Optimum Strategies for Drying Papaya Glace'

Somchart Soponronnarit, Siva Achariyaviriya and Penpun Tasaso

ABSTRACT

A mathematical model for papaya glace' drying based on thermal equilibrium between the drying air and the product was developed. It predicted the drying rate with fair accuracy at an initial product moisture content of about 45% d.b. The effect of temperature on product quality was observed. The effects of temperature, air flow rate and fraction of air recycled on drying time and energy consumption were also observed. The criteria for optimum drying of papaya glace' in a cabinet dryer were product quality, drying time and energy consumption. Experimental and simulated results showed that a drying temperature of 65°C, a specific air flow rate of about 50 kg dry air/h-kg dry papaya glace' and about 0.8 of air recycled should be used.

INTRODUCTION

Papaya is a major economic crop in Thailand. Papaya fruit is commonly processed as papaya glace', usually in small cubes, by dipping fresh papaya in sugar solution then drying in cabinet or tunnel driers. Variables which affect the performance of drying (measured in terms of product quality, drying time and energy consumption) are drying air temperature, air flow rate and fraction of drying air recycled.

In the literature, there are few reports on papaya glace' drying. Tanafranca, Farre, Angeles and Soriano (1985) investigated various glace' processes of papaya. Bhumiratana, Tripetchkul, Yoovidhya, Boonnag and Patamayothin (1988) also investigated glace' processes of papaya and studied mass transfer between papaya and sugar solution. Haruthaithanasan, Chompreeda, Khotavivattana and Vitayanathpisal (1988) studied drying of papaya by solar energy and found it required about three days to reduce the moisture content from 80 to 15% wet-basis. Moy and Kuo (1985) studied drying of papaya by osmosis followed with vacuum drying. They also studied the effect of solar energy in osmosis and drying processes on product quality and drying rate. Drying rate was increased while quality remained the same as without solar energy. Levi, Gagel and Juven (1983, 1985) investigated the effect of various treatments of fresh papaya on drying rate and energy consumption. The drying time for cabinet or solar drying following osmotic treatment of papaya was considerably shortened, giving a significant saving in heat energy. Soponronnarit (1988) developed a mathematical model for grain drying, capable of predicting drying rate and energy consumption, which was used to study the optimum strategies for paddy drying. Krongsap (1989) employed this model to study the optimum strategies for batch drying of corn.

From the above literature, it was noted that mathematical models for fruit drying in cabinets needed to be developed. In most grain drying, exhausted air is seldom recycled but it is usually recycled in fruit drying in cabinet or tunnel dryers. This is due to the much higher air flow rates employed in cabinet or tunnel dryers compared with that for grain drying.

The objectives of this study were to develop a mathematical model for the prediction of drying papaya glace' in a cabinet dryer and to use the model for the investigation of optimum drying conditions. Variables considered were air flow rate, air temperature and fraction of air recycled. Criteria for determining the optimum drying conditions were product quality, drying time and energy consumption.

DEVELOPMENT OF MATHEMATICAL MODEL

The mathematical model of drying developed here is similar to those of Soponronnarit (1988) and Thompson, Peart and Foster (1968). It is assumed that thermal equilibrium exists between the drying air and the product. The model comprises three submodels, namely drying, electrical and heat consumption, and moist air properties.

1. Drying Model

The model was developed for cabinet drying specifically for drying papaya glace'. However, it may be easily modified for use with other products and also for tunnel drying. The details of the drying model are as follows:

1.1 Calculation of product moisture content

The calculation of moisture content of papaya glace' during drying was based on the drying rate equation developed by Achariyaviriya and Soponronnarit (1988). It was applied to cubic papaya glace' having an initial moisture content of about 45% dry-basis. It is written

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as follows:

$$MR(t) = (8/\pi^2)^3 [\exp(-3\pi^2 Dt/L^2) + (3/9)\exp(-11\pi^2 Dt/L^2) + (3/25)\exp(-27\pi^2 Dt/L^2)] \quad (1)$$

where $MR(t) = (M(t) - M_{eq})/(M_{in} - M_{eq})$ (2)

