Fruit Drying Using Heat Pump

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ABSTRACT

The purposes of this research were to design, construct, evaluate performance and conduct cost analysis of a heat pump fruit dryer. The dryer consisted of a cabinet dryer and heat pump. Product capacity of the cabinet dryer was 100 kg to 132 kg with 12 trays and the heat pump capacity was 3.5 kW refrigeration. In this work, papaya glace' was dried in close loop air with drying temperature of 50 °C, air flow rate of 0.45 kg/s and bypass air of 63%. Drying operation was divided into two steps. In the first step, papaya glace' with dimension of 6.35 x 15 x 2.5 cm³ and initial moisture content of 74% dry-basis was dried. In the second step, papaya glace' dried in the first step was cut into 0.98 x 0.98 x 0.98 cm³ and dried to a moisture content of 23% dry basis. The results were as follows: drying rate 0.686 kg water/h, moisture extraction rate from evaporator 0.78 kg water/h and drying time of the two steps approximately 80 h (40 h in each step). Energy consumption was 9.93 MJ/kWh or SMER (specific moisture extraction rate) 0.363 kg water evaporation/kWh at specific air flow rate of 21.42 kg dry air/h-kg dry papaya glace'. The coefficient of performance for the heat pump (COP_{hp}) varied between 3.71 to 3.85. For the quality of papaya glace' after drying in terms of color, it was found that the color of papaya glace' was light reddish-orange (code 34-C from R.H.S. color chart). Cost evaluation found that cost of papaya glace' drying was 12.8 Baht/kg water evaporation of which 5.3 was energy cost, 1.4 was maintenance cost and 6.1 was fixed cost (US$ 1 = 40 Baht).

1. INTRODUCTION

Dried fruit is a modified agricultural product which is in high demand in both domestic and international markets. The drying process is an important step of the production process as it has high operating costs. Cabinet dryers are suitable for drying fruit. Drying temperatures typically used in dryers are approximately 60°C to 70°C. If the drying temperature is higher, the product will be dark colored and its surface is withered and wrinkled. If the drying temperature is lower, the product quality will be acceptable but it requires long drying time. Small dryers use electricity, LPG or solar energy for heating air. Solar energy has limitations in terms of inconsistent energy availability. This research proposes a choice of using heat from heat pump for drying fruit. Fruit drying using heat pump could reduce energy cost with fairly low air temperature and relative humidity. This can be achieved by condensing moisture from the drying air and followed by reheating. Product quality in terms of color and smell could be improved.

Nousook, et al. [1] studied the suitable drying of papaya glace' in a tunnel. The drying was divided into two steps. In the first step, papaya glace' with dimension of 3.1 x 7.8 x 1.4 cm^3 was dried at initial moisture content of 60% dry-basis and drying temperature of 70°C until the final moisture content was 38% dry-basis. In the second step, the dimension of papaya glace' dried from first step was decreased to 0.98 x 0.98 x 0.98 cm^3. Then it was dried at a temperature of 55°C until the final moisture content was 23% dry-basis. The experiment showed that energy consumption of large pieces of papaya glace' was higher than that of the small ones. After drying, the quality of papaya glace' met standards of safety and industrial production of dried fruit.

Chou, et al. [2] studied fruit drying using a window air conditioning heat pump for window air conditioning unit with a capacity of 3.5 kW refrigeration. An electrical heater was also installed in this heat pump. The heat pump was used to dry banana and pineapple in a cabinet dryer with a fixed tray. Banana and pineapple were 10 mm thick. Drying time was 6 hours. Operating conditions were as follows: 1) fruit was dried in an open-loop system at a temperature of 61°C, and 2) fruit was dried in close-loop system at a temperature of 55°C. The experiment showed that the drying rate of the close-loop system was higher than that of the open-loop system.

Clement, et al. [3] studied continuous conveyor drying using a heat pump. Heat pump capacity was 20 kg/h for producing dried rubber. Refrigerant used in the heat pump was R-12 and maximum temperature was 70°C. The experiment showed that the specific moisture extraction rate (SMER) value was 1.5 kg to 2.5 kg of water evaporated/kWh. Parameters affecting the performance of the system were as follows: 1) the coefficient of performance (COP) increased with relative humidity of air passing through the evaporator, and 2) suitable ratio of by-pass air was 60% to 70% of total air flow rate.

Pendyala, et al. [4] studied heat pump drying using R-11 and R-12 as refrigerants with drying temperatures of 120°C and 75°C, respectively. The experiment found that COPs of R-11 and R-12 were 3.5 and 2.5, respectively. COP was low when an electrical heater was switched on.

Rossi, et al. [5] studied vegetable drying using a heat pump. Vegetable was dried in a fixed tray dryer with refrigerant R-12. The fixed tray dryer capacity was 1.3 kg and the drying temperature was 55°C. Drying was in a close-loop system. Experimental results found that parameters affecting heat pump dryer performance were air relative humidity entering the evaporator and evaporator temperature. The heat pump dryer could save energy of 30% to 40%. Product quality was high and drying time was low.

Young, et al. [6] studied drying using a heat pump with a fixed tray. Heat pump dryer capacity was 60 kg to 100 kg. Maximum rate of condensed water leaving the condenser was 8000 cm^3/h. The heat pump dryer system consisted of a 1.3 kW compressor, two condensers, two evaporators including recuperator. Experimental results showed that drying time decreased when temperature and velocity of hot air increased. Drying time was increased with size of material.

