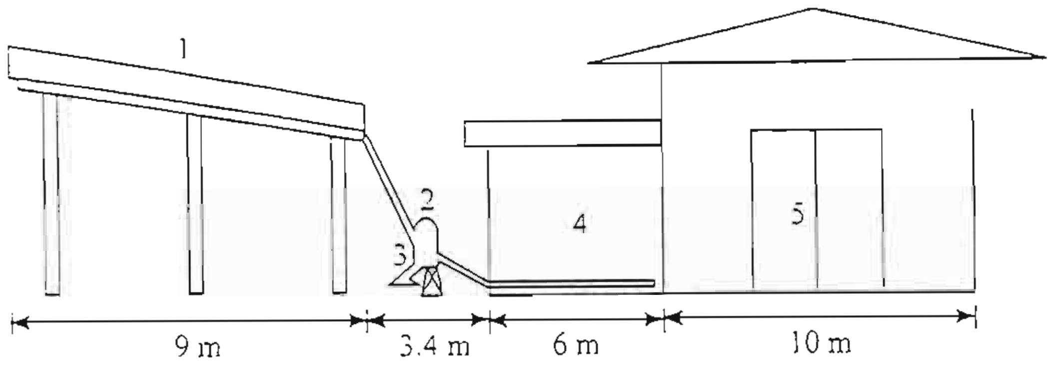

1 = collector, 2 = Blower, 3 = burner stove
4 = cabinet dryer, 5 = Facilitating room
Figure 3 Solar forced convection dryer

Table 1 The results of banana drying testing of various methods

	NCSD[A]	LPGD[B]	FCSD+LPG[C]
Initial weight of bananas (kg)	25	192	360
Final weight of bananas (kg)	9	73	141.1
Water evaporation loss (kg)	16	119	218.9
Total solar radiation at collector surface (MJ)	292.3	-	1,814.9
Total energy consumption of LPG (MJ)	-	971.2	1,060.4
Total electrical consumption of fan (MJ)	-	-	393.6
Total energy consumption (MJ)	292.3	971.2	3,269.2
Latent heat of evaporation (MJ/kg)	2.4	2.4	2.4
First law efficiency (%)	13.1	29.4	16.1
Average first law efficiency (%)[D]	11.1	23.6:28.5:30[E]	15.8
Specific energy consumption (MJ/kg of water evaporated)	18.3	8.2	14.9

Remark: NCSD = Natural Convection Solar Dryer
LPGD = LPG natural convection Dryer
FCSD + LPG = Forced Convection Solar Dryer with LPG as auxiliary
A = test results between 11-16 APR 1995.
B = test results between 13-16 DEC 1995.
C = test results between 15-19 MAY 1995.
D = Average first law efficiency of all experiments.
E = Average first law efficiency of 3, 4 and 5 day drying respectively
LPG Low Heating Value = 46,693 kJ/kg

DRYING OF BANANA FRUIT

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Abstract - A comparative study of various method of banana drying: solar natural convection drying (SNCD), LPG natural convection drying (LPGD) and solar forced convection drying with supplemental heat from LPG (SFCD+LPG), was performed. Experimental results showed that SNCD took 6-7 days (57 h) for completing one batch of banana. Total primary energy consumption and the first law efficiency were 19.2 MJ/kg of water evaporated and 12.5 % respectively. LPGD took 5 days (45 h) for completing one batch of banana. Total primary energy consumption and the first law efficiency were 8.4 MJ/kg of water evaporated and 30 % respectively. The last method, SFCD+LPG took 5 days (44 h) for completing one batch of banana. Total primary energy consumption and the first law efficiency were 14.9 MJ/kg water evaporated and 16.1 % respectively.

1. INTRODUCTION

The region of Phitsanulok and surrounding districts have a considerable amount of "nam-wa" bananas produced, which are commonly dried by open-sun drying, thus exposed to dust, insects, mold and micro-organisms, causing further product quality problems. These problems could be reduced by using an effective solar dryer. Recently, there are 3 drying methods used in this area; solar natural convection drying, LPG natural convection drying and solar forced convection drying with supplemental heat from LPG. Comparative study of these methods of drying would be appropriate.

Drying rate of damp cloth using solar natural convection cabinet dryer was found to be 4.2 kg/m^2-day[1]. The ratio of the area of air exit to the surface area of solar collector of 0.11 delivered the optimum drying efficiency with drying rate of 3.2 kg/m^2-day[2]. Wibulswas and Thaina[3] dried damp cloth with a hybrid solar natural convection dryer and found that drying rate was 5 kg/m^2-day. Furthermore, some research was conducted to develop a model dryer that employed forced convection, e.g. tobacco barn- drying using solar energy[4], modification of the drying barn to dry various fruits[5] and solar banana drying[6]. Additional information is available in the literature[7,8]. In addition to these findings, the research results and developments concerning solar dryer from various Asian countries were reported[9]. Rakwichien et al.[10] studied a hybrid solar forced convection dryer for "nam-wa" bananas and found that thermal efficiency was 30 %. Schirmer et al.[11] studied banana drying in solar tunnel dryer powered by a 53 W solar cell module. The results showed that bananas could be dried within 3 - 5 days compared to 5-7 days needed for natural sun drying. Through the observation of various projects within Thailand, it could be concluded that the use of a solar natural convection dryer for bananas is economically feasible[12], and forced convection is also realized as feasible technology[6,13].

With various types of fruit dryer available, the objective of this research is therefore to compare the performance of various types of the banana dryer, i.e., solar natural convection drying, LPG natural convection drying and solar forced convection drying with supplemental heat from LPG.

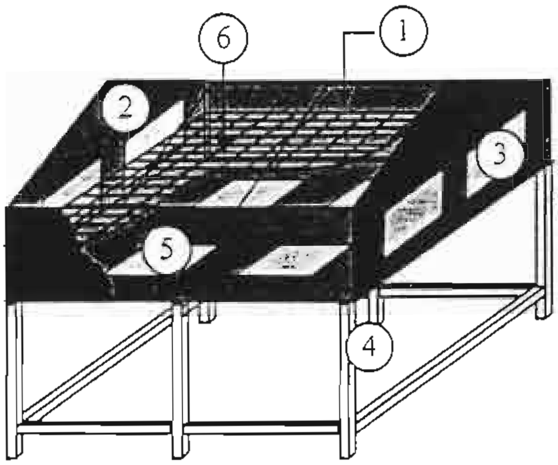
2. MATERIALS AND METHODS

2.1 *Details of dryers*

The details of three banana dryers tested in this research are as follows:

a) Solar natural convection dryer

As shown in fig.1, this block-shape dryer, designed by Department of Energy, Ministry of Sciences, Technology and Environments, is made of plywood coated with black color and its cover is made of transparent plastics. Inside the dryer, there is a bamboo tray with area of 0.2×1.5 m^2. Its collector area is 2.64 m^2 and its capacity is 25 kg of fresh banana with 9 kg of dried banana outputs.

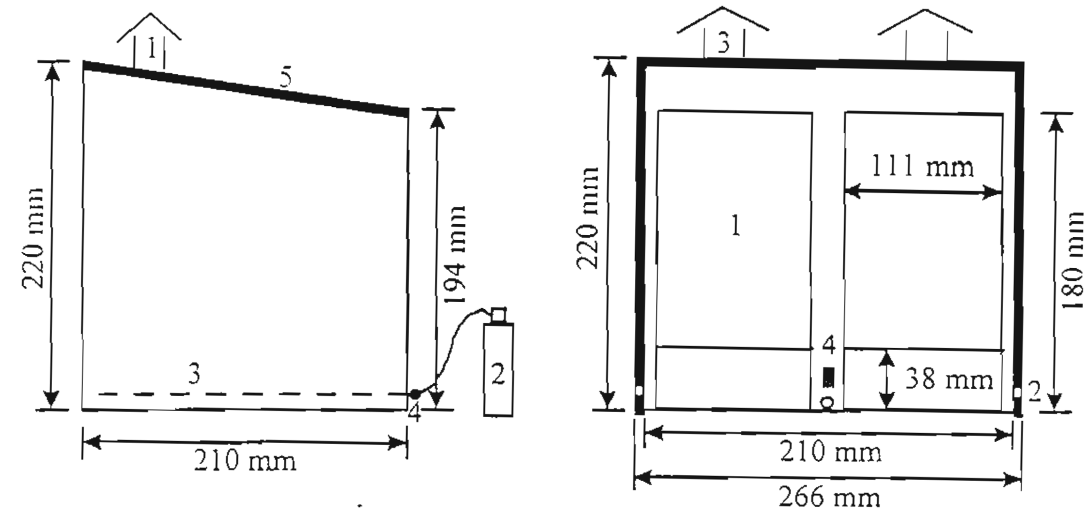


1 = transparent plastic cover, 2 = plywood drying chamber, 3 = air outlet
4 = dryer legs made of wood, 5 = air inlet, 6 = bamboo tray

Figure 1 Solar natural convection dryer

b) LPG natural convection dryer

This dryer, as shown in fig.2, designed by Agricultural Machinery Center, Phitsanulok, uses LPG for heating air. There are two trolleys with eleven 1.1×1.5 m^2 bamboo trays each in the drying chamber. The side and back walls of the dryer are made of brick coated with cement while the door and roof are insulated by rice husk, 2.4 cm thick, covered with zinc sheet. The dryer capacity is 192 kg of fresh banana with 73 kg of dried banana outputs.