$MR(t)$ = moisture ratio, decimal
$M(t)$ = mean moisture content, decimal dry-basis
M_{in} = mean initial moisture content, decimal dry-basis
M_{eq} = equilibrium moisture content, decimal dry-basis
t = drying time, h
L = size of cubic papaya glace', m

D is diffusion coefficient (m^2/h) and is written as follows:

$$D = 0.000917 \exp[-2877.49/((T_{mix} + T_f)/2 + 273)] \quad (3)$$

where T_{mix} = inlet drying air temperature, °C

T_f = exit drying air temperature, °C

M_{eq} was found using the equation of Brunauer, Emmette and Teller (1938) whose parameters were determined by Achariyaviriya and Soponronnarit (1988). It is written as follows:

$$M_{eq} = cM_m RH/(1 + cRH - 2RH - cRH^2 + RH^2) \quad (4)$$

where $c = 163.15 \exp[-0.0647(T_{mix} + T_f)/2]$ (5)

$$M_m = 3.1987 + 0.14077 (T_{mix} + T_f)/2 \quad (6)$$

RH = relative humidity of drying air, decimal

Equation (1) can be used to calculate the mean moisture content of cubic papaya glace' by differentiating it with respect to time and then using the Runge-Kutta method to solve the resulting differential equation over a small time interval Δt. This equation can be written as follows:

$$dM(t)/dt = f(t) = (M_{in} - M_{eq})(-3C_1)(8/\pi^2)^3 [\exp(-3C_1 t) + (11/9)\exp(-11C_1 t) + (27/25)\exp(-27C_1 t)] \quad (7)$$

and $M_f = M_i + (1/6)(k_1 + 2k_2 + 2k_3 + k_4)$ (8)

where $C_1 = \pi^2 D/L^2$
$k_1 = \Delta t\, f(t)$
$k_2 = \Delta t\, f(t + 0.5\,\Delta t)$
$k_3 = \Delta t\, f(t + 0.5\,\Delta t)$
$k_4 = \Delta t\, f(t + \Delta t)$

where M_f = mean moisture content at the end of the time interval, Δt, decimal dry-basis
M_i = mean moisture content at the beginning of Δt, decimal dry-basis
Δt = time interval, h

1.2 Calculation of moist air properties after drying process

From application of the principle of energy conservation, the change of enthalpy of the flowing air stream plus the change in internal energy of the drying product and the cabinet dryer, are equal to the heat exchange between the drier and its surroundings. This can be written as follows:

$$C_a T_f + W_f(h_{fg} + C_v T_f) - C_a T_{mix} - W_{mix}(h_{fg} + C_v T_{mix}) + \Delta U_p + \Delta U_d = q \quad (9)$$

or

$$T_f = [q + C_a T_{mix} + W_{mix}(h_{fg} + C_v T_{mix}) - W_f h_{fg} - \Delta U_p - \Delta U_d]/(C_a + W_f C_v) \quad (10)$$

where $\Delta U_p = [(m_p C_p)/(\dot{m}_{mix}\Delta t)][(T_p + T_{mix})/2 - T_p]$ (11)
$\Delta U_d = [(m_d C_d)/(\dot{m}_{mix}\Delta t)][(T_d + T_{mix})/2 - T_d]$ (12)
ΔU_p = the change in internal energy of papaya glace' per unit mass of dry air, kJ/kg-dry air
ΔU_d = the change in internal energy of the dryer itself per unit mass of dry air, kJ/kg-dry air
T = temperature, °C
q = heat loss per unit mass of dry air, kJ/kg-dry air
C = specific heat, kJ/kg°C
W = humidity ratio of air, kg-H_2O/kg-dry air
h_{fg} = latent heat of vaporization of water, kJ/kg-H_2O
m = dry mass, kg
$\dot{m}$ = mass flow rate of dry air, kg/h

with subscripts :
a = dry air
d = dryer
f = dryer exit
p = papaya glace'
v = vapour
mix = mixed air before entering the dryer

From mass conservation, the increase of moisture in the air equals the decrease of moisture in the product. The equation, after some rearrangement, can be written as follows (see Figure 1):

$$W_f - W_{mix} = (M_i - M_f)R \quad (13)$$
or $W_f = (M_i - M_f)R + W_{mix}$ (14)
where $R = m_p/(\dot{m}_{mix}\Delta t)$ (15)

