Computer Simulation of Solar-Assisted Fruit Cabinet Dryer

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ABSTRACT

The objective of this study was to develop a mathematical model for banana drying using solar energy as supplemental heat. It was found that the results obtained from the model and experiments were in agreement. The model was then used to investigate optimum drying conditions. Simulated results showed that the specific air flow rate of 10 kg/(h - kg dry banana) and the fraction of air recycled of 90% should be used. Under these conditions, the specific energy consumption and drying time were close to the minimum values. In addition, the experimental results indicated that drying air temperature should be around 60°C if product quality was to be maintained.

INTRODUCTION

Drying is a cheap and popular method of food preservation. In Thailand fruit is usually dried in fixed trays in a cabinet or in tunnel dryers. In order to maintain quality, hot air with a temperature below 70°C is usually circulated through the trays with or without recycling the exhausted air. Cabinet dryers are suitable for small scale production. The energy used in cabinet dryers is electricity for driving fans, and heat for heating air. The latter is usually provided by electricity or LPG. In Thailand solar energy is abundant. Soponronnarit et al. (1990) concluded that solar air heating was economical. Therefore, it maybe used to substitute for electricity or LPG. However, solar radiation is uncertain especially during the wet season. As a result, solar energy should be used as a supplementary source of energy.

To reduce drying cost, drying capacity has to be maximized but energy cost has to be minimized. If the drying temperature has to be limited to some level due to quality preservation, air flow rate and fraction of air recycled are then parameters to be investigated. Information on proper air flow rate and fraction of air recycled seems to be unavailable. It may vary from one dryer to another or from one product to another, under typical ambient conditions.

The objective of this study was therefore to develop a mathematical model capable of predicting banana drying, using solar energy as supplemental heat. Influence of temperature, air flow rate and fraction of air recycled on product quality, drying time and energy consumption were investigated and led to an optimum drying condition. Local bananas were selected in this study because they are very popular with Thai people and also easily available throughout the year.

REVIEW OF LITERATURE

Soponronnarit (1988) and Soponronnarit (1991) reviewed the research and development work on solar drying. It may be concluded that solar drying is classified into (a) natural and (b) forced convection, with (c) direct and (d) indirect solar drying. Natural convection solar drying requires low initial investment, is easy to operate and maintain but has a drying rate that is slow due to the low air flow rate. Forced convection solar drying usually yields a faster drying rate due to higher air flow rate. Temperature control is also more accurate. Therefore, the chance of successful and safe drying is higher. Direct solar drying usually yields higher efficiency as compared to indirect solar drying but temperature control is more difficult to obtain. As a result, product quality may be lower. In addition, it is not suitable for products sensitive to direct solar radiation.

Interesting work on natural convection, direct, indirect and mixed mode solar drying in Thailand was conducted by Wibulswas et al. (1977), Wibulswas and Thaina (1980) and Watabutr (1981). Important results were the optimum ratio of the exit area of exhausted air to solar receiving surface area, and the optimum tilt angle of the solar collector. Exell (1980) developed a low cost solar dryer made of plastic film. A simple design method was presented.

Forced convection, indirect solar drying was investigated technically and economically. Pilot-scale solar paddy dryers were designed and tested at farmers' houses by Soponronnarit et al. (1986) and Thongprasert et al. (1985). Results showed that they were technically and economically feasible. A solar banana dryer, forced convection and mixed mode, was studied by Rakwichian and Sudaprasert (1990) or Assayo (1991). It was found that the dryer was technically and economically feasible.

The acceptance of solar drying is still limited in Thailand. According to the authors' knowledge, about 30-40 units of natural convection, direct solar dryers (about $2m^2$ each), have been used for drying local bananas in Phitsanuloke province.

From previous studies, it was found that a mathematical model of solar drying could be developed by considering three parameters, namely, drying temperature, air flow rate and fraction of air recycled. The latter parameter is very important to the system performance. To date, such a model has not been developed. Therefore, the main objective of this study was to develop such a model. The significance of the study is the determination of optimum drying conditions by using the model through a programme applicable to a PC computer.