Strommen and Kraner [7] studied fluidized bed drying using a heat pump. Raw materials were small pieces of shrimp and fish. Experimental conditions were divided into two ranges as follows: drying with a temperature of -5°C, and drying with temperatures of 20°C and 30°C. Experimental results showed that material quality after drying in terms of mass and color was slightly changed. Energy consumption of heat pump dryer was low as compared with other dryers.

Past research showed that there are three types of heat pump dryers: fixed tray dryers, continuous dryers and fluidized bed dryers; and two models of air systems: close-loop (air was recycled in the system) and open-loop (dried air was ejected to surroundings). Drying temperature depended on refrigerant and it could be increased by adding electrical heat into the system.

However, use of the heaters caused COP to reduce. Heat pump dryer performance could be increased by selecting suitable ratios of air entering the evaporator and by-pass air, and using recuperator to exchange heat between hot air from cabinet dryer and cold air from evaporator.

The objectives of this research were to design, construct, evaluate performance and conduct cost analysis of a heat pump fruit dryer. Papaya glace' was selected as the drying product.

2. MATERIALS AND METHOD

The heat pump dryer used in this research was a close-loop system as shown in Fig. 1. It consisted of 0.90 x 0.80 x 0.75 cm^3 drying cabinet, 12 drying trays with area of 0.63 x 0.72 cm^2 each, 1.3 kW two-piston compressor, 4.5 kW internal and external condensers (4 x 13 rows and 14 fins per inch), 3.66 kW evaporator (3 x 8 rows and 14 fins per inch), 2 cycles of capillary tube throttling valves with dimension of 100 x 0.164 cm^2, recuperator heat exchanger with air mass flow rate of 0.14 kg/s and different temperature (between inlet and outlet) of 6°C, 3 kW heater, backward curved blade centrifugal fan with air mass flow rate of 0.4 kg/s to 0.8 kg/s and motor of 0.75 kW with speed adjustment by inverter, axial blade fan for external condenser with air flow rate of 0.14 kg/s and motor of 50 W, and forward curved blade centrifugal fan for evaporator with air mass flow rate of 0.14 kg/s and motor of 50 W.

Experimental fruit in this research was papaya glace' (the production process used was the same as in the royal food processing plant). Papaya glace' was spread on trays which were put on a trolley and dried in a batchwise process. Three drying experiments were undertaken. The conditions for the experiments were as follows: 1) drying in a close loop system, 2) air used for drying was controlled at 50°C, 3) air mass flow rate was constant at 0.45 kg/s and ratio of by-pass air was 63% (air mass flow rate through evaporator was 0.17 kg/s), and 4) papaya glace' quantity was varied between 70 kg to 132 kg. The experiment was divided into two steps. In the first step, papaya glace' with dimension of 6.35 x 15 x 2.54 cm^3 and initial moisture content of 74% dry basis was dried (experiments 1/1, 2/1, and 3/1). In the second step, papaya glace' dried from the first step was cut into dimension of 0.98 x 0.98 x 0.98 cm^3 and dried to final moisture content of 23% dry basis (experiments 1/2, 2/2, and 3/2). Air velocity in the recycled duct was measured by a hot wire anemometer. Temperature of air loop in Fig. 2 and temperature of refrigerant loop in Fig. 3 were measured by a Chromel-Alumel type *k* thermocouple connected to a data logger (accuracy ± 1°C). Budong gauge was used to measure pressure in the refrigerant loop. A load cell with accuracy of 50 g was used to measure weight of material in the cabinet dryer. Maximum weightmass measured was 150 kg. Condensed water from the evaporator was measured by a load cell with accuracy of 0.01 g. Maximum weight measured was 3 kg. Kilowatt-hour and clamp-on meters were used to measure energy consumption in the system. The values measured were dry-bulb temperature, wet-bulb temperature, mass weight of papaya glace', weight of condensed water from air in evaporator and energy consumption. Measurements were made every two hours. Initial moisture content of papaya glace' was measured by the following methods: 1) papaya glace' sample was taken and cut into small pieces; 2) the sample was measured by digital balance instrument (accuracy of 0.01 g); and 3) the sample was put into a cabinet dryer at a temperature of 103°C for 72 h. The papaya glace' quality after drying was studied by checking color with R.H.S. color chart.

