Maintaining Qualities, Minimizing Time and Energy Consumption in Pineapple Glacé Drying

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ABSTRACT

Important factors which affect decision making when drying agricultural products are normally quality, drying time or throughput and energy consumption. Experimental results indicated that the quality of pineapple glacé after drying was maintained if drying air temperature did not exceed 65°C. Drying time and energy consumption were, however, experimentally found to be affected by specific air flow rate and fraction of air recycled. In order to handle uncontrollable parameters during experiments such as ambient temperature, relative humidity and the initial conditions of the drying product, a mathematical model for drying short hollow cylinders of pineapple glacé in cabinets was developed for further investigation of the appropriate operating conditions. It predicted the drying rate with high accuracy. Simulated results showed that a specific air flow rate of about 11 kg dry air/h-kg dry pineapple glacé and about 0.75 of air recycled should be used.

INTRODUCTION

Pineapple is a major economic crop in Thailand. Pineapple fruit is commonly processed as pineapple glacé, usually in relatively short hollow cylinders or small cubes, by dipping fresh pineapple in sugar solution and then drying in cabinet or tunnel dryers. Variables which affect the performance of drying (measured in terms of product quality, drying time or throughput and energy consumption) are drying air temperature, air flow rate and fraction of air recycled.

In the literature, there are some reports on papaya glacé drying but very few reports on pineapple glacé drying. Tanafranca et al (1985) investigated various glacé processes used with papaya. Bhumiratana et al (1988) also investigated glacé processes used with papaya and studied mass transfer between the papaya and the sugar solution. Haruthaithanasan et al (1988) studied the drying of papaya by solar energy and found that 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 was comparable with products dried without using solar energy. Levi et al (1983, 1985) investigated the effect of various treatments of fresh papaya on drying rate and energy consumption. Osmotic treatment of papaya considerably shortened the drying time for cabinet or solar drying, giving a significant saving in thermal energy. Achariyaviriya and Soponronnarit (1990) developed the equations describing the drying rate, equilibrium moisture content, and some parameters necessary for the simulation of papaya glacé drying. Teanchai and Soponronnarit (1991) conducted similar work for pineapple glacé. Soponronnarit et al (1992) developed a mathematical model for drying papaya glacé, having a geometry of small cubes, in cabinets. It predicted the drying rate with fair accuracy. Simulated and experimental results showed that a drying temperature of 65°C, a specific air flow rate of 50 kg dry air/h-kg dry papaya glacé and about 0.8 of air recycled should be used.

From the above literature, it was noted that research work on pineapple glacé drying was needed. The objective of this study was therefore to investigate optimum conditions for drying pineapple glacé in cabinets. A mathematical model was developed and confirmed with experimental results. 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 that of Soponronnarit et al (1992). It is assumed that thermal equilibrium exists between the drying air and the product. The model comprises major equations as follows:

Calculation of Product Moisture Content

The pineapple glacé to be dried has the geometry of a short hollow cylinder. It is assumed that moisture transfer in the drying product is mainly due to moisture diffusion. It is also assumed that the initial moisture content of the product is uniform and the moisture content at the surface of the product is in equilibrium with the surrounding drying air immediately after the start of the drying process. The analytical solutions for a diffusion equation for the geometries of infinite hollow cylinder and infinite slab are available (Crank, 1975). The product of these two different geometric solutions is the solution for a short hollow cylinder. It is written as follows:

$$\begin{aligned} MR(t) = & \left\{ 32 / \left[\pi^2 \left(r_o^2 - r_i^2 \right) \right] \right\} \sum_{n=1}^{\infty} \sum_{m=0}^{\infty} \left[1 / (2m+1)^2 \right] . \\ & \left\{ \left[J_o(r_i \alpha_n) - J_o(r_o \alpha_n) \right] / \left[\alpha_n^2 J_o(r_i \alpha_n) + \alpha_n^2 J_o(r_o \alpha_n) \right] \right\} . \\ & \left\{ \exp \left[\left(-D \alpha_n^2 t \right) - (2m+1)^2 \pi^2 D t / l^2 \right] \right\} \end{aligned} \tag{1}$$

$$MR(t) = \left(M(t) - M_{eq} \right) / \left(M_{in} - M_{eq} \right) \tag{2}$$

where

$MR(t)$ = moisture ratio, dimensionless,

$M(t)$ = mean moisture content, decimal dry basis,
M_{in} = initial moisture content, decimal dry basis,
M_{eq} = equilibrium moisture content, decimal dry basis,
D = moisture diffusion coefficient, m²/h,
$J_o(r_i\,\alpha_n)$ and $J_o(r_o\,\alpha_n)$ = Bessel function of zero order,
r_i = inside radius of cylinder, m,
r_o = outside radius of cylinder, m,
α_n = parameters available in Crank (1975),
l = length of cylinder, m,
t = time, h.

Initially, the equation for the diffusion coefficient developed by Teanchai and Soponronnarit (1991) was used but it was found that the equation could not predict drying rate accurately at low initial moisture contents. In this study, a new equation was, therefore, developed and confirmed with the experimental results of drying of pineapple glacé having a geometry of a small short cylinder. The equation is written as follows:

$$\begin{aligned} \mathrm{D} = {} & \left(7.6085 \times 10^{-7}\right) - \left(2.2108 \times 10^{-10} M_{in}\right) + \left(1.3105 \times 10^{-10} M_{in}^{2}\right) - \left(4.5706 \times 10^{-8} T\right) \\ & + \left(4.3287 \times 10^{-10} T^{2}\right) + \left(7.2929 \times 10^{-10} T M_{in}\right) - \left(5.7446 \times 10^{-14} T^{2} M_{in}\right) \\ & - \left(8.7655 \times 10^{-6} T M_{in}^{2}\right) + \left(7.0060 \times 10^{-14} T^{2} M_{in}^{2}\right) \end{aligned} \quad (3)$$

for $50°\mathrm{C} < T < 90°\mathrm{C}$ and 57% d.b. $< M_{in} < 80\%$ d.b.,
where

T = drying air temperature, °C.