PROCEDURE

Development of Mathematical Model

A mathematical model for cabinet dryers suggested by Achariyaviriya and Soponronnarit (1989 b) was further developed. An assumption of this model is the existence of thermal equilibrium between the drying air and the product. Important equations are as follows:

The drying rate equation of local banana fruit was developed by Achariyaviriya and Soponronnarit (1989 a). It was assumed that the drying rate was limited by moisture diffusion in individual fruits which were considered as short cylinders. The equation is written as follows:

$$dM/dt = (M_{in} - M_{eq})\ (32/\pi^2) \sum_{m=0}^{\infty} \sum_{n=1}^{\infty} [1/(2m+1)^2]\,[1/(\lambda_n r_o)^2]$$
$$\exp\,[-(2m+1)^2 \pi^2 Dt/l^2 - (\lambda_n r_o)^2 Dt/r_o^2]$$
$$[-(2m+1)^2 \pi^2 D/l^2 - (\lambda_n r_o)^2 D/r_o^2] \quad (1)$$

where $$D = 0.480 \exp\,[-4300/(T + 273)] \quad (2)$$

and $$M_{eq} = \exp\,[\{\ln(-(T + 273\mathrm{K})\ln RH) - \ln(10200/R)\}/0.0488] \quad (3)$$

Equation (2) represents the equation of moisture diffusion and Equation (3) represents the equation of equilibrium moisture content developed by Achariyaviriya and Soponronnarit (1989 a) by employing the equation form of Halsey (1948). Symbols in the above equations are as follows:

m and n = integer
M = mean moisture content, decimal dry basis, kg H_2O/kg dry matter
M_{in} = mean initial moisture content, decimal dry basis, kg H_2O/kg dry matter
M_{eq} = equilibrium moisture content, decimal dry basis, kg H_2O/kg dry matter
D = diffusion coefficient, m^2/h
t = drying time, h
l = length of cylinder, m
r_o = radius of cylinder, m
RH = relative humidity, decimal
T = temperature, °C
R = Universal gas constant (8.314 kJ/kg mole K)
$\lambda_n r_o$ = root of Bessel function of zero order, m

Figure 1 shows the experimental solar cabinet dryer which comprises 2.5 m^2 of solar air heater at the top and a drying cabinet of 1x1x0.6 m^3 in which eight trays of bananas are placed. In operation, exhausted air is mixed with fresh warm air from the solar air heater, then through an electrical heater of 2400 W. Air temperature is controlled by a thermostat. Direction of air flow in the cabinet is perpendicular to the trays. Part of the exhausted air is recirculated.

Considering the control volume (CV2) in Fig. 2, the change of the enthalpy of the air stream plus the change of the internal energy of drying product and drying cabinet is equal to the summation of heat exchanging between the system and surrounding. Hence we obtain:

$$T_f = [q_2 + C_a T_{mix} + W_{mix}(h_{fg} + C_v T_{mix}) - W_f h_{fg} - \Delta U_p - \Delta U_d]/(C_a + W_f C_v) \quad (4)$$

where $$q_2 = [0.642 - 0.0280\ (T_{mix} - T_a) + 0.000332\,(T_{mix} - T_a)^2]\ /\ \dot{m}_{mix} \quad (5)$$

Symbols in Equations (4) and (5) are as follows:

q_2 = heat loss per unit mass of dry air, kJ/kg-dry air; determined experimentally.
ΔU_p = the change of the internal energy of banana per unit mass of dry air, kJ/kg-dry air
ΔU_d = the change of the internal energy of cabinet per unit mass of dry air, kJ/kg-dry air
C = specific heat, kJ/kg°C
W = humidity ratio, kg-H_2O/kg-dry air
h_{fg} = latent heat of vaporization, kJ/kg-H_2O
$\dot{m}$ = mass flow rate of dry air, kg/s