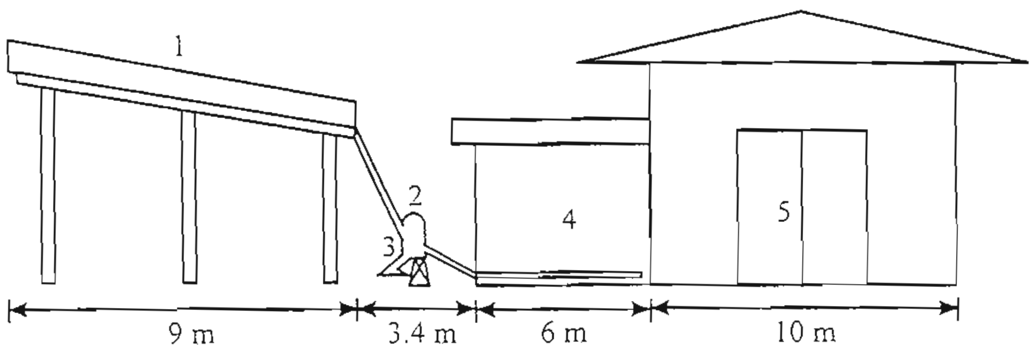
1 = air outlet, 2 = LPG container
3 = burner, 4 = LPG valve
5 = dryer roof

1 = trolleys, 2 = air inlet, 3 = air outlet
4 = the flame from LPG burning

Figure 2 LPG natural convection dryer

c) Solar forced convection dryer

This dryer (fig.3), designed by Asean-Canada Project at Naraesuan University, has solar collector units that separated from drying chambers[14]. Heat transfers from the collectors to the forced air in flow-channel which is later exits at collector outlet. In case of insufficient temperatures, LPG will be a stand-by auxiliary that directly heats ambient air in a junction burner located near the exhaust fan. One drying system comprises of 23.1 m^2 of solar collector area and a drying chamber of 1.73m × 2m × 6m long that accommodates three trolleys, five shelves and sixty trays. In operation, the air passes through the solar collector and directly enters the drying chamber through four perforated ducts located on the chamber floor. After that it further moves vertically past the drying bananas before exits at the chamber roof through six outlets.



1 = collector, 2 = blower (1.5 kW), 3 = LPG burner
4 = cabinet dryer, 5 = facilitating room

Figure 3 Solar forced convection dryer

2.2 *Experiments*

The experiments for each type of dryer are as follows:

a) Solar natural convection dryer

25 kg of peeled ripe bananas were spread on the dryer tray and dried during daytime. At the end of the first and second days of drying, they were collected, put in plastic bag and kept all night to start on sweetening before spreading them on the tray again on the day after. During night time of the third, fourth and fifth day of drying, they were piled in the middle of the tray to prevent case hardening. After the fifth day of drying, all bananas were flattened and further dried for another two days to complete the process. Seven dryers were used in this experiment to obtain continuous output of dried banana every day.

b) LPG Natural convection dryer

192 kg of ripe bananas were dried during daytime every day. At the end of the first, third and fourth day of drying, all bananas were piled in the middle of the tray and left all night to prevent case hardening while at the end of the second day they were collected and kept in plastic bag all night to start on sweetening. In the middle of the fourth day, the bananas were flattened before being further dried on the last day, completing the process. The drying temperature was approximately 55°C

c) Solar forced convection dryer

The experiment was conducted with 360 kg of peeled ripe bananas. The experimental process was the same as the LPG Natural convection dryer.

The three experiments mentioned above collected the following data:

-Air flow rates were determined by the average air-flow velocity of the exhaust air at the cross-section of the air product, with a fan anemometer.

-Temperature, entering and exiting solar collector, was measured by a type K thermocouple connected with data logger with an accuracy of ±1 °C and recorded at one hour intervals.

-Total solar radiation received on the solar collector surface, was measured by a solar indicator with an accuracy of ± 5%.

-LPG consumption was determined by recording LPG weight displaced.

-Electrical consumption of the centrifugal fan was measured with a meter (Yokogawa), with an accuracy of ± 1%

-Moisture content of the product, by the random selection of two banana samples, was weighed by accurate scales, 0.01 g, then cut into small pieces and dried in an oven at 103 °C for 72 hours.

-Water evaporation was measured by large scales (Max.cap. 60 kg), with an accuracy of ± 0.1 kg, and recording weight changes before and after each drying period.

3. RESULTS AND DISCUSSION

The results of banana drying testing of various methods are depicted in Table 1.

Table 1 The results of banana drying testing of various methods

	SNCD[A]	LPGD[B]	SFCD+LPG[C]
Initial weight of bananas (kg)	25	192	360
Final weight of bananas (kg)	9	73	141.1
Water evaporation loss (kg)	16	119	218.9
Total solar radiation at collector surface (MJ)	292.3	-	1,814.9
Total energy consumption of LPG (MJ)	-	971.2	1,060.4
Total electrical consumption of fan (MJ)	-	-	393.8
Total energy consumption (MJ)	292.3	971.2	3,269.2
Latent heat of evaporation (MJ/kg)	2.4	2.4	2.4
First law efficiency (%)	13.1	29.4	16.1
Average first law efficiency (%)	12.5	30.0	16.1
Specific energy consumption (MJ/kg of water evaporated)	18.3	8.2	14.9

Remark: SNCD = Solar natural convection dryer
LPGD = LPG natural convection dryer
SFCD + LPG = Solar forced convection dryer with LPG as auxiliary
A = test results during April 1995.
B = test results during December1995.
C = test results during May1995.
LPG Low Heating Value = 46,693 kJ/kg

From all tests, it was determined that initial moisture content of the fresh banana was between 230-300 % dry basis, and average final moisture content upon SNCD, LPGD and SFCD+LPG of 50, 47 and 47.3 % dry basis respectively. As reported on the table, the specific energy consumption of the LPGD is the lowest. This is caused by the fact that the efficiency of solar collectors are much lower than that of LPG combustion.

The colour of dried banana skin from SNCD, measured by R.H.S. Colour Chart, was Greyed-Yellow 162 group B while those from the LPGD and SFCD+LPG were darker, Greyed-Orange 163 group A. This is caused by higher temperature in drying chamber, 43 °C compared to 55 °C and 53 °C respectively which leads to nonenzymatic browning reaction.

4. CONCLUSION

The average efficiency of LPG drying is higher than those of solar dryers, 30% compared with 12.5% in solar natural convection dryer and 16.1% in solar forced convection dryer. The dried banana skin color of LPG drying and solar forced convection dryer with LPG as stand-by auxiliary are darker than that of solar natural convection dryer.

ACKNOWLEDGMENT

The authors would like to express their thanks to the Thailand Research Fund for supporting the Drying Technology Research Group of King Mongkut's Institute of Technology Thonburi.

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FRUIT DRYING USING HEAT PUMP

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ABSTRACT

The purposes of this research are to design, construct, evaluate performance and conduct cost analysis of heat pump fruit dryer. The dryer consists of cabinet dryer and heat pump. Product capacity of the cabinet dryer is 100-132 kg with 12 trays and capacity of heat pump is 1 ton refrigeration. In this experiment, papaya glace' is dried in close loop air with drying temperature of 50°C, air flow rate of 0.45 kg/s and by pass air of 63 %. Drying operation is divided into two steps. In the first step, papaya glace' with dimension of 6.35x15x2.5 cm^3 and initial moisture content of 74 % dry-basis is dried. In the second step, papaya glace' dried in the first step is cut into 0.98x0.98x0.98 cm^3 and dried to moisture content of 23 % dry basis. The results are as follows: drying rate 0.686 kg water evaporation/h, moisture extraction rate from evaporator 0.78 kg water evaporation/h and drying time of the twosteps approximately 80 h (40 h in each step). Energy consumption is 9.93 MJ/kW-h or SMER(Specific moisture extraction rate) 0.363 kg water evaporation/kW-h at specific air flow rate of 21.42 kg dry air/h-kg dry papaya glace'. The coefficient of performance for heat pump (COP_{hp}) varies between 3.71-3.85. For the quality of papaya glace' after drying in terms of color, it is found that color of papaya glace' is light reddish-orange(code 34-C from R.H.S colour chart). For cost evaluation from this experiment, it is found that cost of papaya glace' drying is 12.8 bath/kg water evaporation of which 5.3 is energy cost, 1.4 is maintenance cost and 6.1 is fixed cost (US$ 1 = 34 baht).

