAND

ABSTRACT

A batch type rotary drum longan dryer is studied in this research work. A mathematical model for dehydration of whole longans to determine appropriate operating conditions of the dryer has been developed. The parameters affecting the drying performances are the drying air temperature, the air flow rate and the drum rotational speed. The experimental results agree very well with those of the simulated values. It is found that the appropriate operating condition is achieved when the drum rotational speed is 0.75 rpm. The drying air temperature is about 95°C when the specific mass flow rate of air is less than about 4.3 kg/h-kg dried longan and when the value is over this, the drying temperature should be 75°C.

1. INTRODUCTION

Longan is an economically valuable fruit grown in the northern part of Thailand. It is nearly spherical in shape with size ranging from 20 mm to 40 mm in diameter. When the fruit is ripe, its peel is light brown in color with a dark brown seed of approximately 10 mm diameter, covered by thick flesh. The flesh of the fruit varies from pale white to light pink in color and has sweet taste. The most popular longan variety is called E-dor which is about 80% of gross rate. This variety has high yield, high disease resistance, good quality (thick flesh, sweet, good aroma and small seed) and is easy to care. E-dor is harvested between July and September each year. The longan produced in 1997 was 195 000 tons, which valued to Baht 2,954 million (Baht 1 = US$ 0.023) and in 2000 the yield was up drastically to about 300 000 tons. The percentage of exported dried whole longans was about 35.41% and the trend is increasing continually [1].

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 preservation period. Dried longan flesh is widely consumed as dried fruit, longan juice, cake decoration, and other forms.

Hot air fixed bed dryers are most widely used for production of dried whole longans. Hot air heated directly by diesel oil or LPG is fed at the bottom of the longan bed. The hot air heats the longan, takes the moisture out and leaves at the top of the bed. It is found that this design has high heat loss. The thermal efficiency is about 32% [2] and the drying period is about 48 to 60 hours. Non-uniform drying is obtained thus resulting in non-uniform moisture content and quality and moreover, the shape of around 20% to 30% of the dried whole longan is deformed [3]. An improvement has been carried out by adjusting the hot air direction to be fed at the bottom and at the top alternately. The drying period could be reduced by 10% to 15% with better uniform drying [2].

Recovery of waste heat from fixed bed longan dryer by a thermosyphon heat pipe to preheat air before entering the heater has been carried out [4]. The payback period is around 4 to 5 years for a 2000 kg longan dryer.

A rotary drum longan dryer having hot air outside has been tested [5]. Hot air stream flows across the rotating drum. The drying period is 56 hours with thermal efficiency of 25%. The quality of the dried product is uniform throughout the drum.

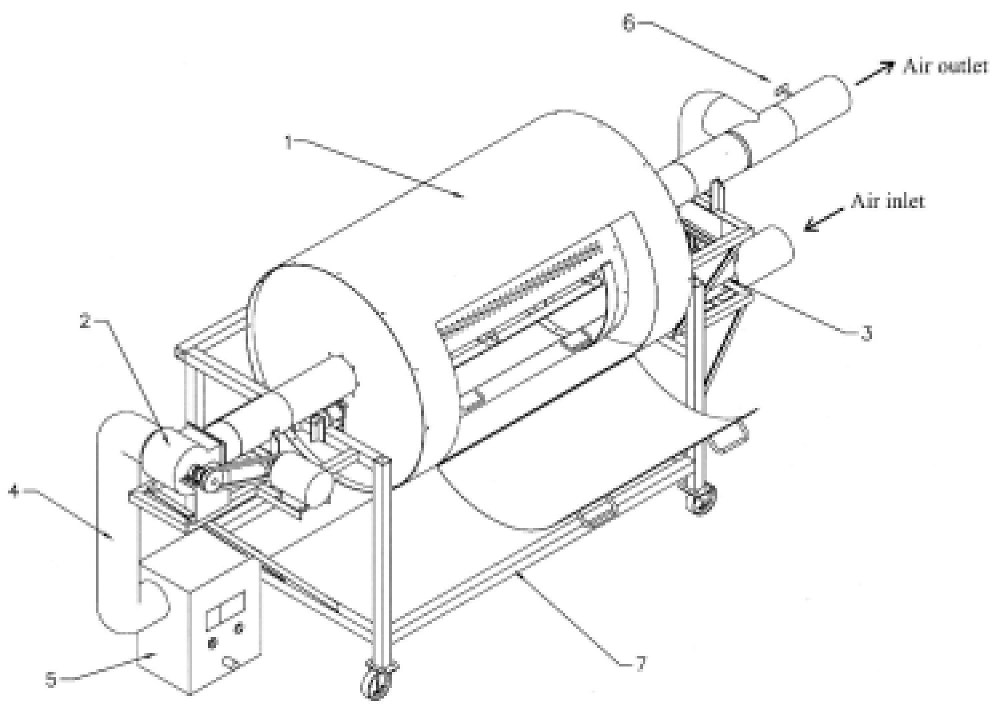
A new design of rotary drum longan dryer has been developed [6]. Hot air enters at the center core of the longan drum and moves radially through the longan bed. The efficiency is found to be about 70% and the drying time is 34 to 40 hours. The quality is found to be uniform throughout the drum.