where subscripts: a = dry air
f = air at the exit of the cabinet
v = vapor

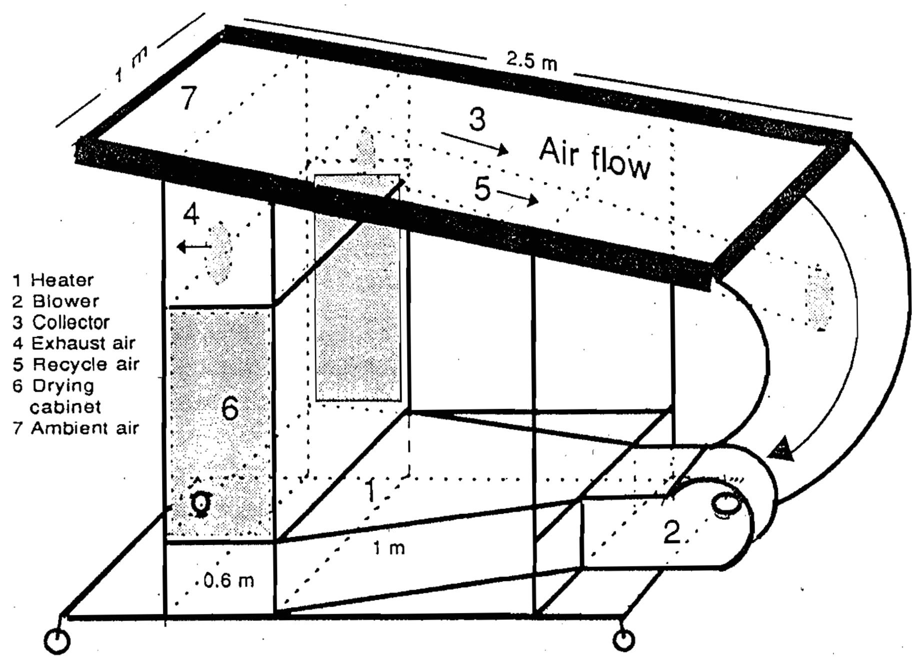

Fig. 1. Solar dryer.

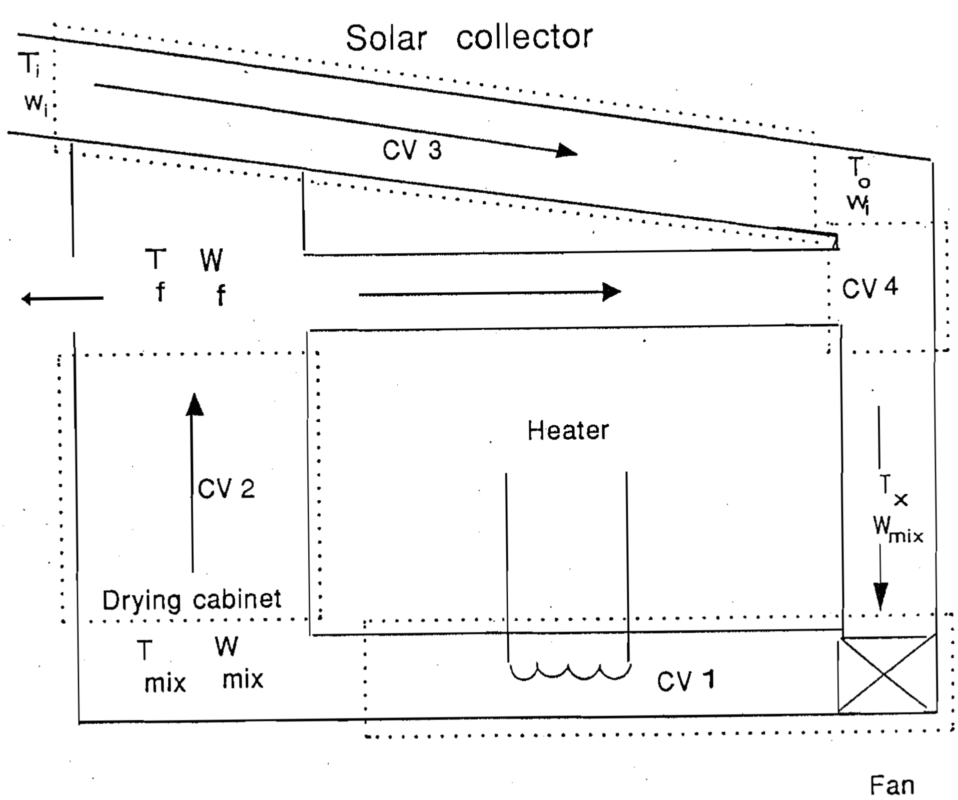

Fig. 2. Control volumes.

mix = mixed air before entering the cabinet

Considering the control volume (CV2) in Fig. 2, moisture gain into drying air is equal to moisture loss from bananas. Rewriting the equation, we obtain for the energy balance over a period Δt:

$$W_f = (M_i - M_f)R + W_{mix} \tag{6}$$

where M_i = mean moisture content at the beginning of Δt, decimal dry basis
M_f = mean moisture content at the end of Δt, decimal dry basis
R = $m_p / (\dot{m}_{mix} \Delta t)$
m_p = dry mass of banana, kg

Considering the control volume (CV4) in Fig. 2, the following equation can be derived from the concept of mass conservation of vapor and dry air.

$$W_{mix} = (1 - RC)\, W_i + RC\, W_f \tag{7}$$

where RC = fraction of air recycled, $\dot{m}_{rc}/\dot{m}_{mix}$

Considering the control volume (CV3) in Fig. 2, useful energy is equal to the change of the enthalpy of flowing air stream plus the change of the internal energy of solar air heater. After rewriting, it is as follows:

$$T_o = (e_c A_c G_t + W_i C_v T_i + C_a T_i - \Delta U_c) / (C_a + C_v W_i) \tag{8}$$

which

$$e_c = 15.1 + 1550\, m - 12700\, \dot{m}^2 \tag{9}$$

Equation (9) was obtained from the experiments of collector efficiency. The efficiency is at the maximum value, i.e., at $T_i = T_a$. Symbols are as follows:

e_c = solar collector efficiency, decimal
ΔU_c = the change of the internal energy of solar collector, kJ/kg-dry air
G_T = radiation flux, W/m²

where subscripts: c = solar collector
o = at the exit of solar collector
i = at the entrance of solar collector