The equilibrium moisture content of pineapple glacé developed by Teanchai and Soponronnarit (1991) was used in this study. It is written as follows:

$$M_{eq} = \left\{\exp\left[2\left(A + B\,RH\right)\right] - M_{0.5}\right\} / \left[2\exp\left(A + B\,RH\right)\right] \quad (4)$$

where

$$A = 3.403 - 0.02049\,T \quad (5)$$

$$B = 1/(0.7288 - 0.005960\,T) \quad (6)$$

$$M_{0.5} = 1/(0.1003 - 0.0006300\,T) \quad (7)$$

$M_{0.5}$ is the equilibrium moisture content at 50 % air relative humidity and RH is the air relative humidity in decimal.

The change of product moisture content over a small time interval can be found by differentiating equation (1) with respect to time and using the finite differences method to solve the resulting differential equation over a small time interval.

Calculation of Air Properties and Energy Consumption

Figure 1 shows the diagram of the experimental cabinet dryer. Exhaust air can be partly recycled. It is first mixed with fresh air and then heated up to the controlled temperature before entering the drying cabinet in which the drying process occurs. From application of the principle of energy conservation for the control volume CV1, the change of enthalpy of the flowing air stream plus the change in internal energy of the drying product, are equal to the heat exchange between the dryer and its surroundings (very small change in internal energy of the dryer). The equation, after some rearrangement, can be written as follows:

$$T_{f1} = \left[Q_1 + C_a T_{mix} + W_{mix} \left(h_{fg} + C_v T_{mix} \right) - W_f \, h_{fg} - \Delta U_p \right] / \left(C_a + W_f \, C_v \right) \quad (8)$$

where
$$Q_1 = U A \left(\Delta T \right) / m_{mix} \quad (9)$$

Q_1 = heat loss between the cabinet and its surroundings, kJ/kg dry air,
ΔU_p = the change in internal energy of the drying product, kJ/kg dry air,
U = overall heat transfer coefficient, kJ/h m² °C,
A = surface area, m²,
ΔT = temperature difference, °C,
m = mass flow rate of dry air, kg/h,
T = temperature, °C,
W = humidity ratio, kg dry air/kg H_2O,
C = specific heat at constant pressure, kJ/kg °C,
h_{fg} = latent heat of vaporization, kJ/kg H_2O.

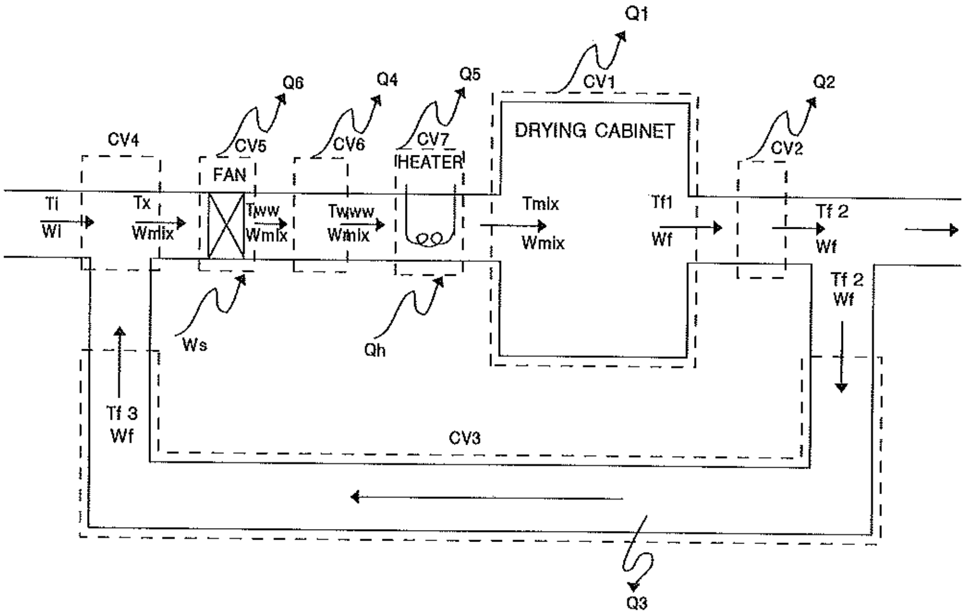

Fig. 1. Control volume.

Subscripts are as follows:

a = dry air
v = vapor
p = pineapple glacé
f_1 = exit of the cabinet
mix = inlet of the cabinet

From computer simulation, it was found that the change in internal energy of the drying product had a very small effect on the simulated results.

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 :

$$W_f = \left(M_i - M_f\right) R + W_{mix} \tag{10}$$

where

R = $M_p/(m_{mix}\,\Delta t)$,
M_p = dry mass of the drying product, kg,
Δt = small calculation time interval, h,
M_i = product moisture content at the beginning of the calculation time interval, decimal dry basis,
M_f = product moisture content at the end of the calculation time interval, decimal dry basis,
W_{mix} = humidity ratio of air at the inlet of cabinet, kg H_2O/kg dry air,
W_f = humidity ratio of air at the exit of cabinet, kg H_2O/kg dry air.

From application of the principle of energy conservation for the control volumes CV2 and CV3, the change of enthalpy of the flowing air stream is equal to the heat exchange between the control volumes and their surroundings. This is the special case of equation (8). The change in temperature of the air can then be determined. It is noted that the humidity ratio remains constant.

From application of the principle of mass conservation for the control volume CV4, the mixture equation can be derived as follows:

$$W_{mix} = \left(1 - RC\right) W_i + RC\, W_f \tag{11}$$

where

RC = fraction of air recycled and is equal to m_{rc} / m_{mix},
m_{rc} = dry mass flow rate of air recycled, kg/h,
m_{mix} = total mass flow rate of dry air, kg/h,
W_i = humidity ratio of fresh air, kg H_2O/kg dry air,
W_{mix} = humidity ratio of mixed air, kg H_2O/kg dry air.