In this paper, the longan dryer developed [6] is tested with different longan sizes. The drying strategy, with appropriate operating conditions such as drying air temperature, air flow rate and drum rotating speed which give low energy consumption, short drying period, good and uniform quality of the dried products, is carried out.

2. MATERIALS AND METHODS

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.



1 = Rotary drum longan dryer
2 = Air blower set
3 = Drum rotating speed control
4 = Air duct
5 = LPG burner
6 = Butterfly valve
7 = Main frame

Fig. 1 Isometric view of the rotary drum longan dryer

Longans were 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 generated heat to the air fed by the blower before entering the central core of the drum which was a perforated closed-end duct. The hot air leaving the central core was forced passing through the longan bed in the dryer uniformly, carried moisture, and left the drum shell to the exhaust duct. Some of the exhaust air could be recirculated and mixed with fresh air before running a new cycle. The schematic diagram of the rotary drum longan dryer is shown in Fig. 2.

3. MATHEMATICAL MODEL

The longan bed in the rotary drum longan dryer is assumed to be comprised of many thin layers positioned normal to the direction of air flow. 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 longan can be estimated from an energy and mass balance of that layer. Since the rotational speed of the drum is rather low, the fixed thin layer model based on the energy-mass equation concept is used to evaluate the drying rate and the bed temperature. Figure 3 shows the model of the longan bed.

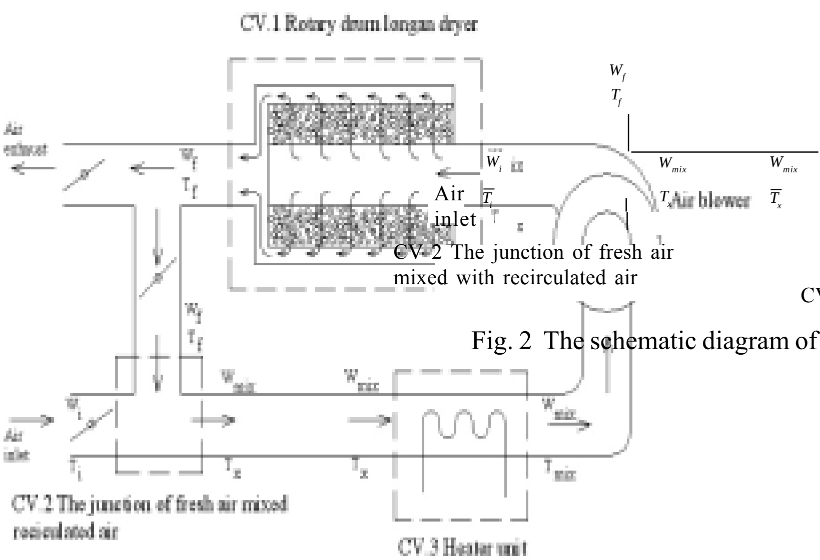


Fig. 2 The schematic diagram of the rotary drum longan dryer

Fig. 3 Element of the longan bed

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

- Drying air temperature and air flow rate are uniform within any longan layer,
- Heat of evaporation is far greater than sensible heat of the longan,
- $\partial T/\partial \tau$ and $\partial H/\partial \tau$ are negligible compared to $\partial T/\partial r$ and $\partial H/\partial r$,
- There is no heat loss by the system,
- Temperatures of the longan and air in each layer 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 of air:

(1)

- Energy balance of the longan:

(2)

- Mass balance of moisture in a thin layer of longan:

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

- Drying rate of a thin layer of longan:

(4)

From Eqs. (1) and (2),

(5)

which could be written in numerical form as:

(6)

Similarly, Eq. (3) could be rewritten as:

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

In constant drying rate period, the drying constant (k) is a function of drying temperature, T (°C), air flow rate, F (m³/min) and the drum rotational speed, V (rpm). The value of k could be experimentally found as:

$$k_1(T, F, V) = (-0.108821) + (1.81 \times 10^{-3}\, T) + (1.99 \times 10^{-3}\, F) + (-0.0274924\, V) \quad (8)$$

In the falling drying rate period, the air flow rate, and the drum rotational speed give little effect and the drying temperature is the main function only. Therefore the value of k is found as:

$$k_2(T) = 0.0019\, T - 0.0807 \quad (9)$$

$$M_{r,(t+1)} - M_{r,t} = -k\,(M_{r,t} - M_{eq})\Delta t \quad (10)$$

The equilibrium moisture content (M_{eg}) could be calculated from modified Oswin's model [7] as:

$$M_{eq} = 0.16187[\phi/(1-\phi)]^{(0.7095-0.00386T)} \quad (11)$$

ϕ is the air relative humidity which is given by:

$$\phi = \frac{P_v}{P_{vs}} = \frac{101.325H}{(0.622P_{vs} + HP_{vs})} \quad (12)$$

P_{vs} is the saturating vapor pressure of water which could be calculated [8] as:

From Eq. (4), the moisture content M_r after the time lapse Δt could be numerically calculated as:

$$\begin{aligned} \ln(P_{vs}) = & -\frac{7511.52}{T_{abs}} + 89.63121 + 0.023998970 T_{abs} - 1.1654551x10^{-5}\, T^2_{abs} \\ & - 1.2810336x10^{-8}\, T^3_{abs} + 2.0998405x10^{-11}\, T^4_{abs} - 12.150799 \ln(T_{abs}), \\ & 273.16\,\mathrm{K} < T_{abs} < 393.16\,\mathrm{K} \end{aligned} \quad (13)$$

H is the humidity ratio that could be calculated by:

$$H = \frac{0.622\phi P_{vs}}{(P_v - \phi P_{vs})} \quad (14)$$

The fuel consumption equation for the rotary drum longan dryer could be experimentally calculated by:

$$E = 0.29522 - 0.00371\, T - 0.14008\, F + 0.00252\, TF \quad (15)$$

where: E = fuel consumption (kg of LPG gas/h),
T = drying temprature (°C),
F = airflow rate (m³/min).