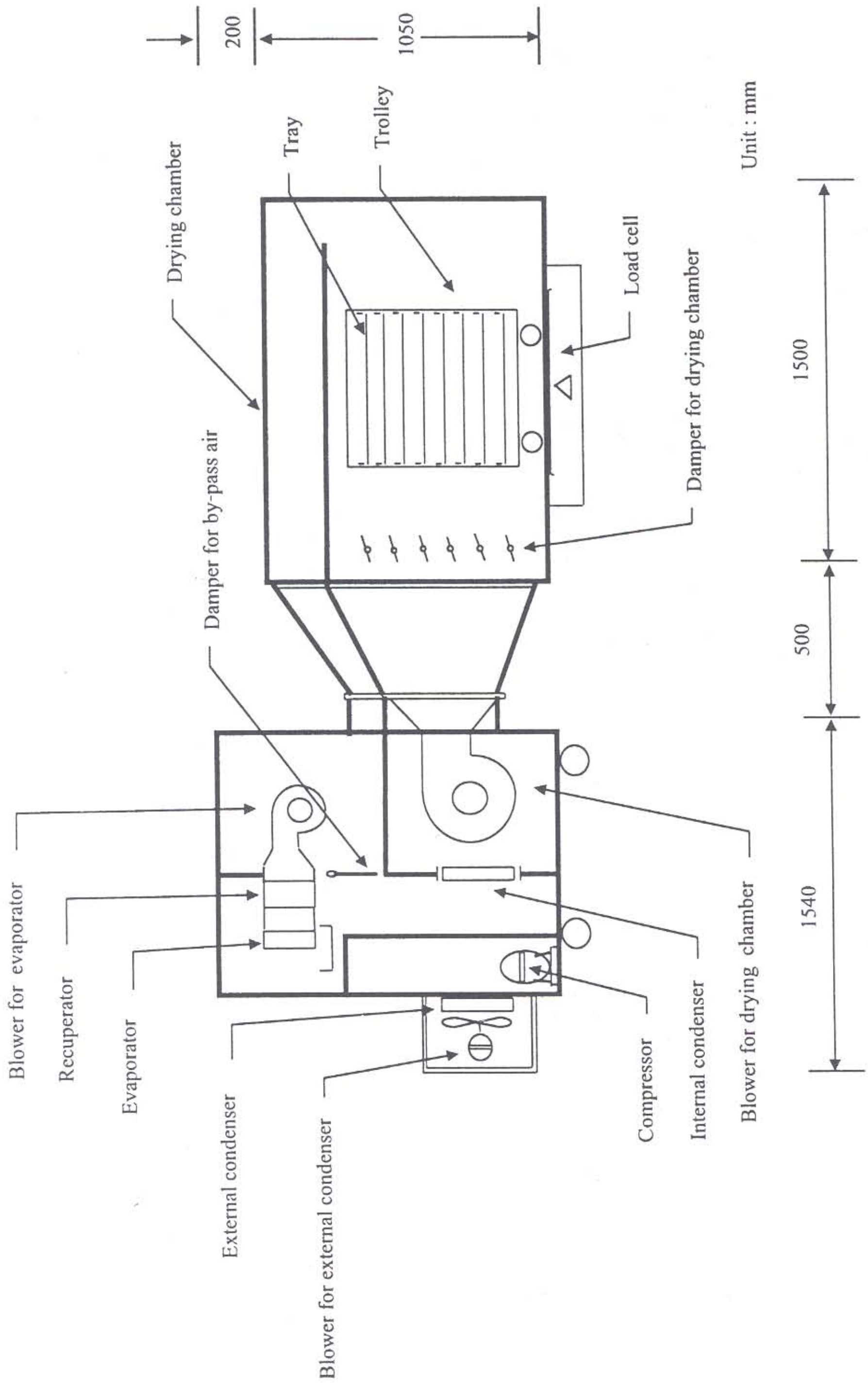
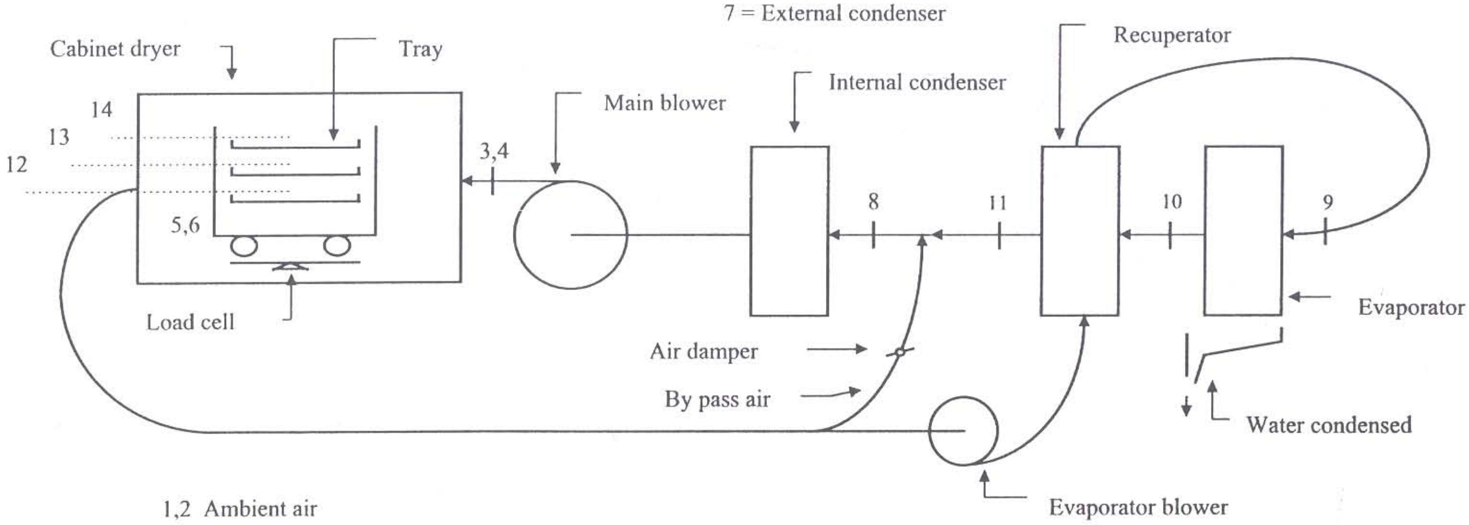
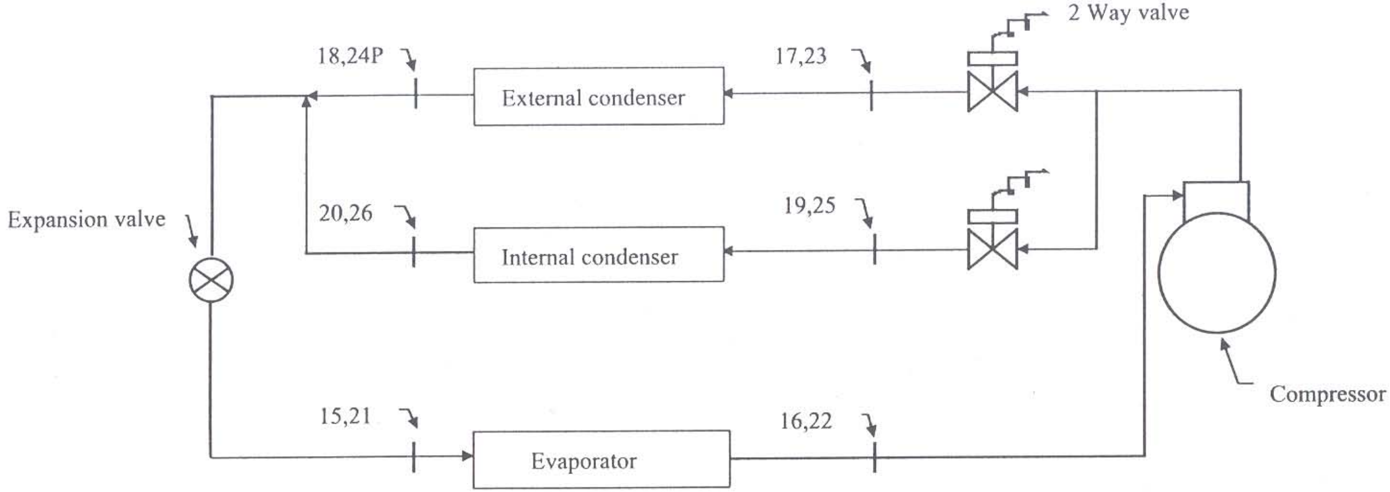