The mixture equations used were (see Figure 1):

$$\dot{m}_{mix} W_{mix} = \dot{m}_i W_i + \dot{m}_{rc} W_f \quad (16)$$
$$\dot{m}_{mix} = \dot{m}_i + \dot{m}_{rc} \quad (17)$$

From Equations (16) and (17), it can be proved that

$$W_{mix} = (1-RC)W_i + RC\, W_f \quad (18)$$

where RC is the fraction of air recycled and is equal to $\dot{m}_{rc}/\dot{m}_{mix}$.

2. Model of Heat and Electricity Consumption

The temperature rise of air while flowing across a fan can be calculated using the following equation (derived from the first law of thermodynamics for steady flow):

$$T_{fan} = P/[\rho_a e_f (C_a + C_v W_{mix})] \quad (19)$$

where T_{fan} = temperature rise across a fan (°C)
P = pressure drop (kPa)
e_f = fan efficiency (decimal)
ρ_a = air density, kg/m^3

The pressure drop can be calculated by the following equation:

$$P = aV^b \tag{20}$$

where V is air velocity (m/s) and a and b are constants. For this study, a and b were estimated to be 420.1 and 1.1, respectively.

Temperature rise due to mixing of the recycled air with fresh air can be calculated using the first law of thermodynamics, which states that the summation of changes of enthalpy of flowing streams during steady flow is equal to zero in the absence of heat losses and at constant pressure. This can be written as follows (see Figure 1):

$$\dot{m}_{mix} C_a T_x + \dot{m}_{mix} W_{mix}(h_{fg} + C_v T_x) - \dot{m}_i C_a T_i - \dot{m}_i W_i (h_{fg} + C_v T_i) - \dot{m}_{rc} C_a T_f - \dot{m}_{rc} W_f (h_{fg} + C_v T_f) = 0 \tag{21}$$

The temperature rise can then be calculated by the following equation:

$$\Delta T_{rc} = T_x - T_i \tag{22}$$

where T_x is the mixing air temperature, T_i is the ambient or fresh air temperature, and ΔT_{rc} is the temperature rise due to the air recycled.

The temperature rise of air by a heater can be calculated as follows:

$$\Delta T_h = T_{mix} - (T_i + \Delta T_{rc} + \Delta T_{fan}) \tag{23}$$

where ΔT_h is the temperature rise of air by heater, °C.

The rate of heat consumption by the heater can then be calculated as follows:

$$Q_h = \dot{m}_{mix} (C_a + C_v W_{mix}) \Delta T_h \tag{24}$$

where Q_h is the rate of heat consumption in kJ/h.

The rate of electricity consumption for driving the fan can be calculated as follows:

$$E = \dot{m}_{mix} P / (\rho_a e_f e_m) \tag{25}$$

where E is the rate of electricity consumption (kJ/h) and e_m is the efficiency of the electric motor (decimal).

Moist air properties were calculated using the equations of Wilhelm (1976).

METHOD OF CALCULATION

The equations were solved by iteration as follows. The calculation starts with Equation (18) by assuming that the exit humidity (W_f) is 0.01 kg/kg. Equation (10) is then used to calculate T_f. In this study T_{mix} is known and in practice this is controlled by a thermostat. Then RH is calculated using the average air properties through the drier, Equation (4) is used for calculating M_{eq}, M_f is obtained from Equation (8) and W_f is calculated from Equation (14). The value of W_f is then compared with the assumed value. If the difference is higher than the set value, the same calculation is repeated again using the new assumed value of W_f which is the average of the two values. If the difference is less than the set value, RH_f is calculated and checked for feasibility (≤ 1). If it is reasonable the calculation is advanced to energy consumption. Otherwise, condensation is simulated (see details in Soponronnarit, 1987) and then the calculation is continued.

The next step is to calculate energy consumption by using Equations (24) and (25) and the simulated results are then presented. The time step is then advanced and the same process repeated. The simulation flow chart is presented in Figure 2.