From the principle of energy conservation, the summation of enthalpy of the air streams flowing in and out of the control volume is equal to zero. It is noted that heat exchange between the control volume and its surroundings is assumed to be negligible due to the small heat exchange surface area. The equation, after some rearrangement, can be written as follows:

$$T_x = \frac{\left[m_i C_a T_i + m_i W_i \left(h_{fg} + C_v T_i \right) + m_{rc} C_a T_{f3} + m_{rc} W_f \left(h_{fg} + C_v T_{f3} \right) - m_{mix} W_{mix} h_{fg} \right]}{\left(m_{mix} C_a + m_{mix} W_{mix} C_v \right)} \tag{12}$$

where

T_x = temperature of mixed air, °C,
m_i = dry mass flow rate of fresh air, kg/h.

From application of the principle of energy conservation for the control volume CV5, the change of enthalpy of the flowing air stream is equal to the summation of heat exchange between the control volume and its surroundings and the mechanical energy for driving a fan (very small change in internal energy of the fan). The equation, after some rearrangement, can be written as follows:

$$T_{ww} = \left(Q_6 + W_s + C_a T_x + W_{mix} C_v T_x \right) / \left(C_a + W_{mix} C_v \right) \tag{13}$$

where

T_{ww} = temperature of exit air, °C,
T_x = temperature of inlet air, °C,
Q_6 = heat exchange, kJ/kg dry air,
W_s = mechanical energy for driving a fan, kJ/kg dry air (found experimentally).

From application of the principle of energy conservation for the control volume CV6, a special case of equation (8), the exit air temperature can be determined.

From application of the principle of energy conservation for the control volume CV7, the change of enthalpy of the flowing air stream is equal to the summation of heat loss between the control volume and its surroundings and heat supplied by an electrical heater. The equation, after some rearrangement, can be written as follows:

$$Q_h = C_a T_{mix} + W_{mix} \left(h_{fg} + C_v T_{mix} \right) - C_a T_{www} - W_{mix} \left(h_{fg} + C_v T_{www} \right) - Q_5 \tag{14}$$

where

Q_h = heat supplied by an electrical heater, kJ/kg dry air,
Q_5 = heat loss, kJ/kg dry air,
T_{www} = inlet air temperature, °C,
T_{mix} = exit air temperature, °C.

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 (11) by assuming that the exit humidity (W_f) is 0.02. Equation (8) is then used to calculate T_{f1}. In this study T_{mix} is known and in practice this is controlled by a thermostat. Then the relative humidity of air is calculated using the average air properties through the dryer; equation (4) is used for calculating M_{eq} and M_f' is obtained from equation (1), differentiated with respect to time and solved by the finite differences method. W_f is calculated from equation (10); 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 latest calculated W_f. If the difference is less than the set value, the relative humidity of air is calculated and checked for feasibility (less than unity). If it is reasonable, the calculation is advanced to the energy consumption. Otherwise, the condensation is simulated (see details in Soponronnarit, 1987) and then the calculation is continued.

The next step is to calculate the energy consumption by using equations (12)-(14) 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 Fig. 2.

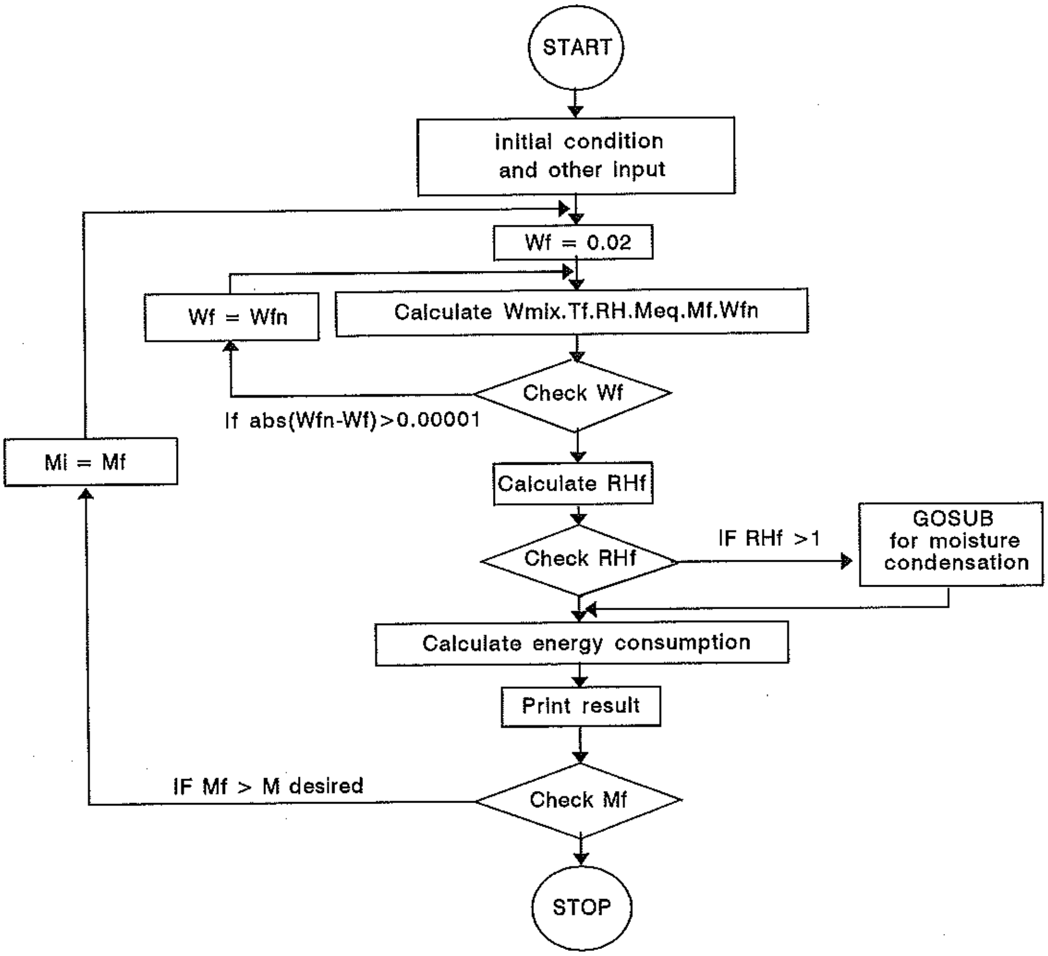

Fig. 2. Computer simulation flow chart.