Fig. 1. Heat pump fruit dryer.



1 = ambient, dry bulb
2 = ambient, wet bulb
3 = before drying, dry bulb
4 = before drying, wet bulb
5 = after drying, dry bulb
6 = after drying, wet bulb
7 = outlet of external condenser
8 = inlet of internal condenser
9 = inlet of evaporator
10 = outlet of evaporator
11 = outlet of recuperator
12 = first tray
13 = sixth tray
14 = twelfth tray

Fig. 2. Temperature measurement for air loop.



For temperature

15,16 = inlet and outlet of evaporator

17,18 = inlet and outlet of external condenser

19,20 = inlet and outlet of internal condenser

For pressure

21,22 = inlet and outlet of evaporator

23,24 = inlet and outlet of external condenser

25,26 = inlet and outlet of internal condenser

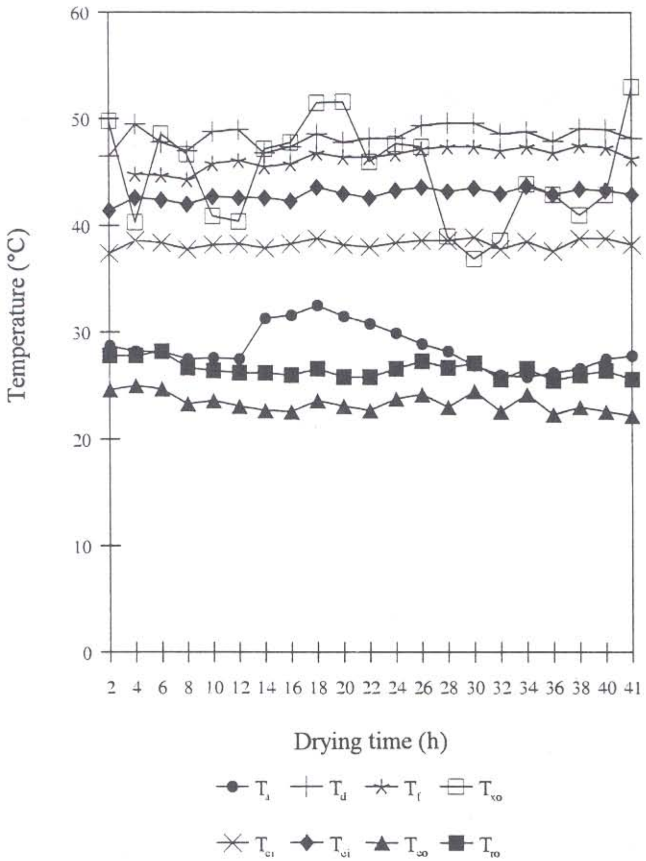
Fig. 3. Temperature and pressure measurements for refrigerant loop.