PROCEDURE

Papaya glace' was prepared by dipping fresh papaya in a solution of C_aCl_2, 0.7%, for 18 hours, leaching in hot water for 25 minutes then dipping it in a sugar solution which started at a concentration of 30° Brix and was increased by 10° Brix each day up to 70° Brix (Tanafranca et al., 1985). The papaya glace' was then cut in cubes (0.5-0.9 cm) and dried in a small drier in which three trays were placed one above the other (Soponronnarit and Nopparatkrailas, 1988). The drying air was directed across these trays. Three tests were conducted. Hereafter, the small drier will be called Dryer No. 1.

Some wet papaya glace' was bought from a royal food factory and from a private food company. The papaya glace' was prepared by cutting into cubes (1.31 cm) and then drying in a cabinet dryer called Dryer No. 2, into which five trays were placed (see Figure 3). The drying air was blown along these trays. Seven tests were conducted.

During the experiments, both dry and wet bulb temperatures were measured by thermistors or thermocouples connected to data loggers with an accuracy of about 1°C. Air relative humidity was calculated from dry and wet bulb temperatures. Moisture loss from the drying product was measured by weighing the trays at certain time intervals. At the end of drying, the dry mass of the product was determined by drying in an air oven at 103°C for 72 hours. The accuracy of the balance was +0.01 gram. The air flow rate was determined by measuring the air velocity in the duct using a pitot-static tube. At the end of drying, the colour, shrinkage and rigidity of the product were observed.

RESULTS AND DISCUSSION

1. Experimental Results

Results of seven tests of papaya glace' drying in Dryer No. 2 (cabinet dryer) are presented in Table 1. Four kilograms for each batch were dried except for test no. 1 (3 kg). Drying air temperatures varied from 45 to 75°C. The specific air flow rate varied from 68 to 462 kg dry air/h-kg dry papaya glace'. The fraction of air recycled varied from 0.16 to 0.84. Initial moisture content varied from 56 to 128% dry-basis.

From Table 1, it can be concluded by comparing tests nos. 2 and 6 that the specific energy consumption decreases with the specific air flow rate. Both tests have the same drying temperature, fraction of air recycled, and initial moisture content. It can also be concluded by comparing tests nos. 3 and 4 that the specific energy consumption decreases when the fraction of air recycled increases, since for both test other drying parameters are similar. Results of tests nos. 5 and 6 indicate that the specific energy consumption increases when the drying air temperature decreases. The comparison of the above results (especially drying rate) obtained from different drying tests should take account of the fact that there is some difference in ambient conditions as well as in the method of preparation of the fresh papaya glace'. Drying times (18-24 hours) among the seven tests did not vary greatly.

The quality of the product after drying was also observed. When papaya glace' was dried with an air temperature below 65°C, the colour was good, (compared with the product available in the market). The product did not shrink too much and its skin was not too hard. When the product was dried at higher temperature (75°C), the colour became darker, the skin was hard and the product shrank significantly. When R.H.S. colour paper is used, the colour of the product before drying at 55°C corresponded to code 28 A and the product after drying corresponded to code 33 A or 34 A.

From the three drying tests done in Dryer No. 1 (small

Table 1. Drying results for Dryer No. 2 (cabinet dryer)

Test No.	1	2	3	4	5	6	7
Drying temperature (°C)	45	55	55	55	65	55	75
Specific air flow rate (kg dry air/h-kg dry papaya glace')	462	344	216	216	89	91	68
Fraction of air recycled	0.32	0.32	0.32	0.16	0.32	0.32	0.84
Mass of papaya glace' (kg)	3	4	4	4	4	4	4
Size of cube (cm)	1.3	1.3	1.3	1.3	1.3	1.3	1.3
<u>Ambient conditions</u>							
Temperature (°C)	30.4	28.3	31.1	32.6	28.4	29.0	33.5
Relative humidity (%)	72.3	79.3	80.0	77.0	68.3	71.3	84.0
Humidity ratio (kg H_2O/kg dry air)	0.0198	0.0194	0.0230	0.0242	0.0167	0.0181	0.0283
<u>Mean moisture content of papaya glace'</u>							
Before drying (% d.b.)	82.2	80.9	127.9	127.9	55.7	80.0	81.1
After drying (% d.b.)	28.7	24.0	23.1	25.8	24.0	20.0	20.6
Dry mass (kg)	1.647	2.211	1.755	1.755	2.560	2.210	2.210
<u>Energy consumption</u>							
Motor (kWh)	3.90	3.50	1.80	1.90	1.25	1.75	1.25
Heater (kWh)	55.90	49.20	32.20	57.50	18.55	24.30	20.65
Total	59.80	52.70	34.00	59.40	19.80	26.05	21.90
Specific energy Consumption (MJ/kg-H_2O)	159.0	106.0	54.5	95.3	49.5	52.4	44.4
Drying time (h)	20	24	24	22	18	24	18