PROCEDURE

Pineapple glacé was prepared by cutting fresh pineapple into short hollow cylinders having an inner diameter of 2 cm, an outer diameter of 6 cm and a thickness of 1 cm, steaming for 15 minutes, cooling suddenly with water then dipping it in a 90°C sugar solution which started at a concentration of 45° Brix and was increased by 10° Brix each day up to 70° Brix (5° Brix increase for the last day) to which sodium metabisulfite was added at a concentration of 0.1% (w/w) (Tanafranca et al, 1985). The initial moisture content of prepared pineapple glacé was about 65 % dry basis.

About 5 kg of pineapple glacé was dried each batch in a cabinet dryer. There were 5 trays in which the direction of air flow was parallel. The specific air flow rate (kg dry air/h-kg dry product), the fraction of air recycled and the drying air temperature were controlled constantly during each batch but were varied from one batch to another. During the experiments both dry bulb and wet bulb temperatures were measured every 30 minutes with an accuracy of ± 1°C by thermocouples (Chromel-Alumel), connected to data loggers. Air relative humidity was calculated from dry bulb and wet bulb temperatures. The moisture loss from the drying product was measured by weighing 3 samples in 3 locations from each tray every 5 hours. At the end of drying (about 23 % moisture dry basis) the dry mass of the product was determined by drying in an oven at 103°C for 72 hours. The accuracy of the balance was 0.01 g. Air flow rate was determined by measuring the air velocity in the duct with a hot wire anemometer having a precision of ±0.1 m/s which was calibrated with a pitot static tube. Energy consumption by a fan and by a heater was measured by kilowatt-hour meters each 5 hours. At the end of drying, the colour (R.H.S. chart), physical appearance, vitamin C, sulfur dioxide and total sugar content (AOAC methods) of the products were determined.

RESULTS AND DISCUSSION

The evolution of simulated and experimental mean moisture content of pineapple glace is shown in Fig. 3. The corresponding evolution of dry bulb and wet bulb temperatures at the outlet of the dryer is shown in Fig. 4. The results indicate that the drying model was able to predict the drying rate and temperatures accurately.

Figure 5 shows the moisture gradient along the air flow direction. The gradient was relatively small. However, there was some variation of moisture content among trays. This was due to non-uniform air flow in the drying cabinet. It was observed that the drying rate decreased with the drying time as shown in Fig. 6 and the energy consumption increased with the drying time as shown in Fig. 7. As both Figs. 6 and 7 show, the mean moisture content decreased with the drying time. At low moisture content, moisture diffusion is low resulting in slow drying rate and high energy consumption.

The qualities of the product after drying are presented in Table 1. The colour of pineapple glacé was acceptable as compared with the products available in local markets, up to the drying temperature not exceeding 65°C. The outer surface is somewhat soft and succulent. With higher drying temperature, i.e., 80°C during the first 5 hours then followed with 65°C, the colour of the product was a little bit darker and the outer surface was somewhat hard. Sulfur dioxide content and sugar content of the product after drying were in the acceptable range according to the standard of the Ministry of Industry, Thailand. Vitamin C could not be found in any of the samples tested.

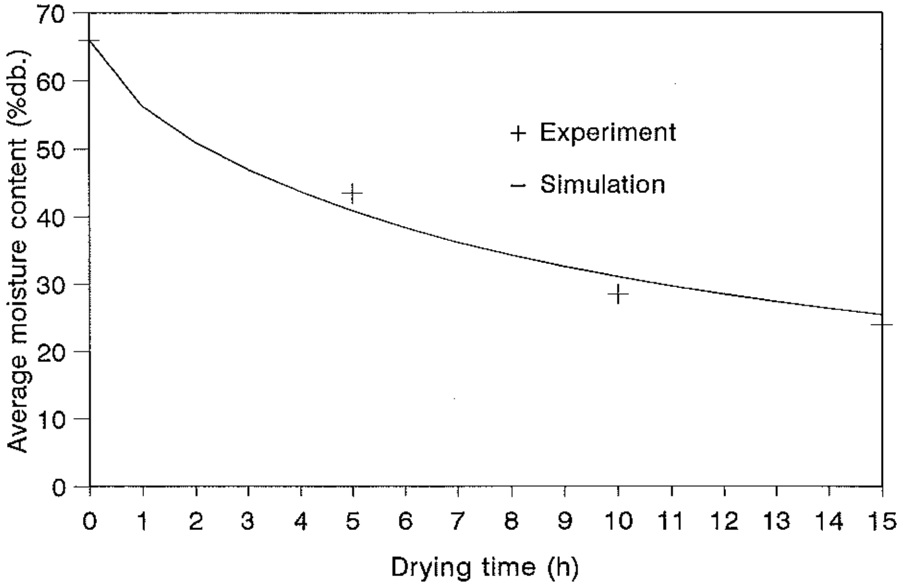

Fig. 3. Evolution of simulated and experimental moisture content [Test No. 3].
[Fraction of air recycled = 73%, Temperature = 66°C]
[Specific mass flow rate = 45.4 kg/h-kg dry pineapple glacé]