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

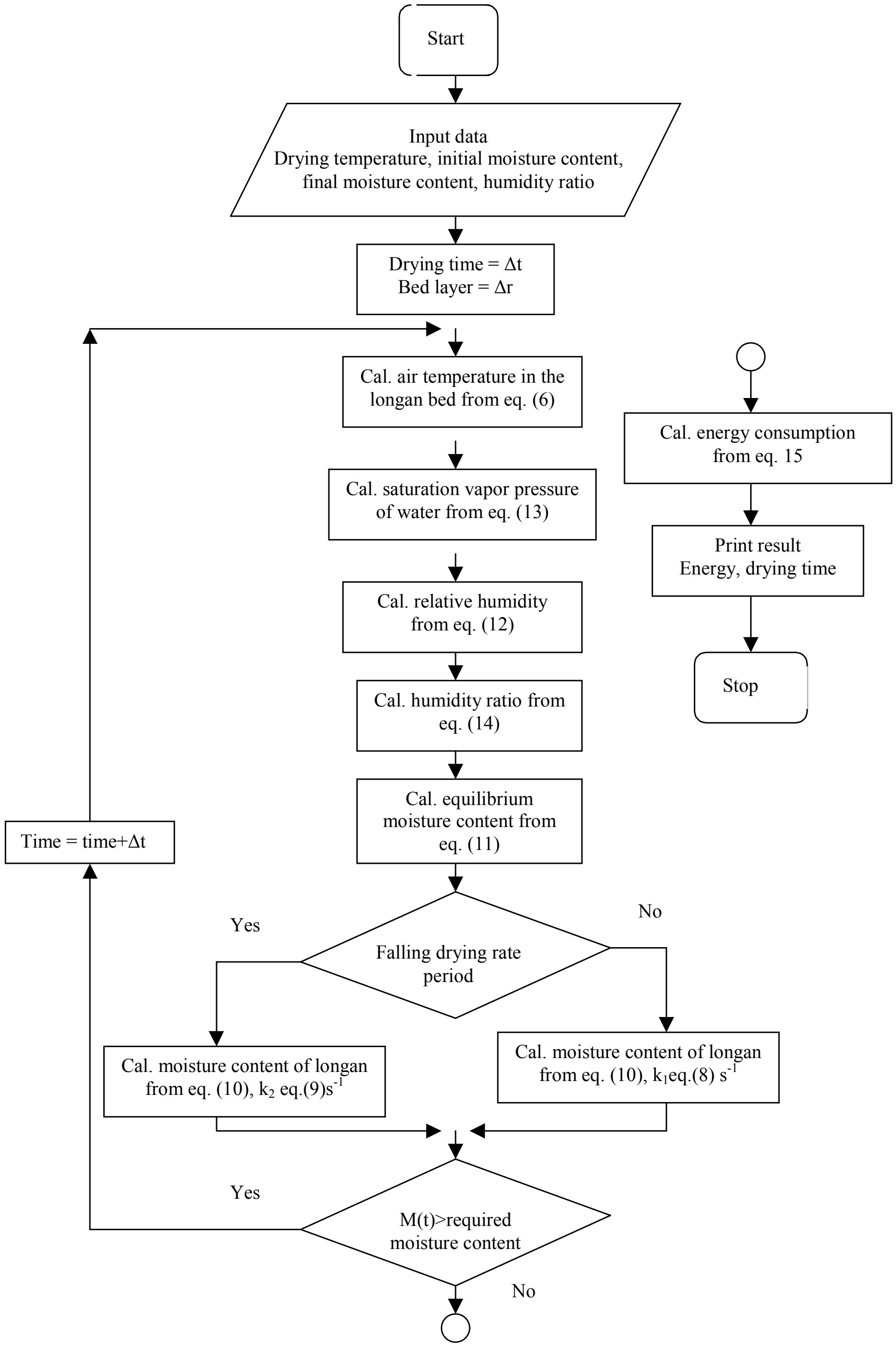


Fig. 4 Flow chart of the longan drying simulation

4. RESULTS AND DISCUSSIONS

Experimental study of the dryer performance has been carried out within the conditions given in Table 1. The system simulation has also been carried out and the results are verified with the experimental data.

Table 1 The Operating Conditions of the Rotary Drum Longan Dryer

Operating conditions	
Drying air temperature (^{o}C)	75 to 95
Drying air flow rate range (m^3/min)	2 to 9
Drum rotational speed (rpm)	0.50, 0.75 and 1.00
Air inlet temperature (^{o}C)	5 to 30
Air relative humidity (%)	70 to 80
Grade A longan size (cm in diameter)	2.21 to 2.51
Grade B longan size (cm in diameter)	1.94 to 2.20
Average initial moisture centent [% (d.b)]	300 to 400
Average final moisture content [% (d.b)]	21 to 25

Effect of Drying Parameters

Figure 5 shows the drying performance when the drying temperatures are 80^{0}C, 90^{0}C and 95^{0}C. It was found that the moisture content decreased as time lapsed. For the first 6 to 8 hours, the moisture content decreased steadily which means that the process was in a constant drying rate zone. After that, the moisture content decreased quickly in the falling drying rate region. The moisture content was at the near equilibrium state after about 40 hours. Higher drying air temperature resulted in higher rate of moisture removal. The rates of heat input at different drying air temperatures of 80^{0}C, 90^{0}C and 95^{0}C were 15.65 MJ/h, 16.67 MJ/h and 17.43 MJ/h, respectively.

Figure 6 shows the effect of air flow rate on drying performance. Higher air flow rate (5 m^3/min) would give better heat and mass transfer than lower air flow rate (2 m^3/min), therefore the moisture could be reduced quicker at higher air flow rate.

Figure 7 shows the effect of the drum rotational speed on the average moisture content of the whole longan bed during drying. It was found that increase of the drum rotational speed, would increase the drying rate because the whole longan body could contact the air thoroughly at higher speed. However, as the speed was increased to above 1 rpm the advantage was not significant. Moreover, if the speed was too high, there would be mechanical damage on the skin of the fruit.

Figure 8 shows the effect of the longan sizes A and B in drying phenomena. It was found that the drying period for the bigger size (A) was longer because of its higher moisture content and thicker flesh.

From Figs. 5 to 8, it could be found that the simulated results agreed very well with those of the experiments. Moreover, the quality of the longan flesh after drying was found to be in a very good condition. The maximum temperature should not exceed 95^{o}C otherwise the longan skin might be burnt.