dryer), the results concerning product quality were similar to the above results for Dryer No. 2 (cabinet dryer).

2. Comparison between Experimental and Simulated Results

Figure 4 shows the evolution of moisture content obtained from the experiment in Dryer No. 1 (test no. 1) and that of simulation. The simulated drying rate was slower at the beginning of drying but faster towards the end of drying. The drying rate of one cube of papaya glace' obtained by Achariyaviriya and Soponronnarit (1988) showed the same tendency. The simulated and experimental results from tests no. 2 and 3 confirm these observations.

3. Determination of Optimum Drying Strategies

In the investigation of strategies for drying papaya glace', product quality, drying time and energy consumption were used as the criteria. Results of product quality were obtained from experiments as a function of drying temperature. Results of drying time and energy consumption were obtained from the mathematical simulation. For the simulation, it was assumed that the initial and final moisture content of papaya glace' (in cubes) were 41 and 21% d.b., respectively. Ambient temperature was 30°C and humidity ratio 0.015 kg water/kg dry air (56% RH). The energy for driving the fan was always less than 5% of the total energy. Heat losses from the dryer were also very small, less than 2%.

Figure 5 shows the results of the drying simulation of papaya glace' in 0.005m cubes using a drying air temperature of 60°C. The specific energy consumption depended on the specific air flow rate and the fraction of air recycled. If the specific air flow rate was small, the specific energy consumption would not decrease when the fraction of air recycled increased. However, the results were reversed when the air flow rate was high. The specific energy consumption decreased with the fraction of air recycled to a minimum, and then increased due to an excessively high humidity ratio in the drying air. The minimum value was obtained at about 0.95 of air recycled. However, the drying time started to increase at about 0.7 recirculation. If both drying time and energy consumption were considered, the point of minimum energy consumption could not be selected (longer drying time). On this basis a specific air flow rate of about 50 kg dry air/h-kg dry matter and a recirculation ratio of about 0.8 is recommended (Figure 5). At this condition the difference between the dry and wet bulb temperatures was about 24°C and this may be more practical for operating dryers (ease of monitoring). At higher specific air flow rates, similar results to that of 50 kg dry air/h-kg dry matter were obtained. However, the proportion of electricty consumption was increased. In practice the economics of increased throughput versus increased electricity costs would determine the optimum flow rate for a given application.

When a drying air temperature of 70°C was used instead of 60°C, the specific energy consumption was lower. This was due to a higher value of the moisture diffusion coefficient at higher temperatures. When the size of the papaya glace' cube was changed from 0.005 to 0.01 m, the specific energy consumption was a minimum when the fraction of air recycled was about 0.98. This was due to the moisture diffusion being slower in larger sized pieces. The minimum specific energy consumption increased from about 11 to 17 MJ/kg water evaporated and the drying time increased from about 8 to 16 hours.

CONCLUSIONS

1. This mathematical model can predict the drying rate with fair accuracy at an initial product moisture content of about 45% d.b. The model includes variation in drying air temperature, air flow rate and fraction of air recycled.

2. When product quality, drying time and energy consumption were considered, there should be a drying air temperature of about 60-65°C, a specific air flow rate of about 50 kg dry air/h-kg dry papaya glace' and a fractional recirculation of about 0.8.