Key words : Fruit drying, heat pump, papaya glace'

Proc. 2nd ASEAN Renewable Energy Conference, Phuket, Thailand
6-9 Nov. 1997, 694-704.

INTRODUCTION

Dried fruit is a type of agricultural modified product which is in high requirement in both domestic and international markets. Drying process is an important step of production process which uses high cost for operating. Cabinet dryer is a dryer which is suitable for drying fruit. Drying temperature used in the dryer is approximately 60-70°C. If drying temperature is higher, product will be dark colored and its surface is withered and wrinkled. The small dryer uses electric, LPG and solar energy for heating air. Solar energy has limitation in inconsistent energy. Therefore it is only added energy. 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. Product quality in terms of color and smell is limited changed and is accepted by consumer.

From the past research (Nousook et al.,1996, Chou et al.,1993, Clement et al.,1993, Pendyala et al., 1990, Rossi et al.,1992, Young et al.,1995 and Strommen and Kraner,1994), it showed that there were three types of heat pump dryer: fixed tray dryer, continuous dryer and fluidized bed dryer, and two models of air system : close-loop system (air was recycled in the system) and open-loop system (dried air was rejected to surrounding). Drying temperature depended on refrigerant and it could be increased by adding heater into the system. However, the heater caused COP reduce. Heat pump dryer performance could be increased by selecting suitable ratio of air entering to 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 are to design, construct, evaluate performance and conduct cost analysis of heat pump fruit dryer. Papaya glace' was selected as drying product.

MATERIALS AND METHODS

Heat pump dryer in this research is a close-loop system as shown in Fig. 1. It consists of 0.90x0.80x0.75 cm^3 drying cabinet, 12 drying trays with area of 0.63x0.72 cm^2 each, 1.3 kW two piston compressor, 4.5 kW internal and external condensers (4x13 rows and 14 fins per inch), 3.66 kW evaporator (3x8 rows and 14 fins per inch), 2 cycles of capillary tube throttling valve with dimension of 100x0.164 cm, 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 0.4-0.8 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 is papaya glace'. Papaya glace' is spread on trays which are put on a trolley. This fruit drying is a batchwise drying. There are three experiments of the drying. The conditions for the experiment are as follows: 1) Drying is a close loop system. 2) Air used for drying is controlled at 50 °C. 3) Air mass flow rate is constant at 0.45 kg/s and ratio of by pass air is 63 % (air mass flow rate through evaporator is 0.17 kg/s). 4) Papaya glace' quantity is varied between 70-132 kg. The experiment is divided into two steps. First step, papaya glace' with dimension of 6.35x15x2.54 cm^3 and initial moisture content of 74% dry basis is dried (experiments 1/1, 2/1, and 3/1). Second step, papaya glace' dried from the first step is cut into dimension of 0.98x0.98x0.98 cm^3 and dried to final moisture content of 23 % dry basis (experiments 1/2, 2/2, and 3/2). Air velocity in recycled duct is measured by hot wire anemometer. Temperature of air loop in Fig. 2 and temperature of refrigerant loop in Fig.3 are measured by Chromel-Alumel type k thermocouple connected to data logger (accuracy ± 1 °C). Budong gauge is used to measure pressure in refrigerant loop. A load cell with accuracy of 50 g is used to measure weight of material in cabinet dryer. Maximum weight measured is 150 kg. Condensed water from evaporator is measured by a load cell with accuracy of 0.01 g. Maximum weight measured is 3 kg. Kilowatt-hour meter and Clamp-on meter are used to measure energy consumption in the system. The values measured are as follows: dry-bulb temperature, wet-bulb temperature, weight of papaya glace', weight of condensed water from moisture air in evaporator and energy consumption. The measurement is conducted every two hours. Initial moisture content of papaya glace' is measured by the methods as follows: 1) Papaya glace' sample is taken and cut into small pieces. 2) The sample is measured by digital balance (accuracy of 0.01 g). 3) The sample is put into a cabinet dryer at temperature of 103 °C for 72 h. Papaya glace' quality after drying is studied by checking color with R.H.S. color chart.

RESULTS AND DISCUSSION

Experimental Results

Air temperature variation

From the experimental results, it is found that differences of inlet and outlet air temperature of each subcomponent of heat pump system are : internal condenser 10 °C, evaporator between 20 °C, recuperator between 3-4 °C and cabinet dryer between 1-5 °C, as shown in Figures 4 and 5. Outlet air temperature at external condenser varied up and down, which is effected from temperature controlling by solenoid valve. For hot air temperature distribution in trolley, it is found that air temperature of the tray on top part, middle part and bottom part of the trolley is slightly different (temperature of top tray is higher than that of bottom tray)

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 is found that value of MER is higher than drying rate , as shown in Figures 6 and 7. It is assumed that surrounding humidity can absorb into drying section of heat pump.

Drying Efficiency Analysis

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

Heat Pump Performance Analysis

In this study, performance of heat pump is determined by experimental results obtained from both air loop and refrigerant loop (average record data every 2 hours). Analytic results show that error percent is in range of being acceptable. Performance of heat pump expressed in terms of coefficient of performance for heat pump (COP_{hp}) varies between 3.71-3.89.

Papaya Glace' Quality

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

Cost Evaluation

Conditions for evaluation of heat pump in this study are as follows: capacity 132.2 kg/batch, operating time 48 batches /year, average drying time 80 hr/batch, dried papaya glace' quantity 6346 kg/year, fixed cost 59,012 baht (US$ 1 = 34 baht), life time of heat pump 10 years, maintenance cost per year 5% of fixed cost, salvage value 10% of fixed cost, evaporation water ability 44.25 kg water evap./batch, electricity price 1.55 baht/kW-h, electricity used rate 1.89 kW-h and interest rate 18%/year. The operating cost is neglected in this study.

In case of life time of heat pump is 10 years

Total annual cost is 27,079 baht/year or 12.8 baht/kg water evap. of which 6.1 is fixed cost, 5.3 is electricity cost and 1.4 is maintenance cost.

In case of life time of heat pump is 5 years

Total annual cost is 32,246 baht/year or 15.2 baht/kg water evap. of which 8.5 is fixed cost, 5.3 is electricity cost and 1.4 is maintenance cost.

CONCLUSION

1. Drying rate (water evaporated rate from papaya glace') of heat pump can be operated to 0.686 kg water evap./h
2. Moisture extraction rate from evaporator is 0.78 kg water condensed/h
3. Total drying time of both steps in the experiment is approximately 80 h (40 h for each step)
4. Energy consumption is 9.93 MJ/kg water evap. or in terms of specific moisture extraction rate is 0.63 kg water evap./kW-h at the condition of specific air flow rate 21.4kg dried air/h-kg dried papaya.
5. Coefficient of performance for heat pump (COP_{hp}) varying between 3.71-3.85 indicates that power supplied by heat pump system for cooling at evaporator is 3.7 kW and for heating at condenser 5.04 kW of which 4.74 is heating power at internal condenser and 0.3 is at external condenser. Power supplied to compressor is 1.31 kW.
6. Cost evaluation of this study is found that total operating cost is 12.8 baht/kg water evap. of which 5.3 is energy consumption cost, 1.4 is maintenance cost and 6.1 is fixed cost.

7. Colour of papaya glace' after drying is light reddish-orange (code 34-C from R.H.S Colour chart), lighter than colour of papaya glace' dried by hot air tunnel(Noosuk et al.,1996). This may be due to the effect of drying temperature which is lower than that of the drying in tunnel.

ACKNOWLEDGMENT

The authors would like to thank the Thailand Research Fund for their financial support and to Rice Engineering Supply Co. Ltd. for her help in construction of heat pump dryer.