Considering the control volume (CV4) in Fig. 2, the change of the enthalpy of flowing air streams is equal to zero if heat loss is negligible (small area of heat loss). After rewriting the equation, we obtain:

$$T_x = [\dot{m}_i C_a T_o + \dot{m}_i W_o (h_{fg} + C_v T_o) + \dot{m}_{rc} C_a T_f + \dot{m}_{rc} W_f (h_{fg} + C_v T_f) - \dot{m}_{mix} W_{mix}\, h_{fg}] / (\dot{m}_{mix} C_a + \dot{m}_{mix} W_{mix} C_v) \tag{10}$$

Considering the control volume (CV1) in Fig. 2, the change of the enthalpy of flowing air stream plus shaft work is equal to heat supplied by the electrical heater minus heat loss to the surroundings. Rewriting the equation, we obtain:

$$Q_h = \dot{m}_{mix} C_a T_{mix} + \dot{m}_{mix} C_v T_{mix} - \dot{m}_{mix} C_a T_x - \dot{m}_{mix} C_v T_x - W_s + q_1 \tag{11}$$

where W_s and q_1 were determined experimentally.

$$W_s = (0.00632 + 0.285\, \dot{m} + 37.4\, \dot{m}^2) \tag{12}$$

$$
\begin{aligned}
q_1 = {} & -0.148 + 0.0160\,(T_{mix} - T_a) + 0.000100\,(T_{mix} - T_a)^2 \\
& + 6.25\,m - 23.2\,m^2 - 0.620\,(T_{mix} - T_a)\,m \\
& - 0.00500\,(T_{mix} - T_a)^2\,m + 10.8\,(T_{mix} - T_a)\,m^2 \\
& + 0.238\,(T_{mix} - T_a)^2\,m^2
\end{aligned} \tag{13}
$$

where q_1 = rate of heat loss, kW
Q_h = power at the heater, kW
W_s = shaft power at fan, kW

Moist air properties were determined by the equations presented by Wilhelm (1976).

Calculation Method

A computer programme written in the PASCAL language applicable to PC computers was developed. The calculation starts at Equation (7) by assuming $W_f = 0.03$, W_{mix} can be calculated. Then T_f is calculated from Equation (4), assuming that T_{mix} is known. M_{eq} is calculated from Equation (3), M_f from Equation (1), and W_f from Equation (6). Then W_f is compared to the assumed W_f, the calculation is terminated if the difference is less than 0.0001. Otherwise, the calculation repeats by using the new assumed value of W_f which is the average value. Next is to calculate the energy consumption at the solar air heater, by the electrical heater and by the fan. The simulation flow chart is shown in Fig. 3.

Experimental Method

During each test, local bananas to a total mass of about 25 kg were loaded into the cabinet. Air was circulated only during the day. Bananas were collected out of the cabinet and put into a bulk covered with a sheet of cloth at night. Product moisture was determined by using an air oven at 103°C for 72 hours. Air flow rate and the fraction of air recycled varied during each test. Temperatures at various points were measured by thermocouples connected to a data logger, having an accuracy of ±1°C. Electricity consumed was measured with Watt-hour meters. Colour and hardness of banana fruit were observed after drying.

Experiments on solar collector efficiency followed the guidelines of ASHRAE Standard 93 - 77.

RESULTS AND DISCUSSION

Experimental results showed that better quality of bananas in terms of bright colour and softer fruit were obtained at a drying air temperature of 60°C as compared to 70°C. The specific air flow rate of about 10-13kg/(h-kg dry banana) yields the minimum energy consumption. Increasing the fraction of air recycled up to 80% could save energy. Energy consumed was divided into electrical energy for heating air, 69-75%; heat from solar air heater, 19-25%; and electrical energy consumed by the fan, 5-7%.