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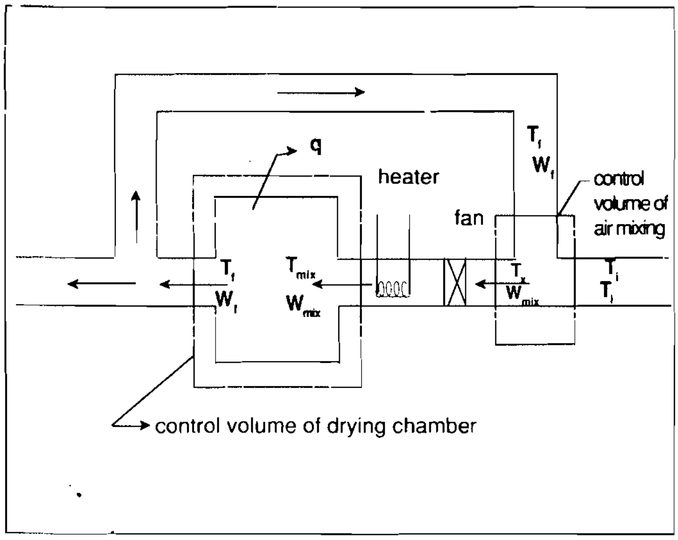


Figure 1. Diagram showing a cabinet dryer

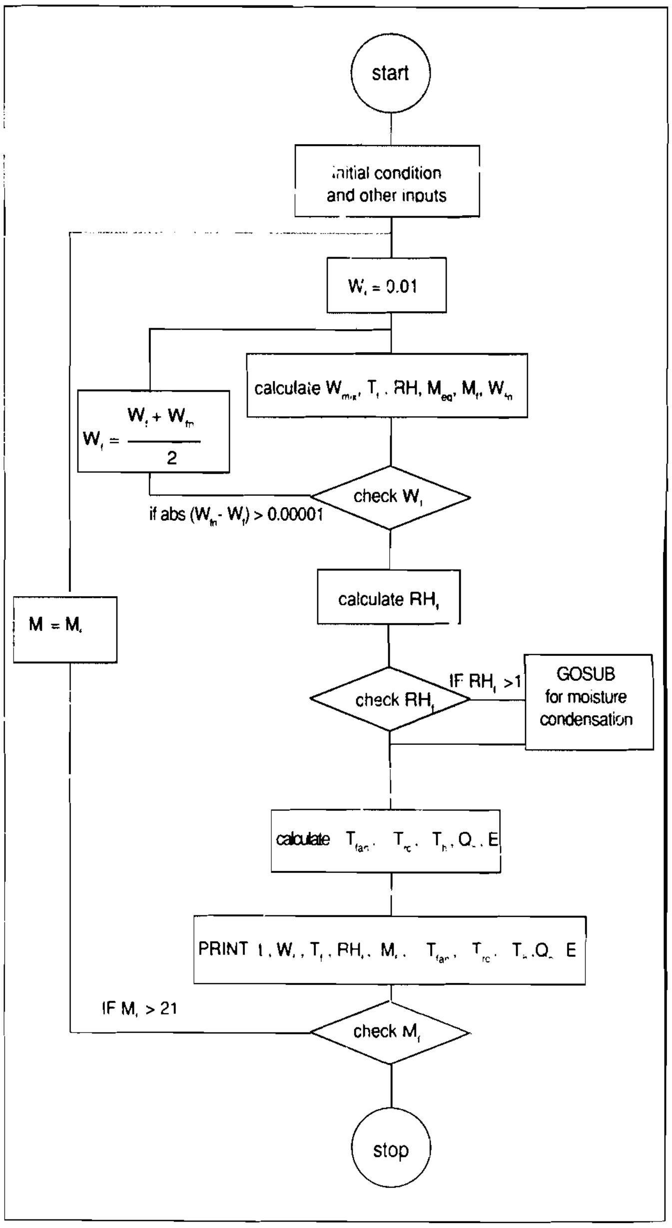
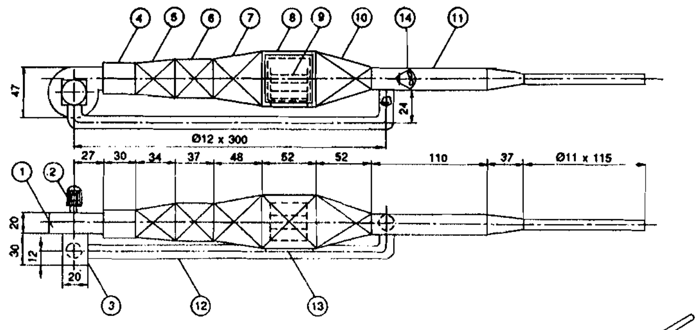