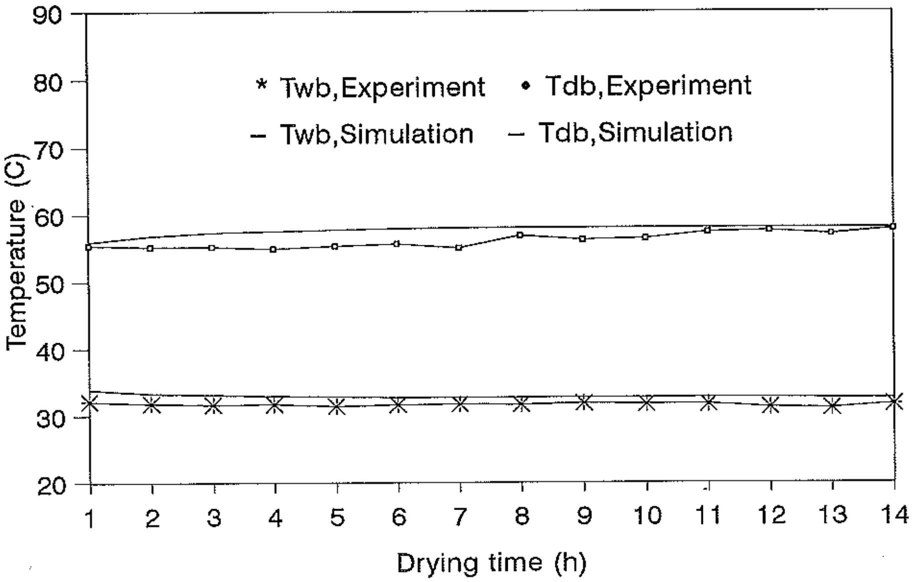

Fig. 4. Evolution of outlet temperature [Test No. 3].
[Fraction of air recycled = 73%, Temperature = 66°C]
[Specific mass flow rate = 45.4 kg/h-kg dry pineapple glacé]

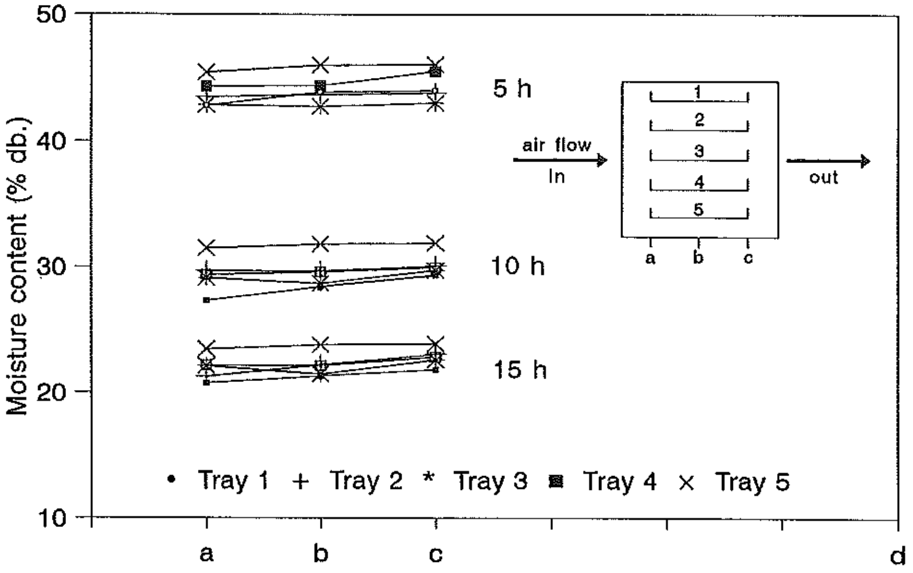

Fig. 5. Moisture gradient along air flow direction [Test No. 3].
[Fraction of air recycled = 73%, Temperature = 66°C]
[Specific mass flow rate = 45.4 kg/h-kg dry pineapple glacé]

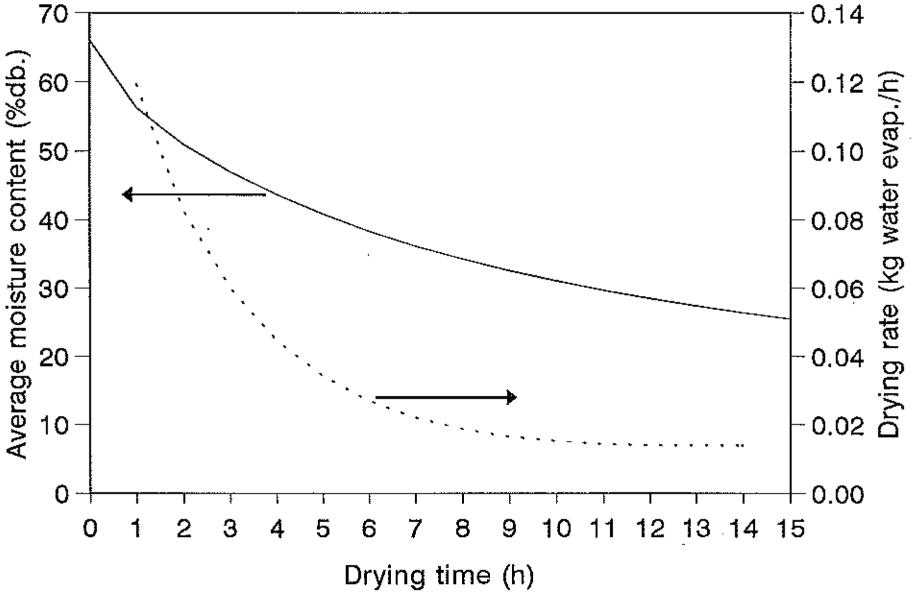

Fig. 6. Evolution of simulated moisture content and drying rate.
[Fraction of air recycled = 73%, Temperature = 66°C]
[Specific mass flow rate = 45.4 kg/h-kg dry pineapple glacé]