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Table 1 Experimental drying results

Description	TEST No.					
	1/1	1/2	2/1	2/2	3/1	3/2
Ambient condition						
Average temperature (°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'						
Average moisture before drying (%db.)	74.8	40.4	73.8	38.3	74.8	36.7
Average 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 (°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	0.78	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

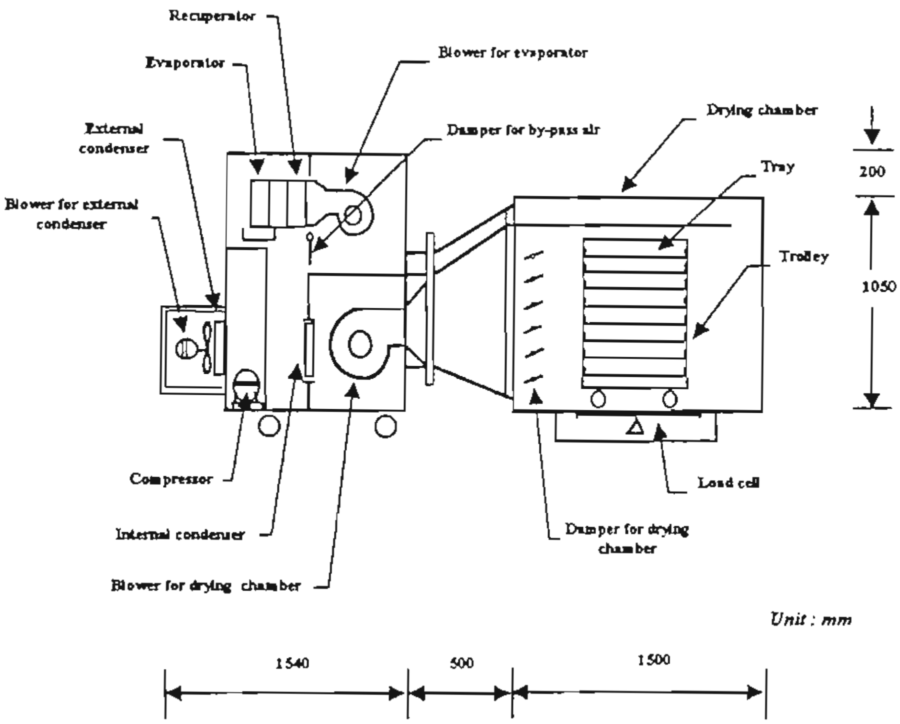

Figure 1 Heat pump fruit dryer

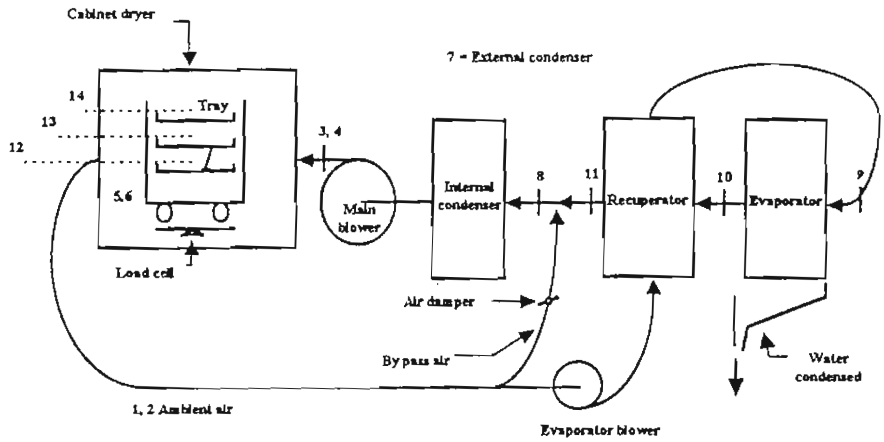

Figure 2 Temperature measurement for air loop

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

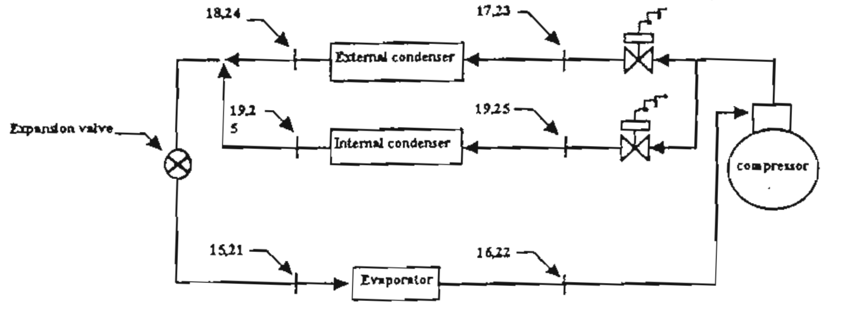

Figure 3 Temperature and pressure measurements for refrigerant loop

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

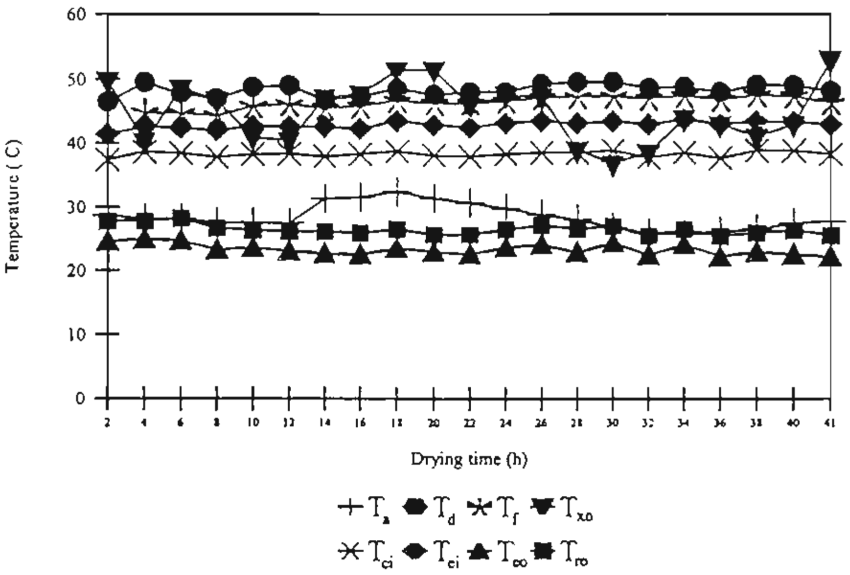

Figure 4 Evolution of temperatures in air loop for the 2nd test, 1st stage

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

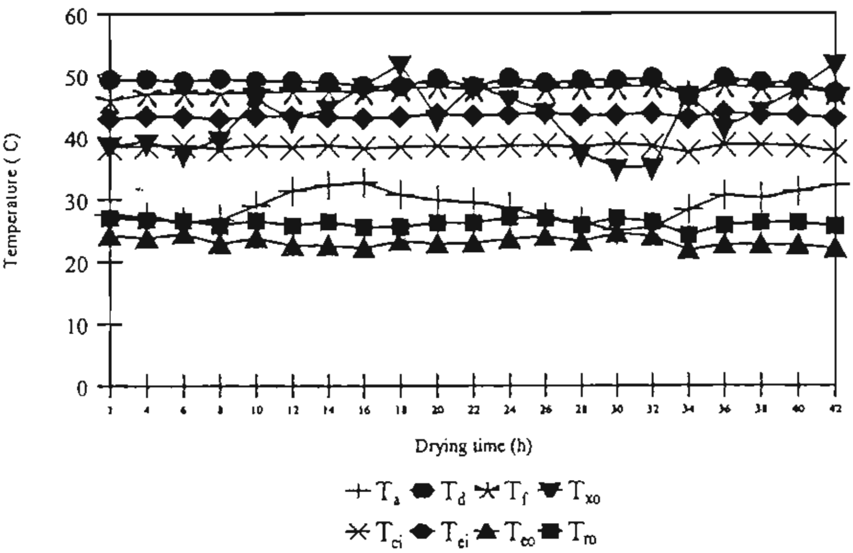

Figure 5 Evolution of temperatures in air loop for the 2nd test, 2nd stage

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

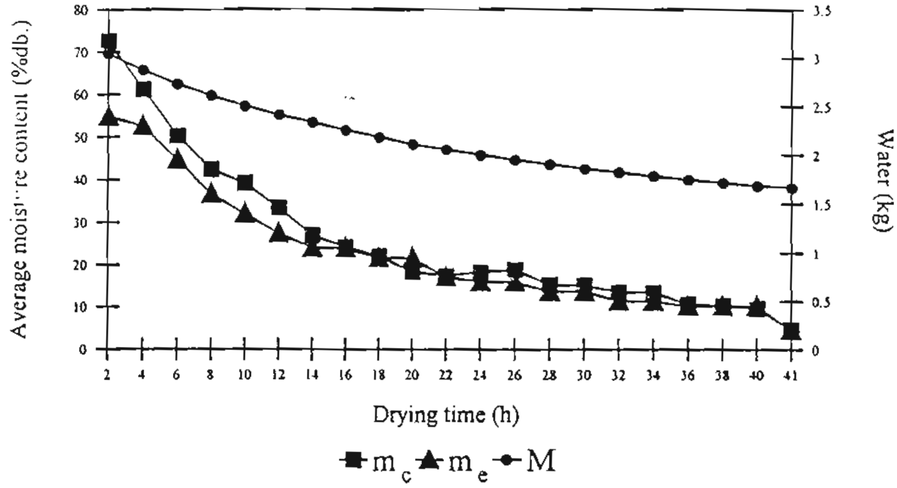

Figure 6 Evolution of average moisture content of papaya glace', water condensed at evaporator and water evaporated from papaya glace' for the 2nd test, 1st stage