Hot air recirculation was also experimentally performed after 20 hours of drying. Since the air leaving the bed was too humid, 20% by volume of the leaving air was recirculated and mixed with fresh air before entering the heater section. With the inlet conditions of air (90^{o}C, 84% RH of air temperature, 4.5 m^3/min of air flowrate, 1 rpm of drum rotational speed), the drying rate was rather low compared with that without the recirculation. Longer drying period would consume more fuel thus the recirculation was not recommended.

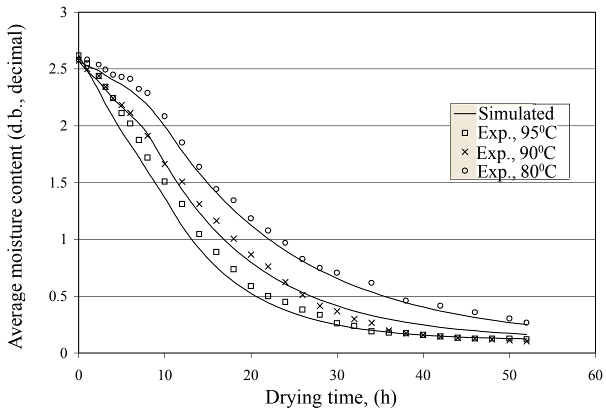


Fig. 5 Effect of different drying air temperatures at 80°C, 90°C and 95°C; drum rotational speed of 0.75 rpm; and air flow rate of 6 m^3/min or 4.3 kg/h-kg dried longan (dry matter)

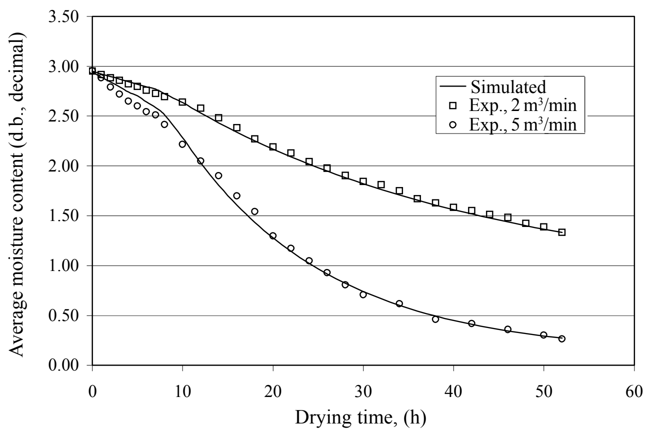


Fig. 6 Effect of different air flow rates at 2 and 5m^3/min, drum rotational speed of 0.75 rpm, drying air temperature of 80⁰C, and relative humidity of 84%

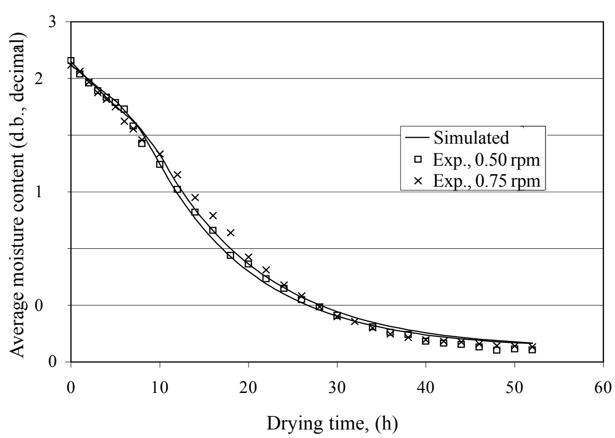


Fig. 7 Effect of drum rotational speeds at 0.50 and 0.75 rpm, air flow rate of 5 m^3/min, drying air temperature of 80°C, and relative humidity of 84%

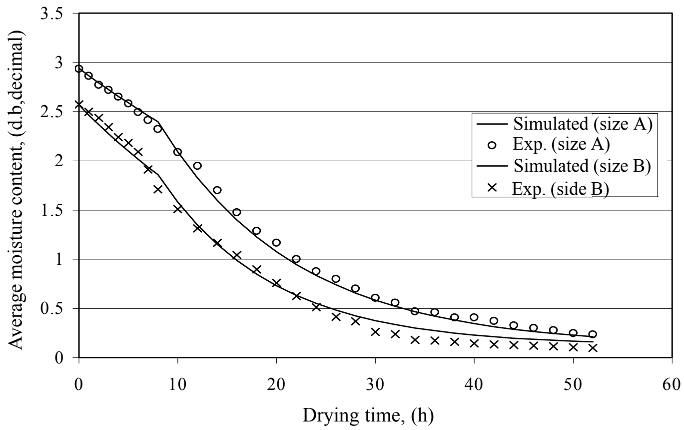


Fig. 8 Comparison of simulated and experimental moisture content of whole longans (A and B grade) at drying temperature of 90°C, relative humidity of 84%, air flow rate of 4.50 m^3/min, and drum rotational speed of 1 rpm

Figures 9 to 11 show the simulated results of the specific air mass flow rate and the drying temperature on the specific energy consumption and the drying period using B-grade longan.