3. RESULTS AND DISCUSSION

3.1 Experimental Results

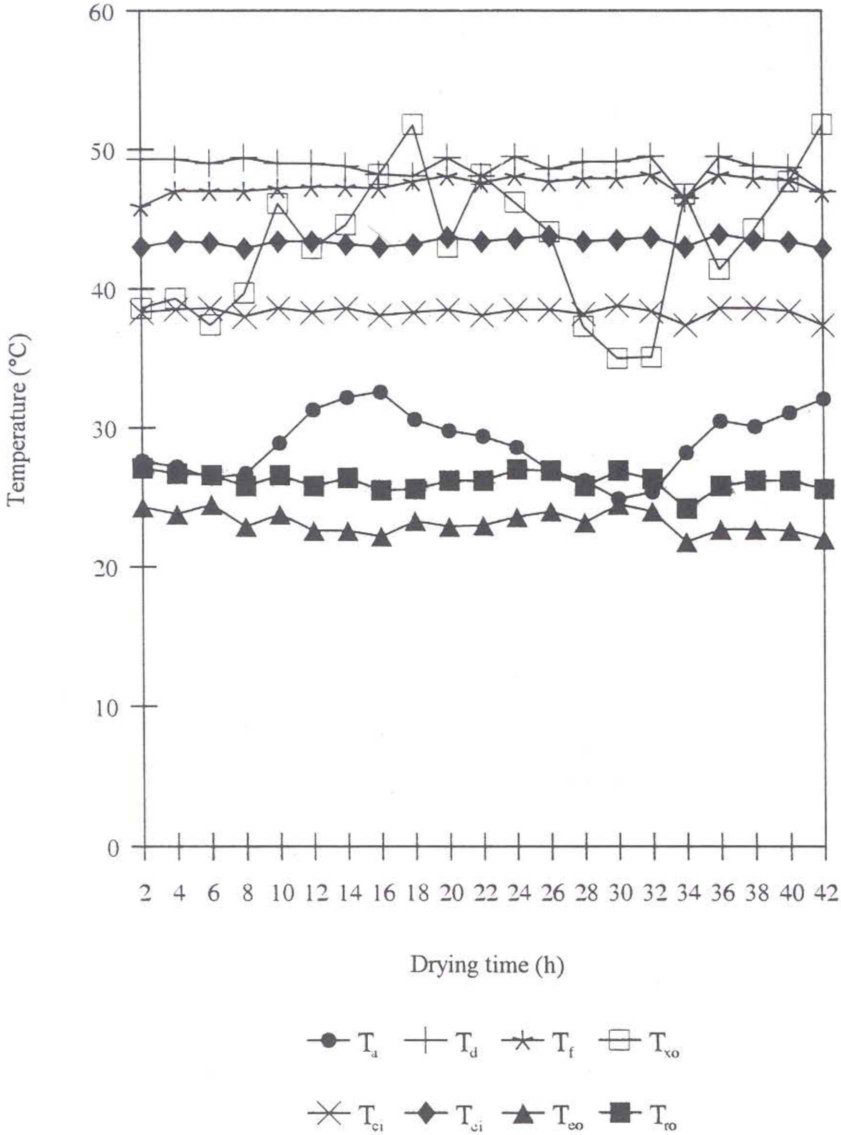
3.1.1 Air Temperature Variation

It was found that differences of inlet and outlet air temperature of each subcomponent of the heat pump system were: internal condenser, 10°C; evaporator, between 3°C to 4°C and cabinet dryer, between 1°C to 5°C, as shown in Fig. 4 and Fig. 5. Outlet air temperature at the external condenser varied up and down due to solenoid valve temperature control. For hot air temperature distribution in the trolley, it was found that the air temperatures of the tray on the top part, middle part and bottom part of the trolley were slightly different (temperature of top tray was higher than that of bottom tray) as shown in Fig. 6 and Fig. 7.



T_a = ambient temperature
T_f = temperature after drying
T_d = temperature before drying
T_{xo} = outlet temperature at external condenser
T_{ci} = inlet temperature at internal condenser
T_{ei} = inlet temperature at evaporator
T_{eo} = outlet temperature at evaporator
T_{ro} = outlet temperature at recuperator

Fig. 4. Evolution of temperatures in air loop for the second test, first stage.



T_a = ambient temperature
T_f = temperature after drying
T_d = temperature before drying
T_{xo} = outlet temperature at external condenser
T_{ci} = inlet temperature at internal condenser
T_{ei} = inlet temperature at evaporator
T_{eo} = outlet temperature at evaporator
T_{ro} = outlet temperature at recuperator

Fig. 5. Evolution of temperatures in air loop for the second test, second stage.

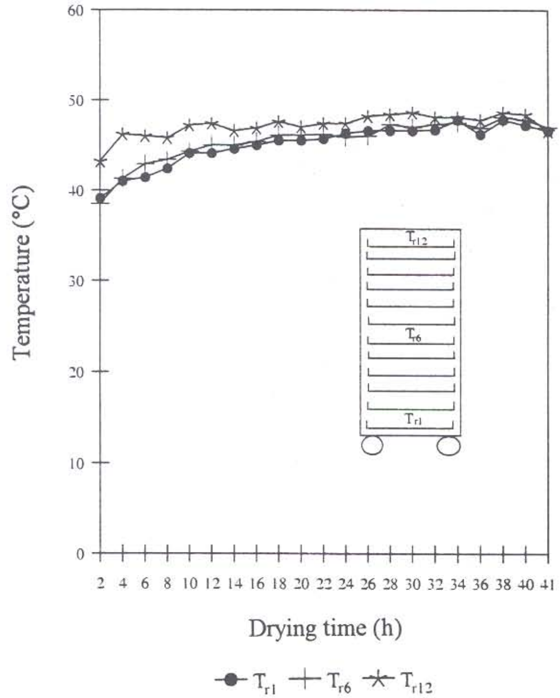


Fig. 6. Evolution of air temperature at different trays for the second test, first stage.