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

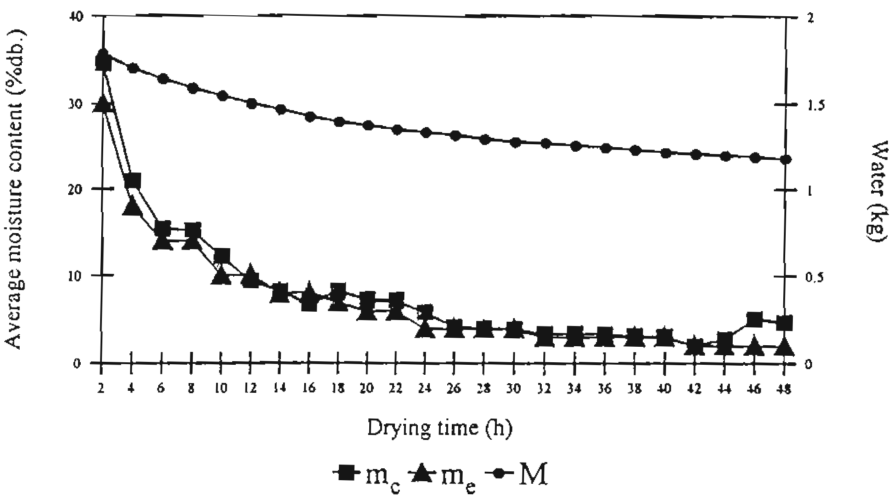

Figure 7 Evolution of average moisture content of papaya glace', water condensed at evaporator and water evaporated from papaya glace' for the 2nd test, 2nd stage

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

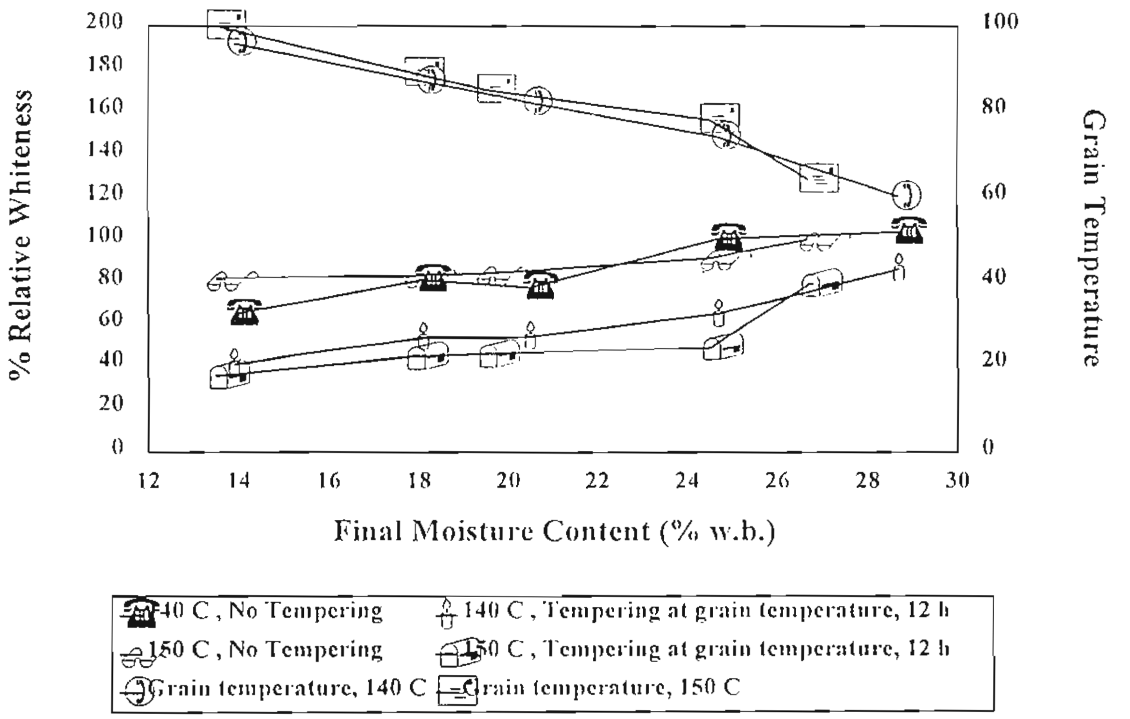

Figure 5 Relative whiteness at different heating process : initial moisture content = 30.7 %w.b., reference whiteness = 43.7

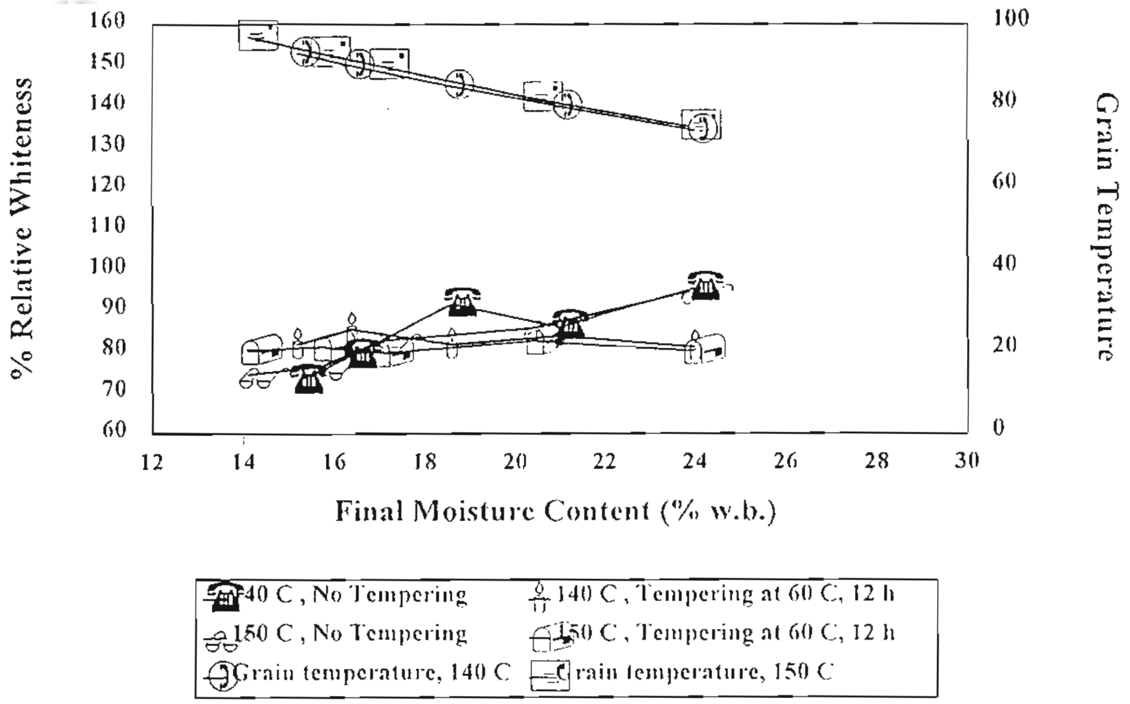

Figure 6 Relative whiteness at different heating process : initial moisture content = 26.7 %w.b., reference whiteness = 46.9