Figure 4 shows the comparison between measured mean moisture evolution and that obtained from the mathematical model. Both values are close together. Exit measured dry bulb and

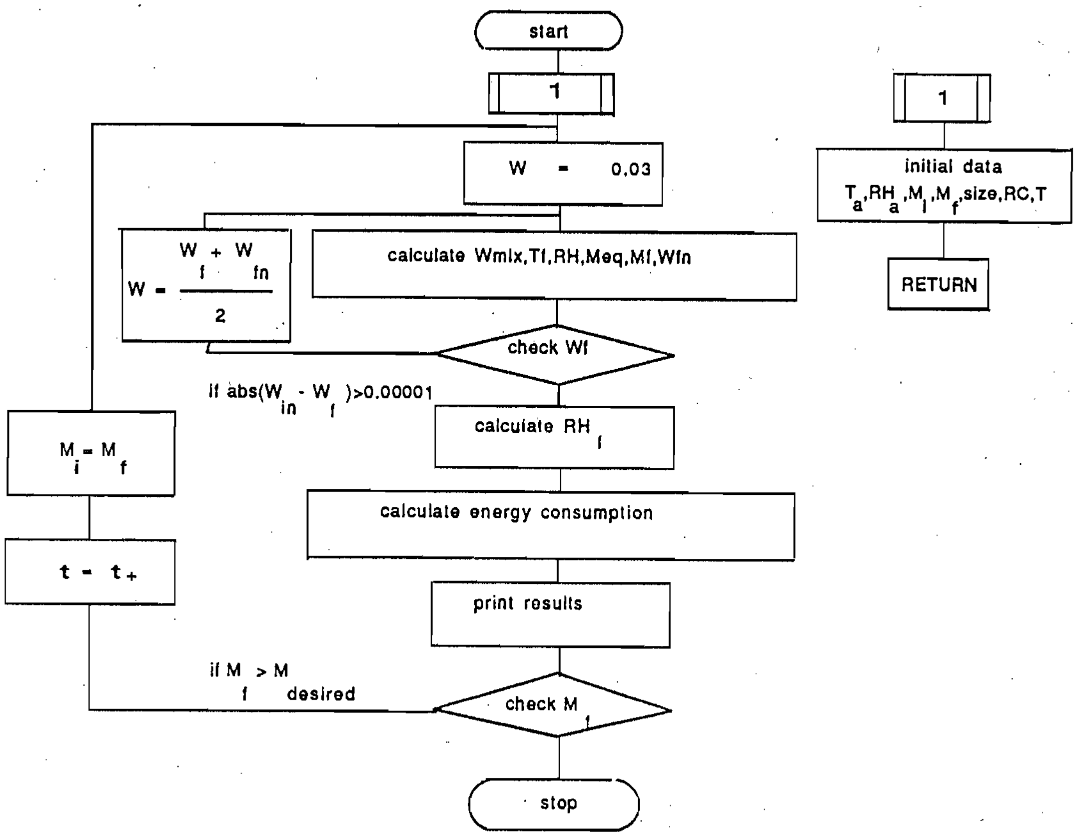

Fig. 3. Computer simulation flow chart.

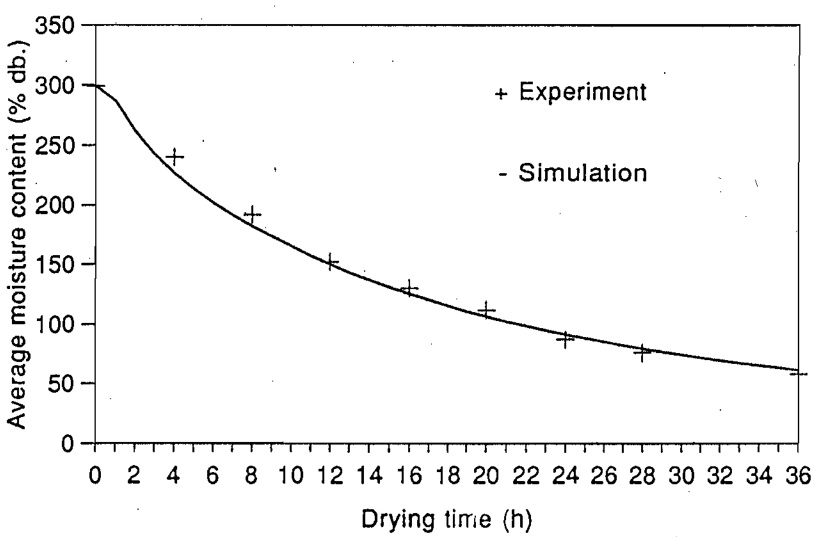

Fig. 4. Evolution of simulated and experimental moisture content.
[Test No. 5, Fraction of air recycled = 80%, Temperature = 60°C]
[Specific mass flow rate = 20.8 kg/ (h-kg dry banana)]

wet bulb temperatures were also compared to those obtained from the model as shown in Fig. 5. For the first 18 hours, the measured dry bulb temperature is slightly lower than the calculated one but closer after that. The difference between the wet bulb temperatures is less than the dry bulb temperatures.