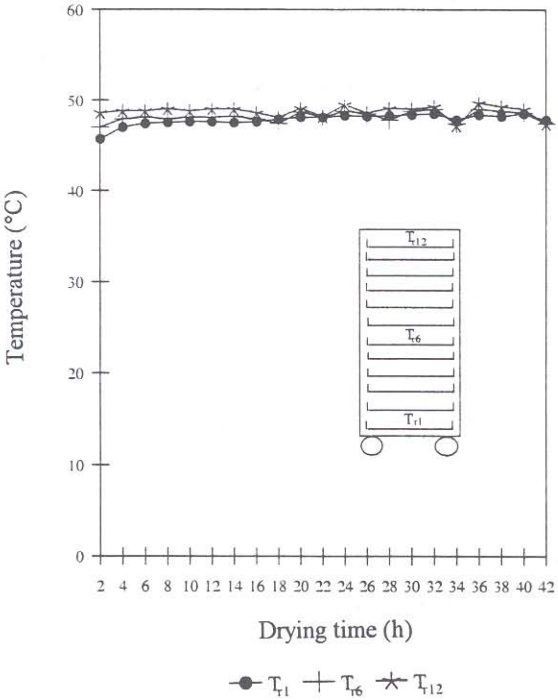


Fig. 7. Evolution of air temperature at different trays for the second test, second stage.

3.1.2 Papaya Glace' Moisture Content Variation

The results of papaya glace' moisture content variation from the experiment can be shown in relative data with drying time, in terms of average moisture content, water evaporated from papaya glace' (or drying rate) and water condensed at evaporator (or moisture extraction rate, MER). It was found that MER was higher than drying rate, as shown in Fig. 8 and Fig. 9. It was assumed that surrounding air could enter drying section of the heat pump resulting in a greater moisture loading.

3.2 Drying Efficiency Analysis

Drying efficiency of heat pump can be determined by analytical results of drying rate, moisture extraction rate (MER) from evaporator, energy consumption and specific moisture extraction rate (SMER) at desired specific air flow rate. The analytical results from each experiment are given in Table 1. Energy consumption decreases with the specific air flow rate while drying rates, MER and SMER increase.

3.3 Heat Pump Performance Analysis

In this study, performance of the heat pump was determined by experimental results obtained from both air loop and refrigerant loop (average record data every two hours). Analytical results in Table 2 show that the percentage error was acceptable. Performance of the heat pump expressed in terms of coefficient of performance for heat pump (COP_{hp}) varied between 3.71 to 3.89.

3.4 Papaya Glace' Quality

For the quality of papaya glace' after drying, it was found from the two steps of experiment that the color of the product was light reddish-orange (in code 34-C from R.H.S color chart) which was lighter than that of drying papaya glace' in hot air tunnel.

3.5 Cost Evaluation

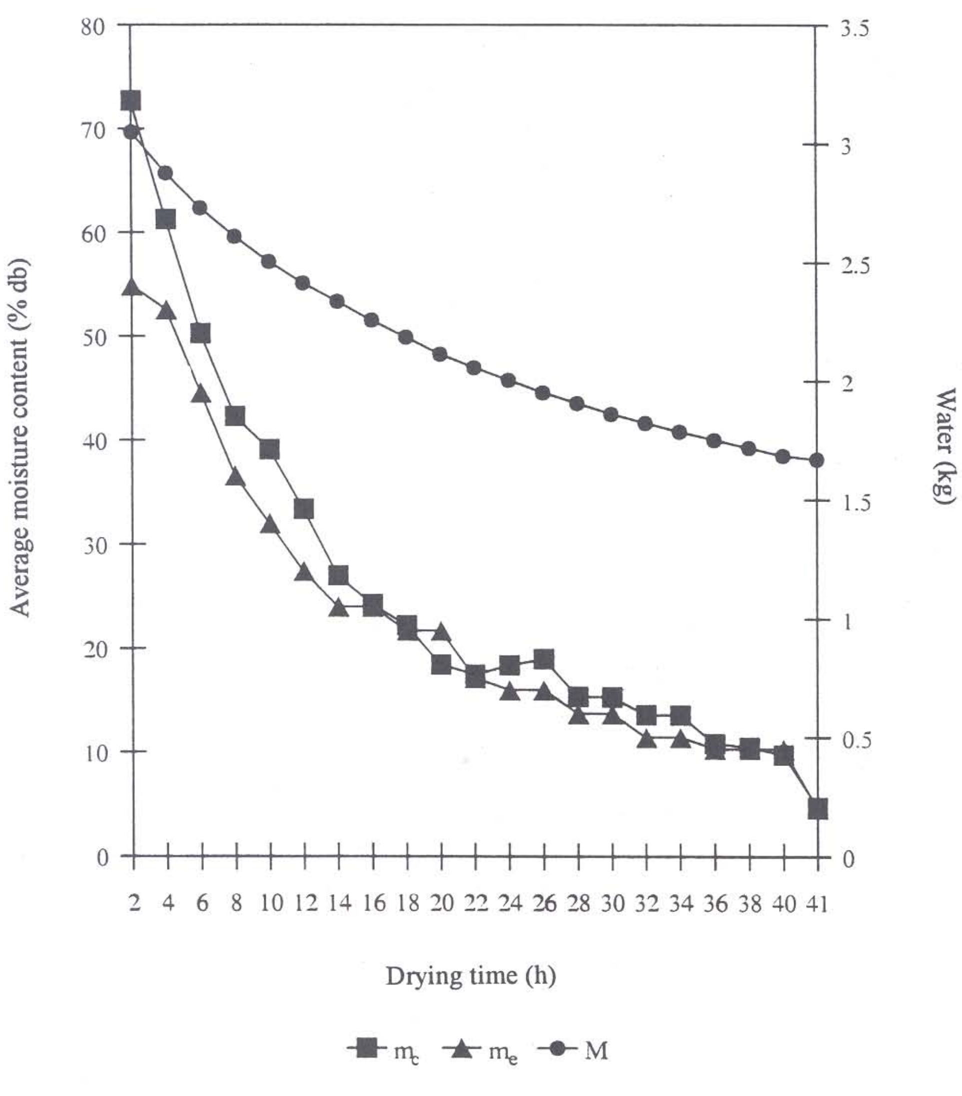
Conditions for evaluation of the heat pump in this study were as follows: capacity was 132.2 kg/batch, operating time was 48 batches/year, average drying time was 80 hr/batch, dried papaya glace' quantity was 6346 kg/year, fixed cost was 59,012 Baht (US$ 1 = 40 Baht), life time of heat pump was 10 years (in case of poor maintenance), maintenance cost per year was 5% of fixed cost, salvage value was 10% of fixed cost, evaporation water ability was 44.25 kg water evaporated/batch, electricity price was 1.55 Baht/kWh, electricity use rate was 1.89 kWh/h and interest rate was 18%/year. Operating costs were neglected in this study.