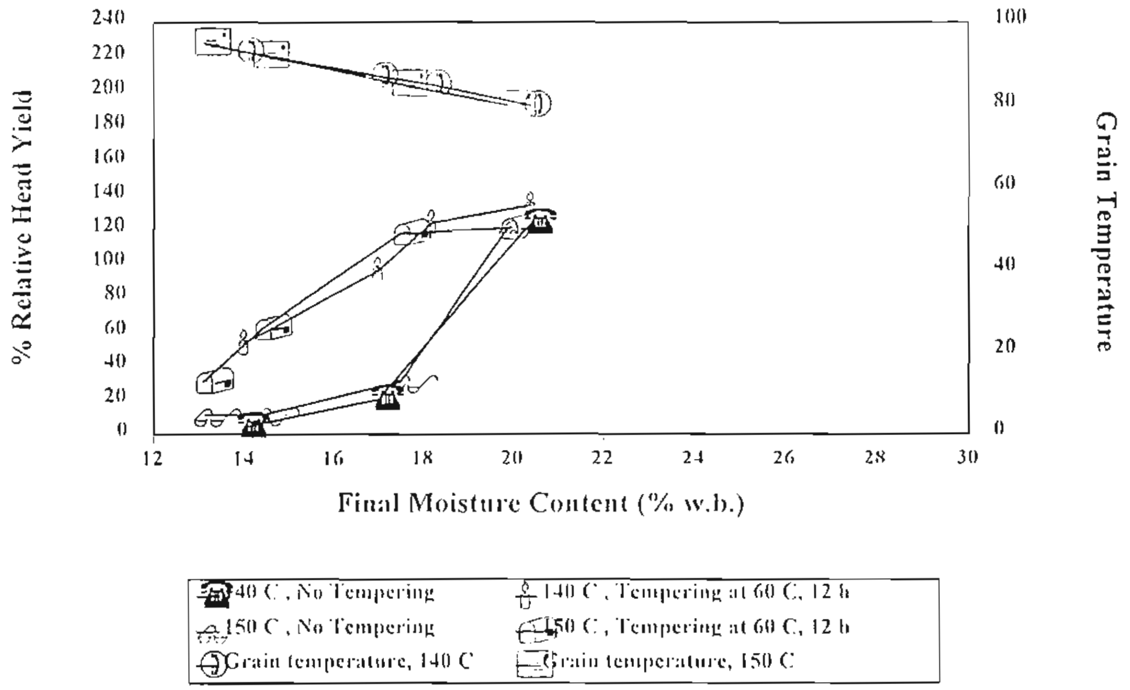

Figure 3 Relative head yield at different heating process : initial moisture content = 23.8 %w.b., reference head rice yield = 39.3 %

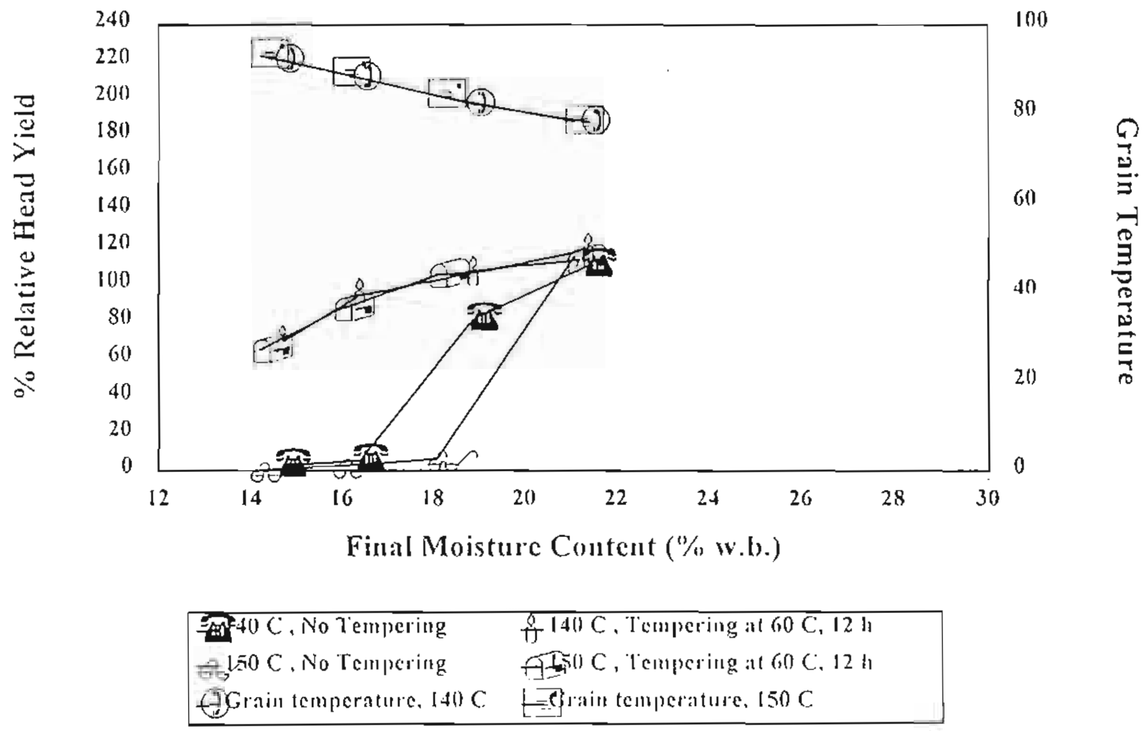

Figure 4 Relative head yield at different heating process : initial moisture content = 23.1 %w.b., reference head rice yield = 43.8 %

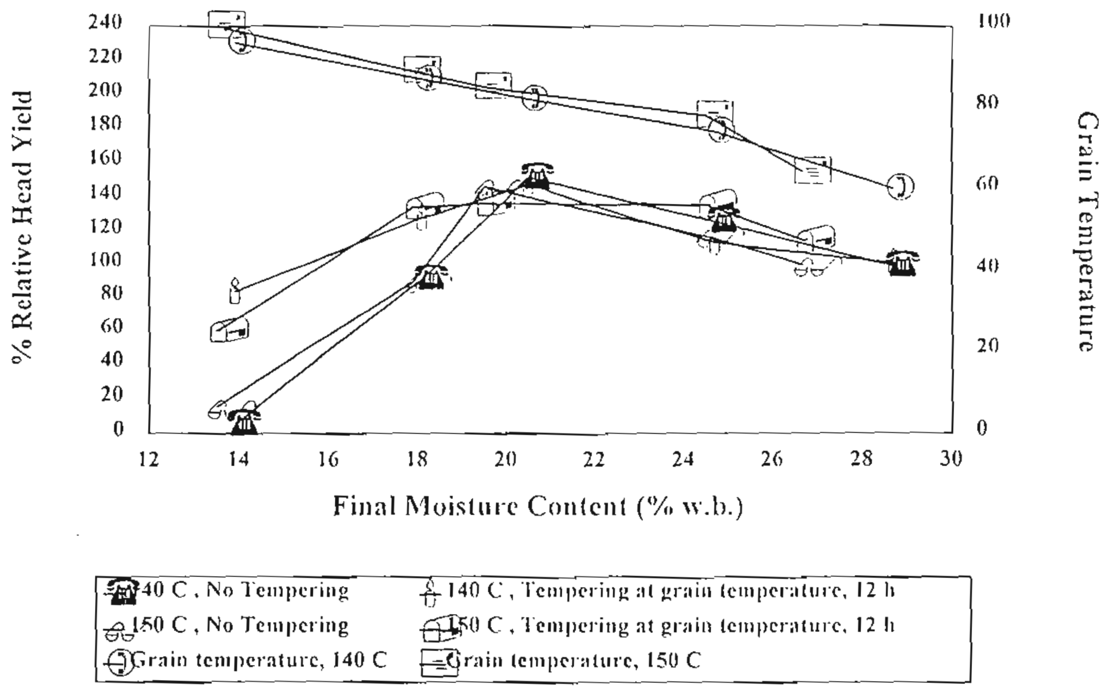

Figure 1 Relative head yield at different heating process : initial moisture content = 30.7 %w.b., reference head rice yield = 38.6 %