Experimental results showed that the specific energy to evaporate unit mass of water in the crop increased with the decrease of product moisture content, as shown in Fig. 6. This can be explained by realizing that the drier the crop, the more energy is needed per unit of moisture for further drying and from Fig. 7 which shows that the drying rate is faster at a higher product moisture content.

Although there are six tests of banana drying, it is not possible to determine the optimum drying conditions. This is due to uncontrollable parameters such as ambient conditions and initial and final product moisture content. Therefore, the mathematical model was employed as a tool to investigate the optimum drying conditions for banana. The criteria to be considered were the specific energy consumption and drying time. Drying temperature was fixed at 60°C according to the experimental results which showed that product quality was acceptable if the temperature was not higher than 60°C. It was assumed that the initial and final moisture contents were 250% and 50% dry-basis, respectively. Ambient temperature and relative humidity were 30°C and 70%, respectively.

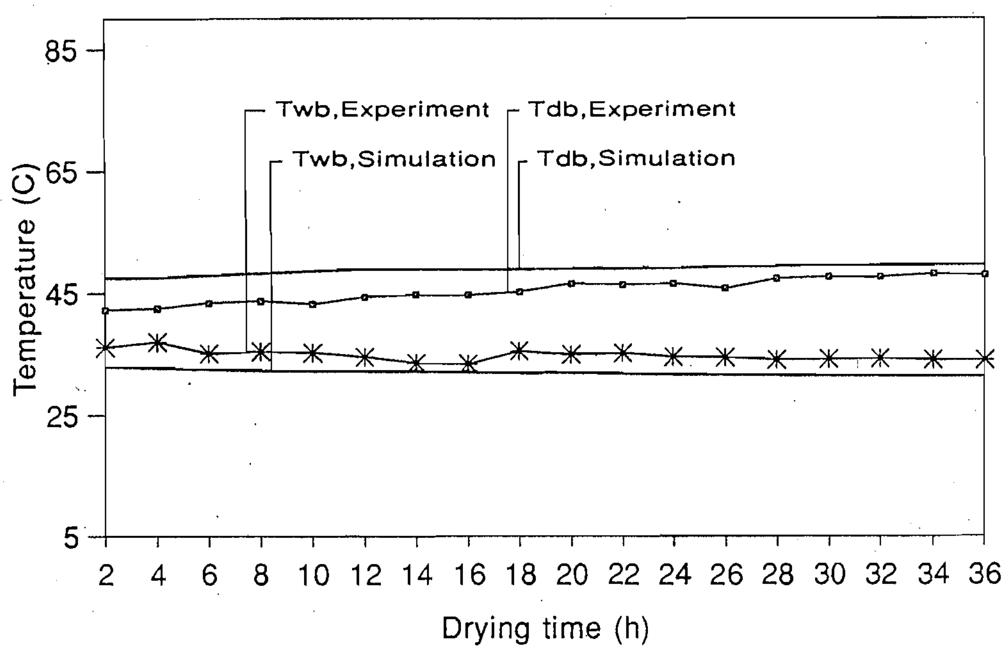

Fig. 5. Evolution of outlet temperature.
[Test No. 5, Fraction of air recycled = 80%, Temperature = 60°C]
[Specific mass flow rate = 20.8 kg/ (h-kg dry banana)]