3.5.1 Ten-year Life of Heat Pump

Total annual cost was 27,079 Baht/year or 12.8 Baht/kg water evaporation of which 6.1 Baht/kg was fixed cost, 5.3 Baht/kg was electricity cost and 1.4 Baht/kg was maintenance cost.

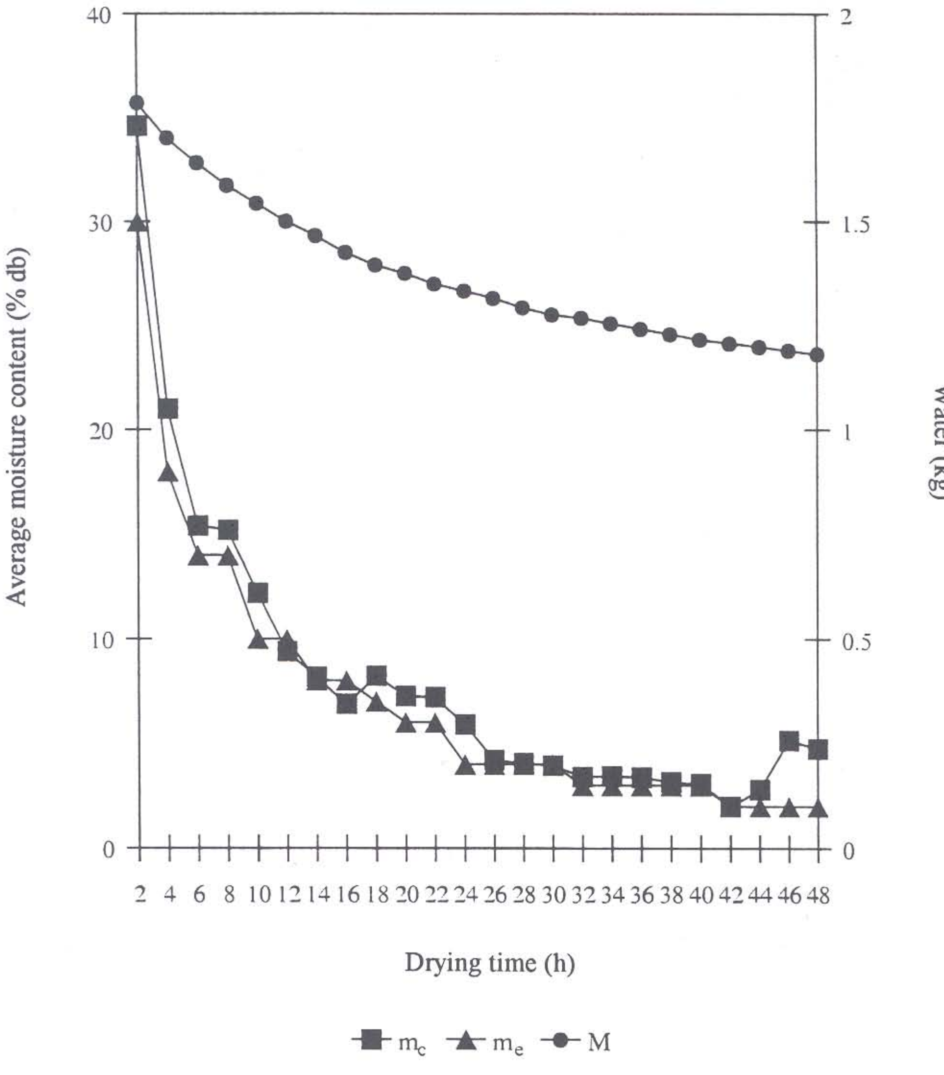
3.5.2 Five-year life of heat pump

Total annual cost was 32,246 Baht/year or 15.2 Baht/kg water evaporation of which 8.5 Baht/kg was fixed cost, 5.3 Baht/kg was electricity cost and 1.4 Baht/kg was maintenance cost.



m_c = water condensed at evaporator
m_e = water evaporated from papaya glace'
M = average moisture content of papaya glace'

Fig. 8. Evolution of average moisture content of papaya glace', water condensed at evaporator and water evaporated from papaya glace' for the second test, first stage.



m_c = water condensed at evaporator
m_e = water evaporated from papaya glace'
M = average moisture content of papaya glace'

Fig. 9. Evolution of average moisture content of papaya glace', water condensed at evaporator and water evaporated from papaya glace' for the second test, second stage.