As shown in Fig. 9, with higher drying temperature, the rate of moisture removal was higher, thus shorter drying time in each batch was obtained. Higher specific mass flow rate also reduced the drying period because of higher heat and mass transfer coefficients.

As shown in Figs. 10 and 11, at low specific air mass flow rate, higher drying temperature resulted in shorter drying period and lower specific energy consumption, thus the operating energy consumption in each batch were obtained. However, at high drying temperature (80°C and over) when the air flow rate was too high, high energy was consumed. When the specific air mass flow rate was over about 4 kg/h-kg dried longan, the reversed results in energy consumption were obtained. With the drying air condition at 80°C, 87% RH and the specific air mass flow rate of 4.35 kg/h-kg (dried longan) the specific energy consumption of the rotary drum dryer was about 3.86 MJ/kg (water evaporated) which was significantly lower than that of the common fixed bed dryer [7.42 MJ/kg (water evaporated)] [1].

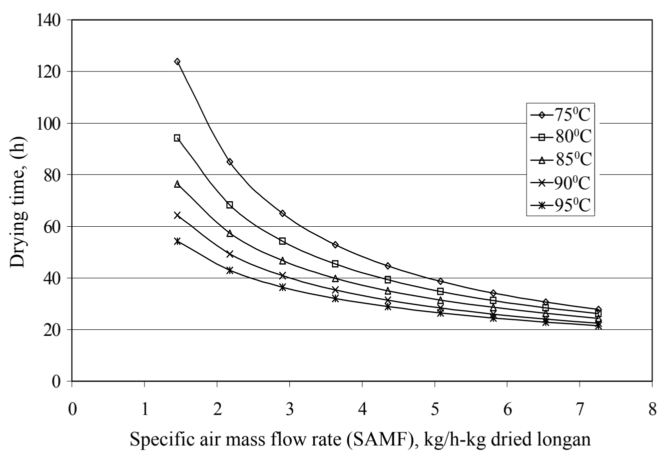


Fig. 9 Simulation of drying time at different drying temperatures of 75°C to 95°C, different specific air mass flow rate (SAMF) of 1.451 to 7.25 kg/h-kg dried longan, drum rotational speed of 0.75 rpm and relative humidity of 84%

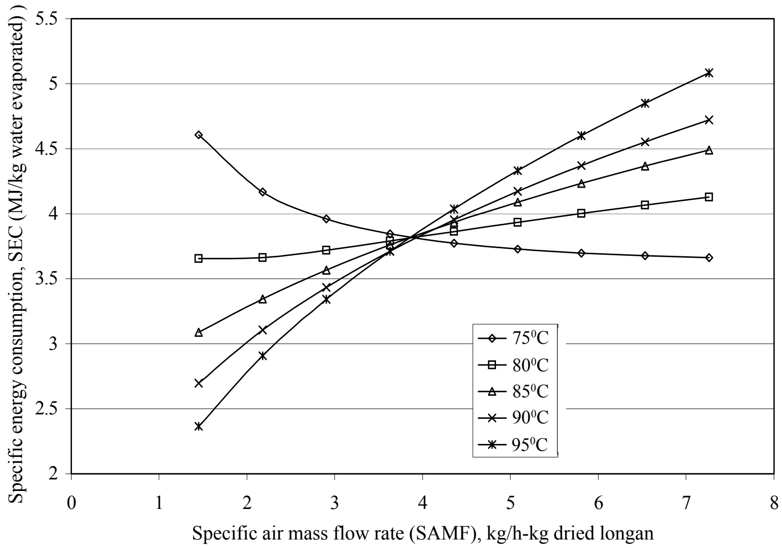


Fig. 10 Simulation of specific energy consumption (SEC) at drying temperatures of 75°C to 95°C (84% RH), specific air mass flow rates (SAMF) of 1.45 to 7.25 kg/h-kg dried longan and drum rotational speed of 0.75 rpm. The energy consumption includes gas fuel and electrical power at the blower