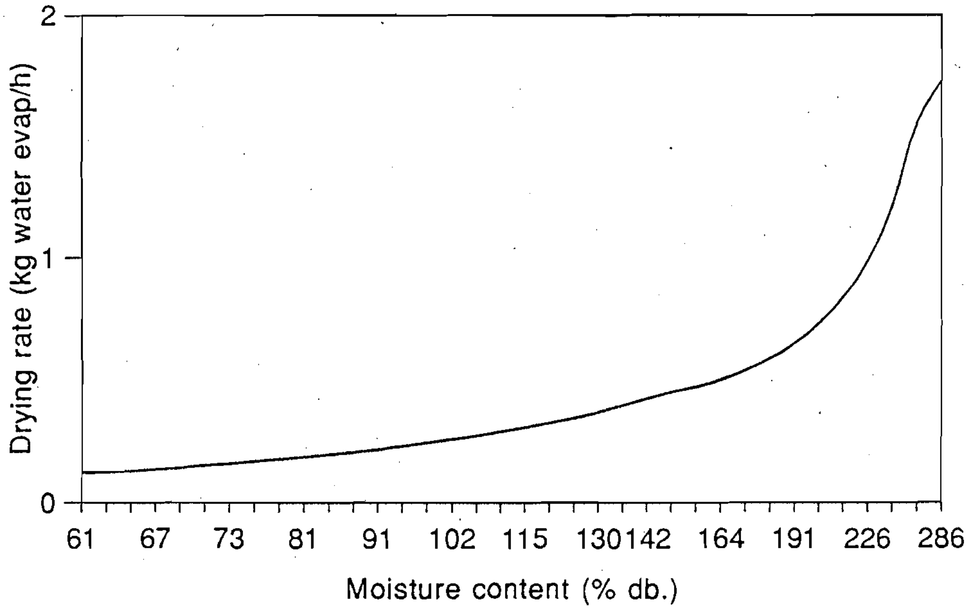

Fig. 6. Effect of average moisture content on specific energy consumption.
[Test No. 5, Fraction of air recycled = 80%, Temperature = 60°C]
[Specific mass flow rate = 20.8 kg/ (h-kg dry banana)]

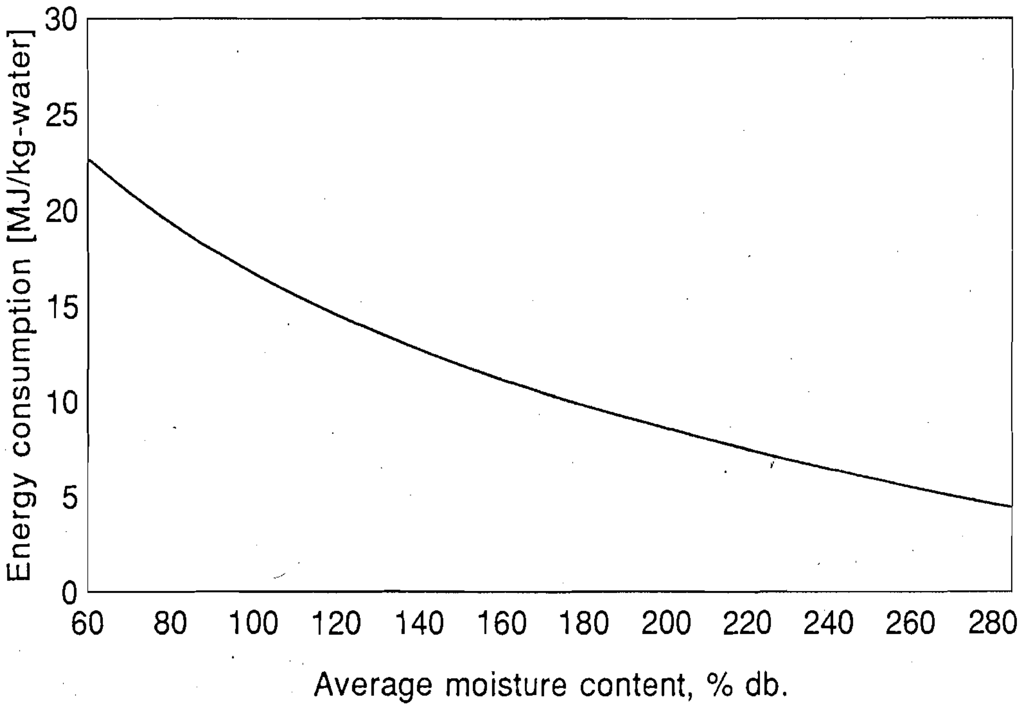

Fig. 7. Effect of moisture content on drying rate.
[Test No. 5, Fraction of air recycled = 80%, Temperature = 60°C]
[Specific mass flow rate = 20.8 kg/ (h-kg dry banana)]

Figure 8 shows the simulated results from which it can be concluded that the minimum specific energy consumption occurs at the specific air flow rate of 10 kg/(h-kg dry banana) and the fraction of air recycled of 95%. At higher fraction of air recycled, the specific energy consumption increased due to longer drying time as a result of the relative humidity of drying air being excessively high. Figure 9 shows that drying time for each specific air flow rate is not a function of the fraction of air recycled until it reaches 90%. At the point where the fraction of air recycled is low enough (0-90%), the drying rate is not affected much as shown by Equation (1) that (M_{in} - M_{eq}) is nearly constant for the indicated range of air recycled. Beyond 90% air recycled, (M_{in} – M_{eq}) decreases rapidly, resulting in the decrease of the drying rate and the increase of the drying time. In the food industry, drying capacity is as important as product quality. In this study, experimental results showed that the quality in terms of colour and softness was acceptable if the drying air temperature was not higher than 60°C. Therefore, the optimum drying conditions should be at 90% air recycled and the specific air flow rate of 10 kg/(h-kg dry banana).