Table 1. Experimental drying results.

Description	TEST No.					
	1/1	1/2	2/1	2/2	3/1	3/2
Ambient condition						
Average temperature (^{o}C)	28.9	29.3	28.5	28.9	29.3	29.3
Average relative humidity (%)	77.5	71.6	65.6	56.9	74.6	74.9
Condition of papaya glace'						
Averge moisture before drying (%db)	74.8	40.4	73.8	38.3	74.8	36.7
Averge moisture final drying (%db)	40.4	23.2	38.3	23.6	36.3	19.1
Initial weight (kg)	70.4	56.5	101.1	80.1	132.2	101.0
Final weight (kg)	56.6	49.7	80.5	71.6	103.4	88.0
Drying air condition						
Temperature (^{o}C)	50	50	50	50	50	50
Specific air flow rate						
(kg dry air/h-kg dry papaya glace′)	40.3	40.2	27.9	29.8	21.4	21.9
By pass air (%)	63	63	63	63	63	63
Energy consumption						
Energy consumption (MJ/kg water evap.)	15.95	39.73	13.56	38.02	9.93	19.75
Drying time (h)	42	40	41	48	42	38
Performance of heat pump						
Drying rate (kg water evap./h)	0.327	0.171	0.504	0.177	0.686	0.343
MER (kg water condensed/h)	0.541	0.316	0.578	0.195	0.780	0.544
SMER (kg water evap./kW-h)	0.172	0.091	0.266	0.095	0.363	0.343
COP_{hp}	3.82	3.76	3.85	3.73	3.83	3.81

Where MER = Moisture extraction rate from evaporator

SMER = Specific moisture extraction rate

COP_{hp} = Coefficient of performance for heat pump

Table 2. Comparative results analyzed from air and refrigerant loops.

Description	Test No.					
	1/1	1/2	2/1	2/2	3/1	3/2
W_c	1.31	1.31	1.31	1.31	1.31	1.31
m_f	0.02335	0.02424	0.02409	0.02350	0.02335	0.02266
m_{fi}	0.02092	0.02320	0.02137	0.02244	0.02077	0.02090
m_{fx}	0.00243	0.00104	0.00272	0.00106	0.00259	0.00176
$Q_{e,a}$	3.69	3.61	3.73	3.58	3.71	3.68
$Q_{e,f}$	3.64	3.85	3.81	3.68	3.69	3.54
% error of Q_e	1.23	6.51	2.14	2.74	0.44	3.89
$Q_{x,a}$	0.43	0.18	0.48	0.18	0.46	0.31
$Q_{i,a}$	4.57	4.74	4.56	4.72	4.56	4.68
$Q_{i,f}$	4.06	4.53	4.17	4.36	4.08	4.08
% error of Q_i	11.09	4.38	8.54	7.57	10.6	12.74
$COP_{hp,a}$	3.82	3.76	3.85	3.73	3.83	3.81
$COP_{hp,f}$	3.78	3.94	3.91	3.81	3.82	3.70
% error of COP_{hp}	1.34	6.35	2.04	2.84	0.37	3.92

Where W_c = Power input at compressor, kW

m_f = Mass flow rate of refrigerant, kg/s

m_{fi} = Mass flow rate of refrigerant in internal condenser, kg/s

m_{fx} = Mass flow rate of refrigerant in external condenser, kg/s

$Q_{e,a}$ = Net cooling effect at evaporator calculated from air loop, kW

$Q_{e,f}$ = Net cooling effect at evaporator calculated from refrigerant loop, kW

$Q_{i,a}$ = Net heat rejected at internal condenser calculated from air loop, kW

$Q_{i,f}$ = Net heat rejected at internal condenser calculated from refrigerant loop, kW

$Q_{x,a}$ = Net heat rejected at external condenser calculated from air loop, kW

$COP_{hp,a}$ = Coefficient of performance for heat pump calculated from air loop

$COP_{hp,f}$ = Coefficient of performance for heat pump calculated from refrigerant loop

4. CONCLUSION

1. Drying rate (rate of water evaporated from papaya glace') from heat pump can be operated to 0.686 kg water evaporated/hr.
2. Moisture extraction rate from evaporator was 0.78 kg water condensed/hr.
3. Total drying time of both steps in the experiment was approximately 80 hr (40 hr for each step).
4. Energy consumption was 9.93 MJ/kg water evaporated or in terms of specific moisture extraction rate was 0.63 kg water evaporated/kWh at the condition of specific air flow rate of 21.4 kg dried air/h-kg dried papaya.
5. Coefficient of performance for heat pump (COP_{hp}) varied between 3.71 to 3.85 which indicated that power supplied by the heat pump system for cooling at the evaporator was 3.7 kW and for heating at condenser was 5.04 kW of which 4.74 kW was heating power at internal condenser and 0.3 kW was at external condenser. Power supplied to compressor was 1.31 kW.
6. Cost evaluation found that total operating cost was 12.8 Baht/kg water evaporated, of which 5.3 was energy consumption cost, 1.4 was maintenance cost and 6.1 was fixed cost.
7. The color of papaya glace' after drying was light reddish-orange (code 34-C from R.H.S color chart), lighter than the color of papaya glace' dried by hot air tunnel [1]. This may be due to the effect of drying temperature which was lower than that of the drying in tunnel.

5. ACKNOWLEDGMENT

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