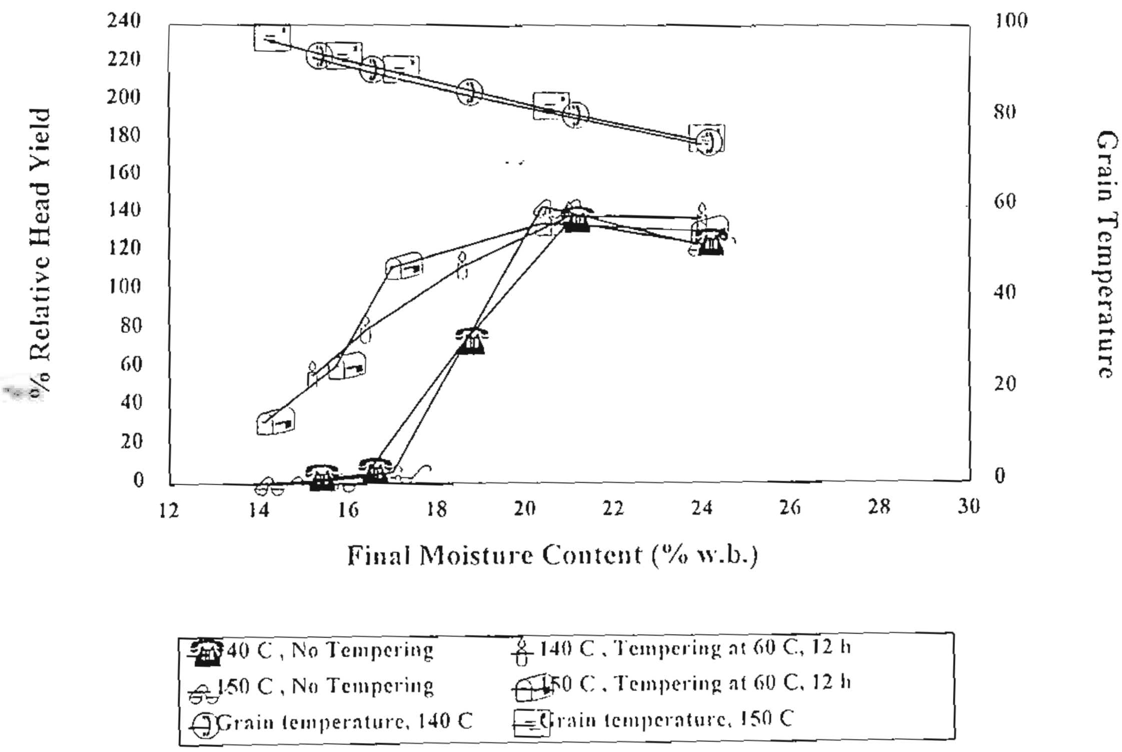

Figure 2 Relative head yield at different heating process : initial moisture content = 26.7 %w.b., reference head rice yield = 39.6 %

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CONCLUSION

From the experimental results of this study, it could be concluded as follows:

1. Drying temperatures for increasing head rice yield were in a range of 140 to 150 °C. It could be increased higher than 50 %.
2. Initial moisture contents of paddy that could increase head rice yield were in a range of 23-31 % wet-basis. As initial moisture content increased head rice yield increased.
3. Final moisture contents of paddy that could increase head rice yield to a maximum value were in a range of 19-22 % wet-basis.
4. In case of reducing moisture content of paddy to lower than 19 % wet-basis, head rice yield of tempered paddy was higher than that of no-tempered one.
5. Rice whiteness of dried paddy was mostly accepted. However, if tempering temperature was higher than 60 °C, it may cause the problems for trade.
6. For consumer acceptance, tested rice without tempering was not significantly different from reference rice while tested rice with tempering had problems about higher bad smell and lower whiteness of cooked rice.

ACKNOWLEDGMENT

The authors would like to thank the Thailand Research Fund and Australian Centre for International Agricultural Research for financial support, and Patum Thani Rice Research Center for helping in testing of rice milling quality, rice whiteness, and rice consumer acceptance.

Consumer Acceptance

Tables 2-3 showed mean eating-quality scores of various attributes of cooked rice from paddy with and without tempering, tasted and noted by testers, and analyzed by a statistical program "IRRISTAT" (IRRI = International Rice Research Center) for evaluation consumer acceptance. Comparative results between tested rice and reference rice (paddy dried by ambient air and had the same initial moisture content as tested rice) showed that the attribute values of tested rice without tempering were nearly the same as that of the reference rice. The results indicated that paddy with increasing head rice yield by fluidized bed drying had the same attributes as normal rice whereas whiteness of tested rice was slightly lower.

In case of tested rice with tempering the result showed that glossy, sticky and texture of cooked rice were nearly the same as that of the reference rice, but there were problems about higher bad smell that was more than normal level acceptance (3-3.5) and whiteness of cooked rice was lower than untempered rice and reference rice.

Changing drying air temperature from 140 ^{o}C to 150 ^{o}C had not much effect about consumer acceptance of tested rice with and without tempering. Table 4 showed that the increasing of tempering time from 0-12 hours had effect in higher bad smell and lower whiteness of cooked rice, other attributes were nearly the same as that of the reference rice. Almost of the testers indicated that tempering could make rice become old (aging) rice. Increasing tempering time from 2-12 hours had not much effect about the oldness.

Effect of tempering time on head rice yield was investigated as shown in Figure 9. Head rice yield could be significantly increased when paddy was tempered from 0 to 12 hours. However, tempering from 2 to 12 hours had no effect.

Rice Whiteness

Figure 5 showed that percentage relative whiteness decreased with final moisture contents of paddy and more decreasing (more yellow) in case of tempering. At lower final moisture content, grain temperature was higher and thus resulted in more yellow color. Not much effect of temperatures between 140 and 150 °C was observed. Rice color changed from white to yellow because of the reaction of rice browning, without enzyme involving.

Figures 6-8 showed percentage relative whiteness against final moisture contents of paddy, for other values of initial moisture contents of paddy. Tempering temperature was fixed at 60 °C instead of grain temperature. Percentage relative whiteness was nearly constant at about 80 % or higher except at the range of very low final moisture content. This value was normally accepted for rice trade. The whiteness (absolute value) was approximately 37 or higher (paddy dried by ambient air has values of whiteness about 44-46.).

Figure 10 showed that tempering time from 0 to 8 hours had little effect on whiteness of rice. However, whiteness was slightly lower when tempering time was 10-12 hours.

quality was tested by 9-10 skilled testers. The values of score were in a range of 1-9 (depending on intensity of each attributes). The meaning of score is shown in Table 1.

RESULTS AND DISCUSSION

Head rice yield

Figure 1 shows results of paddy drying at temperatures of 140 and 150 °C with and without tempering. Relative head rice yield increased to maximum values (about 150 %) when moisture contents of paddy was reduced to 19-22 % wet-basis. As final moisture content was higher than 22 % wet-basis, paddy temperature was lower than temperature that could result in complete gelatinization (approximately 78 °C, Thongyong and Detkumheang,1987). Therefore, head rice yield was lower as compared to drying paddy with final moisture contents of 19-22 % wet-basis. In reducing moisture content to lower than 19 % wet-basis, paddy was heated for a long time and drying rate decreased, thus resulted in more breakage. However, tempering for 12 hours could reduce the percentage of breakage significantly compared to the case without tempering. Drying air temperatures of 140 and 150 °C gave approximately the same results. Comparing among Figures 1-4, higher initial moisture contents yielded higher percentage relative head rice yield. Lower initial moisture content especially at 23.1 % wet-basis would be the minimum initial moisture that could increase head rice yield.

MATERIALS AND METHODS

A batch-type fluidized bed dryer was used in the experiment. It comprised a drying column (a diameter of 20 cm, a height of 140 cm), a 12 kW electrical heater with a temperature controller and a 1.5 kW backward curve-blade centrifugal fan with an air velocity adjuster. Exhaust air could be recycled by butterfly valves.

In the experiment, paddy was dried in the fluidized bed dryer from moisture contents of 23-31 % wet-basis to 13-29 % wet-basis at drying air temperatures of 140 and 150 °C. Then paddy was further dried with one of the following operations : paddy was left in the ambient air for 20-30 minutes, and then dried in a tray dryer with ambient air to reduce moisture content to 14 % wet-basis; or paddy was tempered for 12 hours (in case of initial moisture content of paddy 30.7 % wet-basis, tempering temperature was equal to dried paddy temperature exited from fluidized bed dryer, but for other values of initial moisture content tempering temperature was 60 °C), and then dried in a tray dryer with ambient air to reduce moisture content to 14 % wet-basis. Finally it was taken to milling process.

The qualities of paddy were considered were as follows : 1) Relative head yield (the ratio of head rice yield of paddy dried by fluidization technique to head rice yield dried by ambient air) ; 2) Rice color, indicated in relative whiteness (the ratio of whiteness of paddy dried by fluidization technique to whiteness of paddy dried by ambient air). The whiteness was measured by a Kett meter; 3) The consumer acceptance, indicated in score of 5 attributes of paddy. This moisture content from 22 to 17 %wet-basis, head rice yield was in a range of 58-61 %, but when moisture content was reduced down to16 %wet-basis, head rice yield decreased to a very low level (15-24 %). In case of reducing moisture content from 26 to 19 %wet-basis, head rice yield was in a range of 55-58 %, but if paddy moisture content was reduced to lower than 19 %wet-basis, head rice yield decreased to a very low level.