Figure 2. Flow chart showing drying simulation



No	Details	Size	Amount
14	valve		2
13	door	□ 45 x 45	1
12	circular duct	○ 12 x 300	1
11	exit duct	□ 20 x 20	1
10	air duct	□ 52 x 20 x 52	1
9	trays	34 x 38 x 39	1
8	drying chamber	□ 52 x 52	1
7	air duct	⊠ 37 x 52 x 48	1
6	air duct	□ 37 x 37	1
5	air duct	⊠ 22 x 37 x 34	1
4	air duct	○ 22 x 30	1
3	inlet duct	□ 20 x 20 x 30	1
2	motor		1
1	fan	○ 47	1

Figure 3. The cabinet dryer

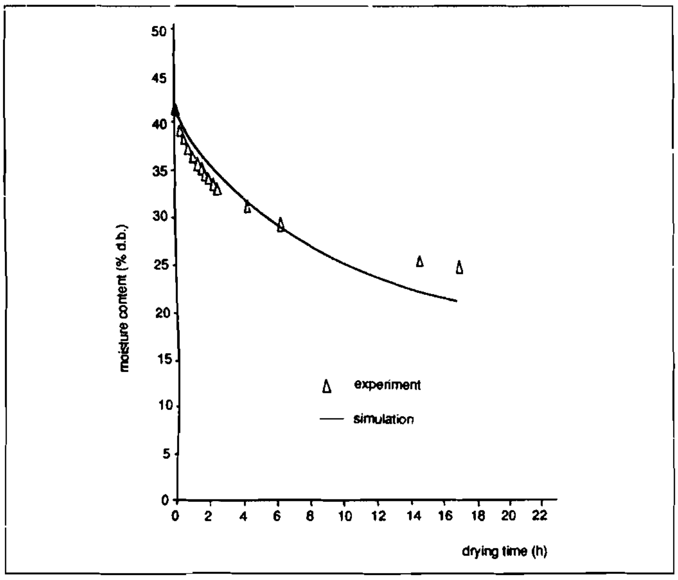


Figure 4. Comparison of evolution of experimentqal and simulated moisture content of papaya glacé (Dryer No. 1: test no . 1)

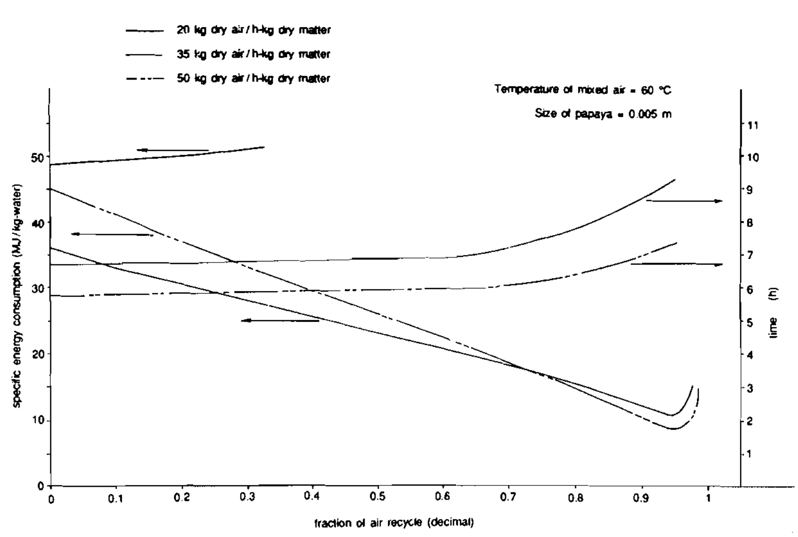


Figure 5. Simulated results of papaya glacé drying at 60 °C (0.5 cm)