CONCLUSION

It may by concluded from this study that the mathematical model developed is of acceptable accuracy and is useful as a tool for the investigation of the optimum drying conditions. For a case study using local banana as the drying product, the optimum drying conditions are a specific air flow rate of 10 kg/(h-kg dry banana) and a fraction of air recycled of about 90%. Under these conditions, the drying capacity is high and energy consumption is close to a minimum. Product quality is maintained if drying temperature is not higher than 60°C.

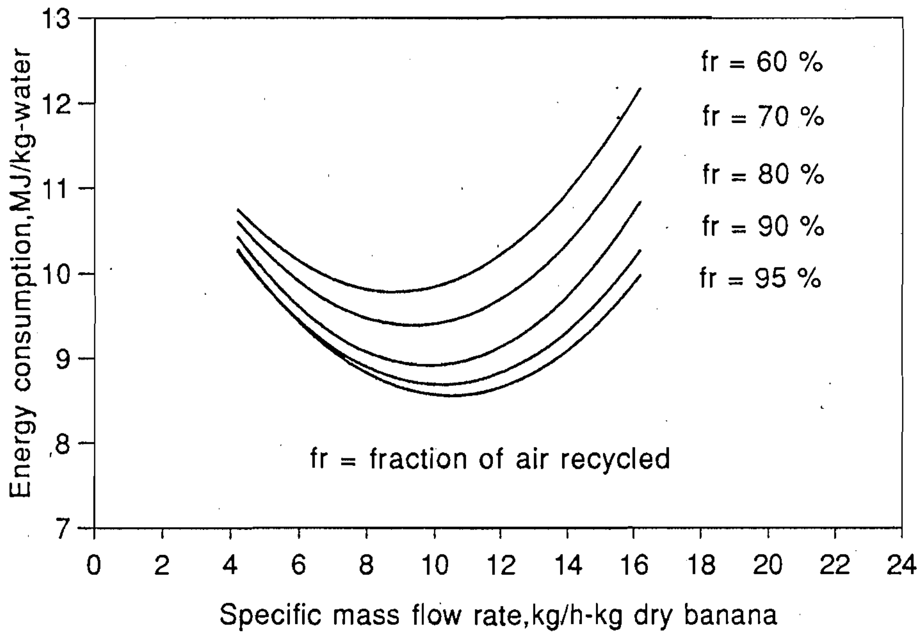

Fig. 8. Effect of specific mass flow rate on energy consumption at different fraction of air recycled (Temperature = 60°C).

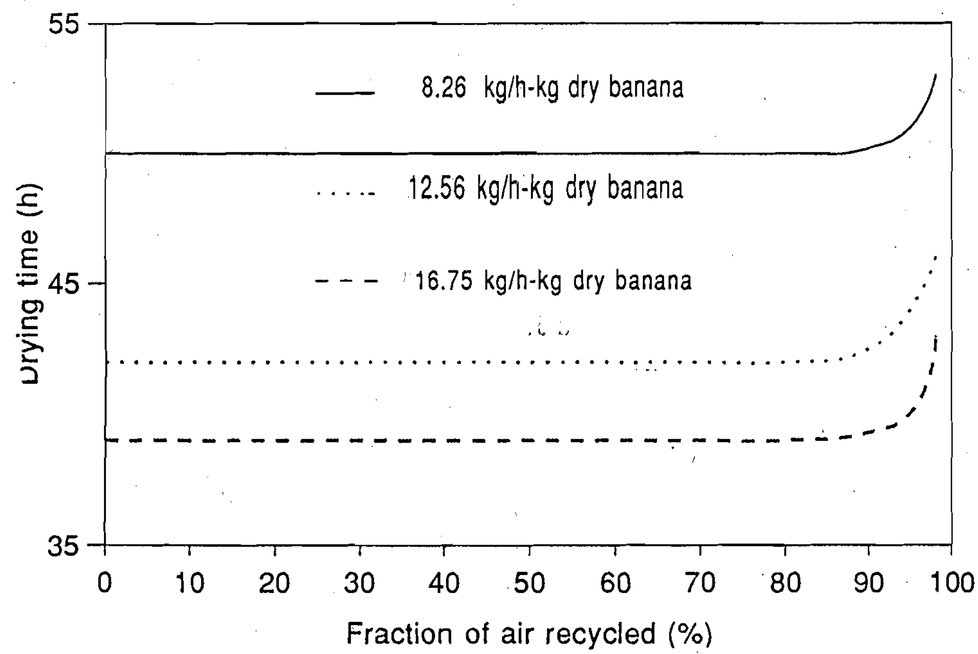

Fig. 9. Effect of fraction of air recycled on drying time at different specific mass flow rate (Temperature = 60°C).

RECOMMENDATION

Further study is needed to clarify the economics of the solar air heater. Optimum solar fraction is of considerable interest and should be investigated.

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