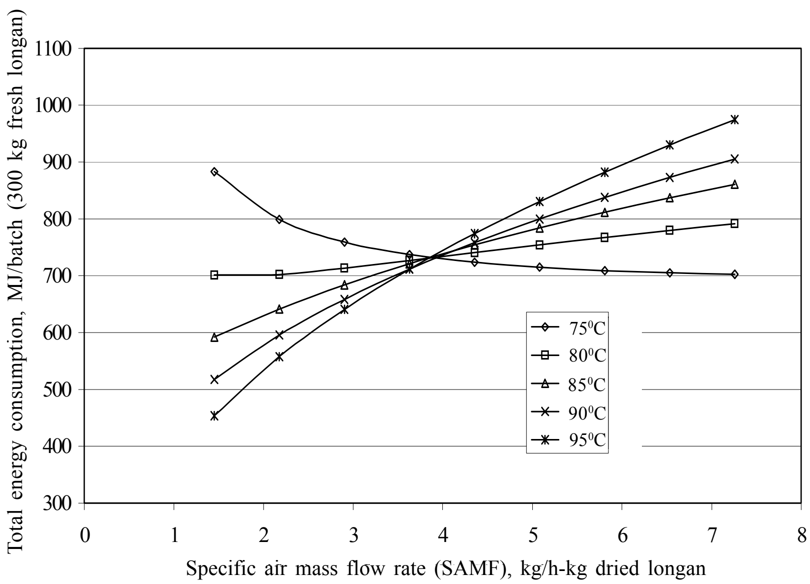


Fig. 11 Simulation of total energy consumption, MJ/batch (300 kg fresh longan) at drying temperatures of 75°C to 95°C, specific air mass flow rates (SAMF) of 1.45 to 7.25kg/h-kg dried longan and drum rotational speed of 0.75 rpm. The energy consumption includes gas fuel and electrical power at the blower

With shorter drying time, more batch drying operations could be performed in each year. Figure 12 shows productivity (numbers of batch) of longan drying. High drying temperature and specific air mass flow rate (SAMF) can yield more productivity than low drying temperature since the drying time is shorter.

The cost of dried B-grade longan in the market is about 50 Baht/kg, then the net income in each batch could be obtained by subtracting the selling price with the operating cost in each batch (investment cost). Figure 13 shows that at low SAMF and higher drying temperature, the dryer consumes lower energy thus more net income per batch is obtained. The results are reversed when the SAMF is over about 4.3 kg/h-kg dried longan.

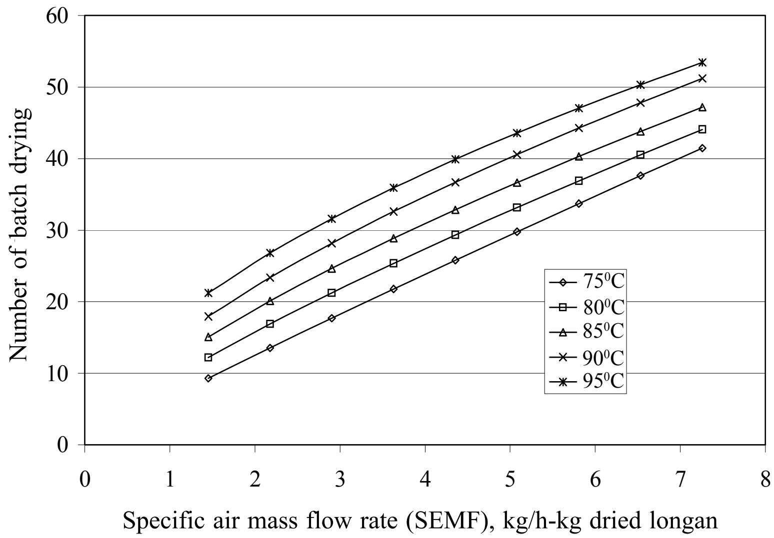


Fig. 12 Simulation of the number of batch drying in one year at drying temperatures of 75°C to 95°C, specific air mass flow rates (SAMF) of 1.45 to 7.25 kg/h-kg dried longan, and drum rotational speed of 0.75 rpm