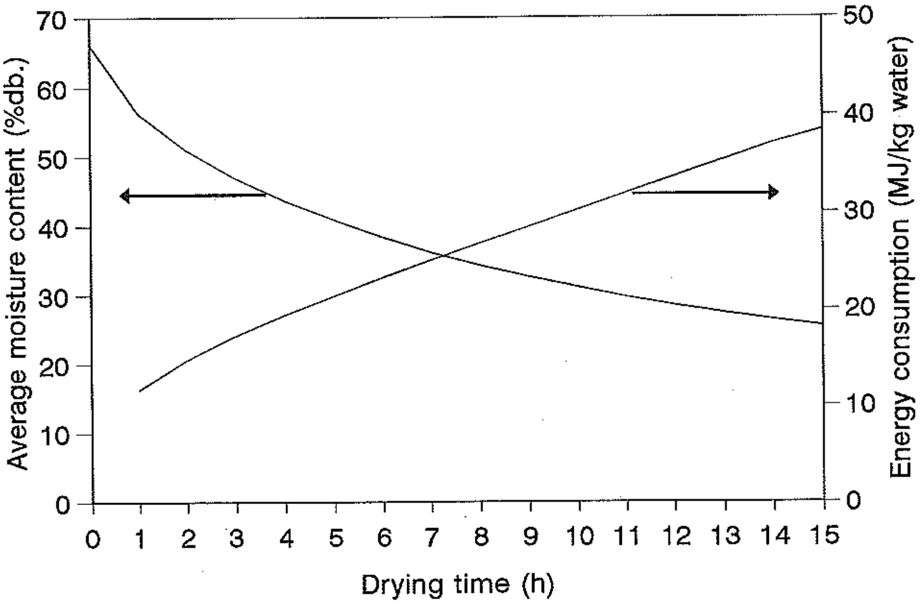

Fig. 7. Evolution of simulated moisture content and specific energy consumption.
[Fraction of air recycled = 73%, Temperature = 66°C]
[Specific mass flow rate = 45.4 kg/h-kg dry pineapple glacé]

Table 1. Qualities of pineapple glacé from experiments and from the local market.

Drying temp.	R.H.S color chart	Total sugar (%)	SO_2 (mg/kg)	Vitamin C (mg/kg)	Appearance of pineapple glacé
48°C	14-A	90.46	138	none	yellow, dry on outer surface, somewhat soft and succulent
65°C	15-A	87.83	38	none	yellow, dry on outer surface, somewhat soft and succulent
80°C (5 h) 65°C	17-B	N.A.	31	none	yellow, dry and hard on outer surface
TAVEEPOL Co., Ltd.	13-B	84.31	250	none	yellow, dry on outer surface, somewhat soft and succulent
SAKULSUK Co., Ltd.	15-A	83.69	N.A	none	yellow, dry on outer surface, somewhat soft and succulent

There were 10 pineapple glacé drying experiments at different specific air flow rates, fractions of air recycled and drying temperatures. However, optimum strategies could not be concluded. The experimental results showed the trend for the effect of these three parameters on product quality, drying time and energy consumption which was in agreement with the simulated results obtained from the mathematical model, as discussed later. Details of the experimental results are shown in Table 2.

During the drying simulation, the following assumptions were made: the initial moisture content was 65% dry basis, the final moisture content was 23% dry basis, the initial mass of pineapple glacé was 10 kg (dry mass of 6.1 kg), the ambient temperature and absolute humidity were 30°C and 0.02 kg water/kg dry air, respectively, and the drying air temperature was fixed at 65°C. The results are shown in Figs. 8-12. The energy was divided into electricity for the fan and thermal energy for heating the air. Due to the small fraction of electricity consumed (about 5%), only total final energy consumption was presented.

Table 2. Experimental results of pineapple glacé drying.

Description	Test no.									
	1	2	3	4	5	6	7	8	9	10
Drying air condition										
temperature (°C)	48.4	68.5	66.0	68.7	68.2	68.9	69.8	69.9	80.0 65.0	90.0 68.0
specific mass flow rate (kg dry air/h-kg dry product)	114.2	42.9	45.4	20.0	18.0	18.2	8.2	7.5	8.4	9.4
fraction of air recycled (%)	31.0	61.0	73.0	79.0	80.0	81.1	74.0	87.0	87.0	87.0
Ambient condition										
temperature (°C)	31.3	31.2	31.4	31.3	31.4	31.7	31.3	31.4	31.6	31.7
relative humidity (%)	65.0	64.0	65.0	68.0	68.0	66.0	66.0	68.0	70.0	70.0
Condition of pineapple glacé										
before drying (%db.)	48.4	67.0	66.0	66.0	58.0	64.0	65.0	61.0	67.7	69.7
after drying (%db.)	23.0	23.0	23.0	23.0	23.0	23.0	23.0	22.7	23.0	23.0
initial weight (kg)	2.2	2.1	2.0	1.9	1.8	1.8	4.8	4.7	4.5	4.0
Specific energy consumption										
heater (MJ/kg-H_2O evap.)	132.8	48.4	42.6	31.0	32.3	30.6	27.0	24.8	21.5	22.4
motor (MJ/kg-H_2O evap.)	15.4	7.4	8.7	9.2	11.0	9.2	3.8	3.5	3.2	2.9
total (MJ/kg-H_2O evap.)	148.2	55.8	51.3	40.2	43.3	39.8	30.8	28.3	24.7	25.3
Specific primary energy consumption										
heater (MJ/kg-H_2O evap.)	138.8	48.4	42.6	31.0	32.3	30.6	27.0	24.8	21.5	22.4
motor (MJ/kg-H_2O evap.)	40.4	19.2	22.6	23.9	28.6	23.9	9.9	9.1	8.3	7.5
total (MJ/kg-H_2O evap.)	172.8	67.6	65.2	54.9	60.9	54.5	36.9	34.7	29.8	29.9
Drying time (h)	20.0	13.5	13.5	10.0	10.0	10.0	15.0	18.0	13.0	14.0

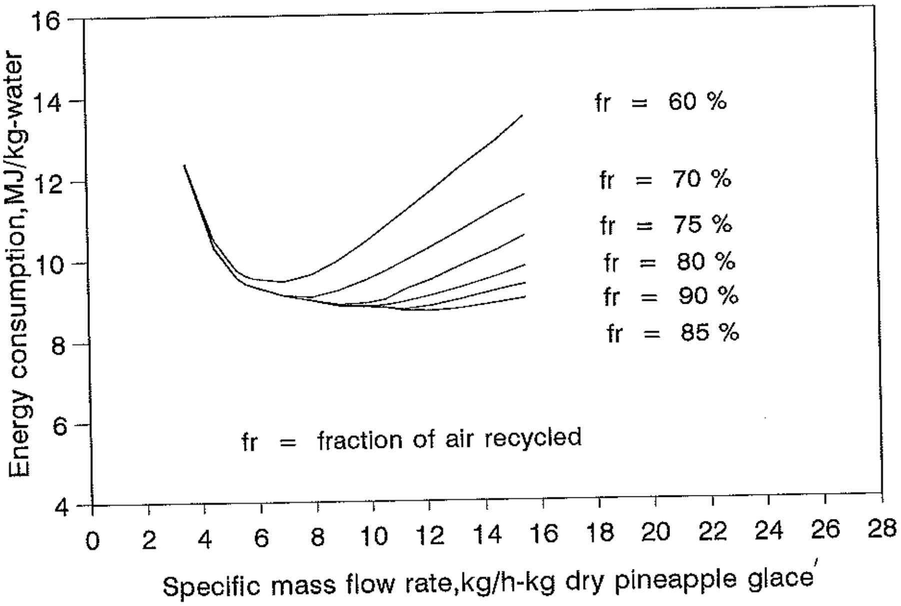

Fig. 8. Effect of specific mass flow rate on energy consumption at different fractions of air recycled (simulated result). [Temperature = 65°C, Thickness of pineapple glacé = 1 cm]

Figure 8 shows the simulated effect of specific air flow rate on energy consumption at different fractions of air recycled for drying pineapple glacé at 65°C and thickness of 1 cm. It was found that there was an optimum specific air flow rate for each fraction of air recycled. It was also found that there was an optimum fraction of air recycled. When the specific air flow rate was too high, the temperature and the absolute humidity of the air at the outlet of the drying cabinet were still high and low, respectively. This resulted in significant energy losses. When the specific air flow rate was too low, the state of the air at the outlet was reversed. As a result, a longer drying time was needed resulting in an increase of energy consumption.

Figure 9 shows the corresponding drying time. It was found that the drying time remained nearly constant up to the fraction of air recycled of 70%; then it increased rapidly. Therefore, the drying time must be considered in parallel with energy consumption. It can be concluded that the specific air flow rate should be about 11 kg/h-kg dry pineapple glacé and the fraction of air recycled should be about 75%. At these operating conditions, energy consumption and drying time are compromised. They are 9.5 MJ/kg H_2O evaporated and 20 hours, respectively.

Figures 10-11 show the simulated results of drying pineapple glace having a thickness of 2 cm. The results were similar to the case of a thickness of 1 cm. However, energy consumption was higher and drying time was longer. These were due to moisture diffusion being more difficult in thicker products.

Figure 12 shows the effect of ambient air conditions on energy consumption. It was found that energy consumption increased when the temperature decreased or the relative humidity increased.

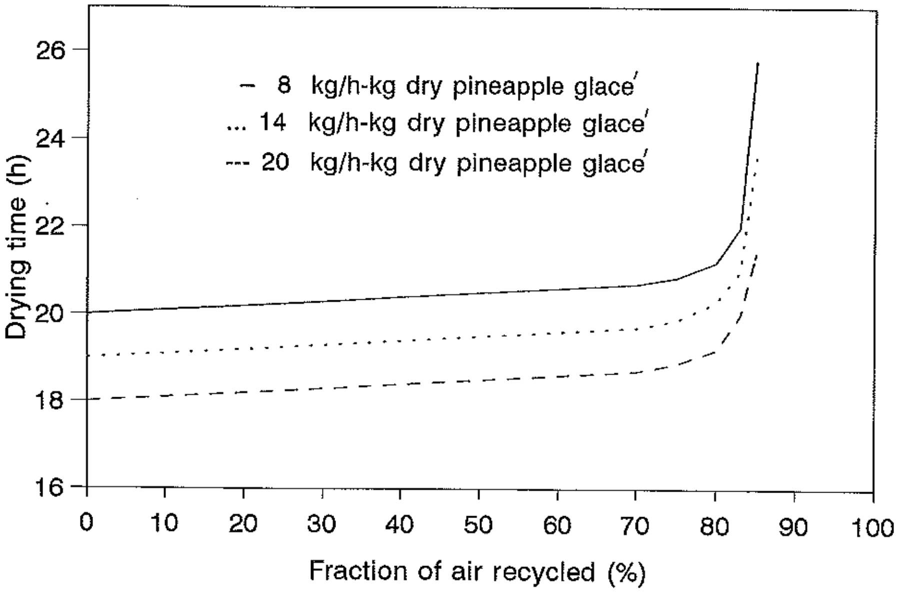

Fig. 9. Effect of fraction of air recycled on drying time at different specific mass flow rates (simulated result). [Temperature = 65°C, Thickness of pineapple glacé = 1 cm]