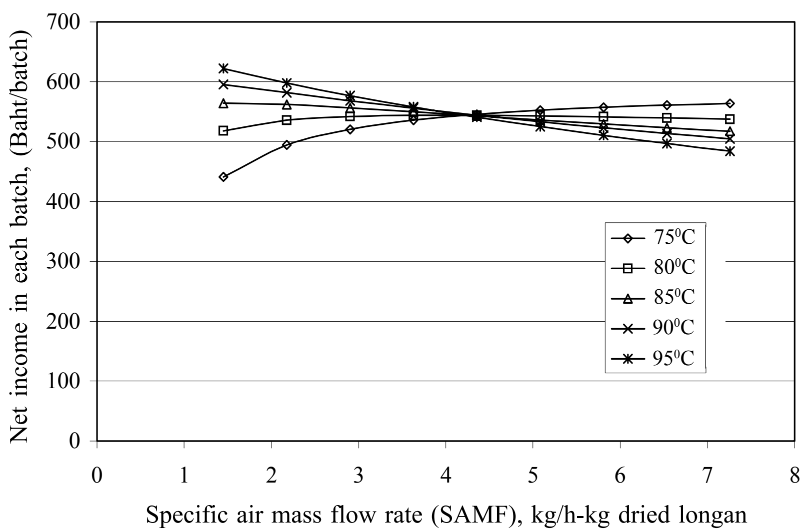


Fig. 13 Simulation of the net income in one batch at drying temperatures of 75°C to 95°C, specific air mass flow rates (SAMF) of 1.45 to 7.25 kg/h-kg dried longan and drum rotational speed of 0.75 rpm (1 Baht = US$ 0.023)

Table 2 shows the cost of total energy consumed (gas fuel and electrical power at the blower) in one batch at different air flow rates and air temperatures. The cost of raw material (fresh longan) is Baht 3,000 and the labor cost is Baht 300. The revenue is the sale price of dried longan which is Baht 4,750.

Table 2 Cost of Total Energy Consumed in One Batch (Baht)

Temp.	Air mass flow rate (kg/h-kg dried longan)								
	1.45	2.18	2.90	3.63	4.36	5.08	5.81	6.53	7.26
75^0C	358.80	305.79	279.70	264.41	254.52	247.69	242.75	239.07	236.25
80^0C	281.99	264.31	258.01	256.03	256.05	257.09	258.68	260.58	262.65
85^0C	235.95	237.91	243.68	250.42	257.31	264.07	270.60	276.86	282.87
90^0C	204.41	218.24	231.75	244.32	255.96	266.78	276.89	286.38	295.34
95^0C	177.78	202.10	223.25	242.09	259.18	274.90	289.50	303.18	316.08

From the above results, the appropriate drying temperature of the rotary drum longan dryer should be about 95°C and the specific air mass flow rate should be less than about 4.3 kg/h-kg dried longan. When the specific air mass flow rate was over this, the appropriate drying temperature should be about 75°C.

5. CONCLUSIONS

The rotary drum longan dryer can be used for drying whole longan and other similar products. The parameters affecting the drying performance are the air drying temperature, air flow rate and drum rotational speed. The maximum drying temperature should not exceed 95°C otherwise the longan skin might be burnt. The drying temperature should be 95°C and 75°C when the specific air mass flow rate is less than and over about 4.3 kg/h-kg dried longan, respectively. The drum rotational speed should be about 0.75 rpm.

6. ACKNOWLEDGEMENTS

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7. NOMENCLATURE

C_a, C_c	=	specific heat constant of air and crops respectively, J/kg-K
F	=	air flow rate, m^3/min
G	=	superficial mass velocity (mass flow rate per unit area of bed), kg/m^2s
h_v	=	volumetric heat transfer coefficient, W/m^{3o}C
H	=	humidity ratio of drying air, kg of water /kg of dry air.
k	=	drying constant of the rotary drum longan dryer, h^{-1}.
L	=	specific latent heat (enthalpy of evaporation), J/kg.
M	=	moisture content of crops (d.b), kg of water/kg of dry matter.
M_{in}	=	initial moisture content of crops, kg of water/kg of dry matter.
M_{eq}	=	equilibrium moisture content of crops (d.b), kg of water/kg of dry matter.
P_v	=	working vapor pressure, P_a

P_{vs} = saturation vapor pressure of water, P_a
r = thickness of bed, m.
t = time, h.
T_{abs} = absolute temperature, K.
T_a, T_c = temperature of air and crops, ^oC.
V = the drum rotational speed, rpm

Greek Letters

ϕ = relative humidity of air
ρ_c = bulk density of crops, kg/m^3

Subscripts

a = air
abs = absolute
c = crop
eq = equilibrium
in = initial
v = vapor
vs = saturated vapor

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