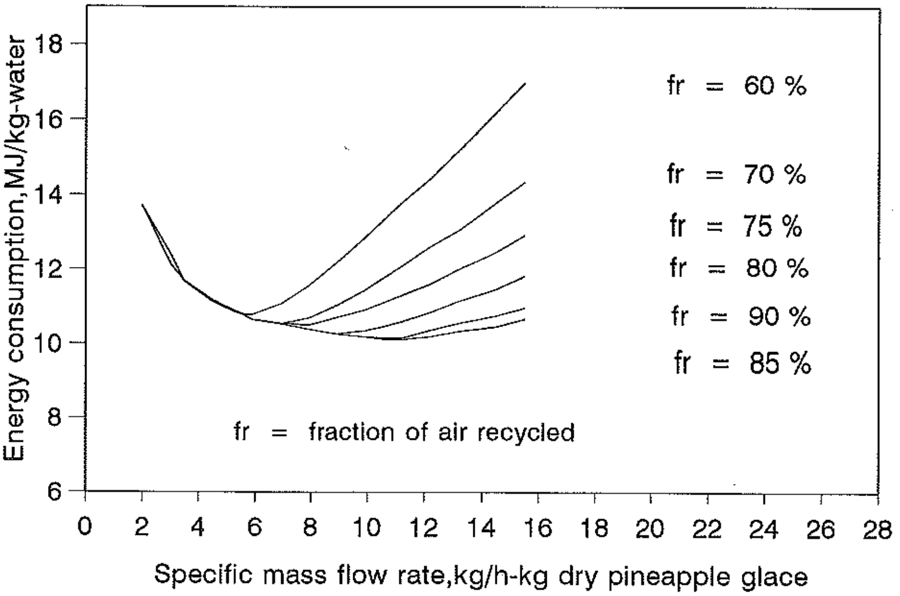

Fig. 10. Effect of specific mass flow rate on energy consumption at different fractions of air recycled (simulated result). [Temperature = 65°C, Thickness of pineapple glacé = 1 cm]

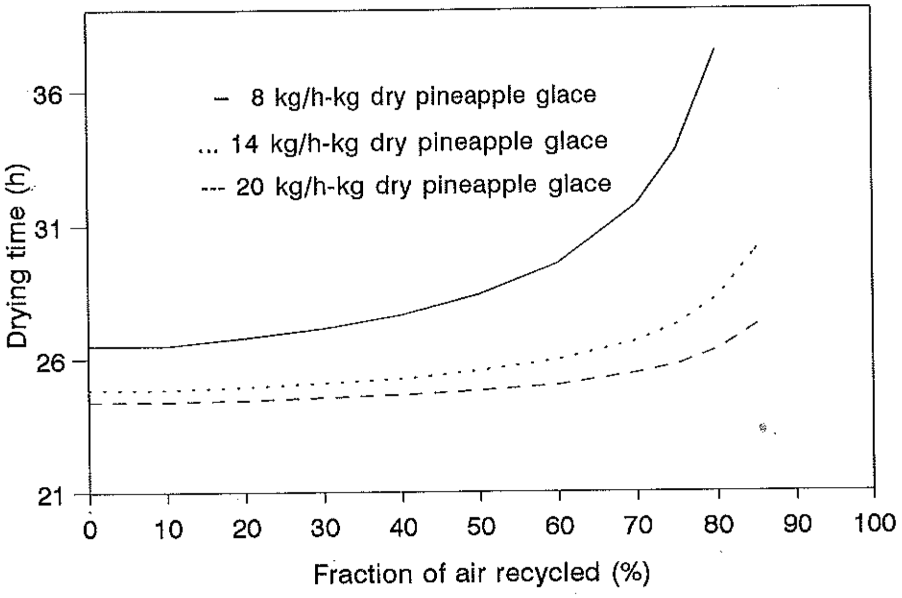

Fig. 11. Effect of fraction of air recycled on drying time at different specific mass flow rates (simulated result). [Temperature = 65°C, Thickness of pineapple glacé = 2 cm]

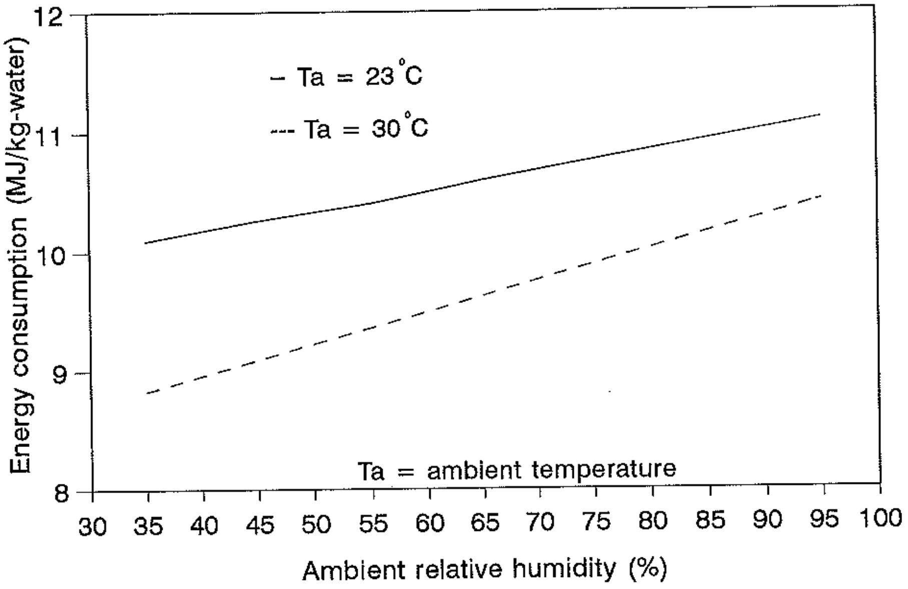

Fig. 12. Effect of ambient relative humidity on energy consumption at different ambient temperatures (simulated result). [Fraction of air recycled = 80 %]
[Specific mass flow rate = 12.05 kg/h-kg dry pineapple glacé]

CONCLUSION

The mathematical model developed could predict the drying rate of pineapple glacé and the outlet air temperatures relatively well. In a drying operation, product quality, drying time and energy consumption have to be considered. It was found that the optimum operating conditions should be as follows: a drying air temperature of 65°C, a specific air flow rate of about 11 kg/h-kg dry pineapple glacé and about 0.75 of the air recycled.

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