Soponronnarit and Prachayawarakorn (1994) studied drying of high moisture paddy by using fluidized bed technique. The factors which affected paddy quality and energy consumption were investigated. Results showed that drying rate increased with specific air flow rate and drying air temperature. Energy consumption decreased when specific air flow rate decreased or ratio of recycle air increased. It was concluded that paddy drying conditions to obtain good paddy quality were: drying air temperature not higher than 115 °C and final moisture content not lower than 24-25 % dry-basis (mainly considered in head yield percent and whiteness of rice). In drying paddy with initial moisture content 45.3 % dry-basis, at drying air temperatures of 100 and 130 °C, percentage head rice yield decreased with decreasing final moisture content ,but at a drying temperature of 150 °C, percentage head rice yield increased. It could be assumed that there was gelatinization in the outer part of paddy kernel.

Past research work showed that to increase head rice yield was feasible, especially by using fluidization technique at a drying temperature of 150 °C. Therefore, the objective of this research was to investigate experimentally appropriate drying conditions which could increase the percentage head rice yield. Drying technique was limited to fluidized bed drying.

INTRODUCTION

Rice is the most important crop of Thailand, a large quantity is exported each year. Price of rice varies, depending on rice quality such as head yield percent, whiteness, etc. Percentage head rice yield is one of the important factors that affects price. For this reason, a study of paddy drying for increasing head rice yield is most useful for rice trade.

Sihawong (1978) studied paddy drying by hot air at drying temperatures of 43, 49 and 60 °C, air flow rates of 6.7, 13.3, 20.0 and 26.7 m^3/min-$m^3$of paddy, and bed thickness of 0.9 m. It was found that drying air temperature should not be higher than 49 °C because higher temperature would decrease head rice yield. Bed thickness should not be higher than 0.6 m to avoid steep grain moisture gradient. The study showed that air flow rate had no effect to rice quality after milling.

Reyes and Jindal (1988) studied effect of heat treatment on head yield of paddy by sun drying method. Moisture content of paddy was reduced from 26-30 %wet-basis to 16-19 %wet-basis. After that, paddy was fed to heat treatment process and passed to a rotary conduction heating unit. It was found that of head rice yield increased. It could be assumed that this was resulted from gelatinization of starch in paddy kernel.

Sutherland and Ghaly (1990) studied paddy drying by fluidization technique. Moisture contents of paddy was reduced from 22-26 %wet-basis to 16-19 %wet-basis, bed thickness was 2.5 cm and drying temperatures was 40-90 °C. Experimental results showed that in case of reducing

Spin-off from Paddy Drying by Fluidization Technique

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Key words : grain drying ; fluidized bed; quality

Abstract

Fluidized bed paddy dryer has been commercialized in five countries, i.e., Thailand, the Philippines, Indonesia, Malaysia and Taiwan. Approximately 80 units were sold and installed in private rice mills. Initially, the fluidized bed dryer was aimed for rapid drying of high moisture paddy with low drying cost and uniform product moisture content. During using these dryers, however, some more positive results were noticed. Therefore, additional research work of effect of flidization drying on paddy quality were conducted. This paper describes the spin-off from fluidized bed paddy drying by high air temperature at various initial and final moisture contents. Experimental results showed that head rice yield could be increased while other qualities of rice were acceptable. Maximum value of head rice yield was obtained when final moisture content of paddy was in the range of 19-22 % wet-basis. The factors affecting the increase of head rice yield were initial and final moisture content of paddy and tempering process while drying air temperature of 140 and 150 °C gave similar result.

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ACKNOWLEDGMENT

The authors would like to thank to the Thailand Research Fund and Australian Centre for International Agricultural Research for supporting this project. Thanks are also due to Rice Engineering Supply Co., Ltd. for supporting fabrication and installation of the test unit, Koong Li Chan rice mill for supporting during experiment and Rice Research Center for supporting quality test.

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were 28.5 % and 32.6 % dry-basis respectively. At high enough moisture content, it was believed that partial gelatinization of starch in paddy kernel occurred. As a consequence, existing crack was bound thus yielded higher head yield compared to that of the reference dried by ambient air. The result was similar to that reported by Soponronnarit et al., 1994, that partial gelatinization occurred at the conditions of high enough initial moisture of paddy and drying air temperature (about 150 °C)

Heating process during drying would cause rice kernel turning yellow. In rice industry, the yellowness is indicated by the whiteness measured by Kett meter. For the first test, average whiteness obtained from fluidized bed paddy dryer was 43.6 which was about 1 point less than that obtained from ambient air drying. For the second test, the whiteness obtained from fluidized bed paddy dryer was 44.9 which was about 2.5 points less than that obtained from ambient air drying. It could be concluded that quality in terms of whiteness obtained from fluidized bed dryer is acceptable. In rice industry, the whiteness value above 35-37 is normally accepted.

Energy Consumption

Energy used in the fluidized bed paddy drying was electricity and heat obtained from burning diesel oil. For the first test with paddy feed rate of 2.8 t/h, diesel consumption was 17.56 l/h. Primary energy consumption was 755.1 MJ/h of which 115.3 was electricity (measured electricity value multiplied by 2.6) and 639.9 was heat from diesel oil. Water evaporation rate was 196.7 kg/h. Average specific primary energy consumption was 3.8 MJ/kg water evaporated. For the second test with paddy feed rate of 3.8 t/h, consumption of diesel oil was 21.71 l/h. Primary energy consumption was 910.9 MJ/h of which 120.4 was electricity and 790.5 was heat from diesel oil. Water evaporation rate was 218.8 kg/h and average specific primary energy consumption was 4.2 MJ/kg water evaporated.

Cost Analysis

Initial cost of the mobile fluidized bed paddy dryer excluding electrical generator was estimated at 571,786 baht (US$ 1 = 34 baht). Assuming that operating time was 1080 h/y, moisture evaporation rate 218.8 kg/h, paddy moisture content was reduced from 32.6 % to 25.8 % dry-basis with capacity of 3.8 t/h, service life 10 y, interest rate 18 %/y and salvage value 24,309 baht, drying cost was 1.48 baht/kg water evaporated of which 0.53 was fixed cost and 0.95 was energy cost (electricity 9.5% and diesel oil 90.5%).

CONCLUSION

Conclusion from this work can be drawn as follows

1. High paddy feed rate (maximum at 3.8 t/h) would be more interesting. Drying air temperature of 144 °C is safe for drying paddy from 32.6 to 25.8 % dry-basis with air flow rate of 3.5 m^3/s (corresponding to air speed of 2.8 m/s). Paddy bed depth is 13.5 cm and fraction of air recycled is 0.8.

2. Quality of paddy dried by fluidized bed dryer in terms of head yield and whiteness is good as compared to the reference dried by ambient air. Head yield of paddy dried by fluidized bed dryer can be increased significantly if high enough moisture paddy is dried at the above- mentioned temperature.

3. Specific primary energy consumption is 4.2 MJ/kg water evaporated [(electricity x 2.6 + heat)/ kg water].

4. Drying cost is 1.48 baht/kg water evaporated (US$ 1 = 34 baht) of which 0.53 is fixed cost and 0.95 is energy cost (electricity 9.5% and diesel oil 90.5%).

Knowing the drying time (or residence time), hold-up could be calculated by the equation that hold-up was equal to residence time multiplied by feed rate. Finally, the perforated floor area (in this case, width and length of 0.6 and 2.1 m respectively) was found out by assuming that bed depth of paddy was 10 cm. The next step was to determine pressure drop in the fluidized bed drying system.

After completing construction, the unit was installed and tested at a private rice mill, Koong Li Chan. Results of two tests will be reported and discussed. In the first test, paddy bed depth was 10 cm, initial moisture content of paddy was 28.5 % dry-basis, air flow rate was 3.5 m^3/s and average inlet air temperature was 148 °C. In the second test, it was tested at maximum bed depth, 13.5 cm with other drying conditions as follows: 32.6 % dry-basis initial moisture content, 3.5 m^3/s air flow rate and 144 °C average inlet air temperature. During the experiments, paddy samples before and after drying were collected every 20 minutes for determining moisture content and quality in terms of head yield and whiteness. Temperatures at various positions were measured by a type k thermocouple connected with a data logger with an accuracy of ± 1 °C, and air speed was measured by hot wire anemometer. Electricity consumption was measured by clamp on meter and diesel consumption was recorded each hour. During each experiment, paddy samples before and after drying were collected and further dried by ambient air down to 16 % dry-basis moisture content before stepping to quality test.

Paddy quality was determined in terms of head yield and whiteness. The head yield was defined as weight of unbroken rice kernel (length over 8/10 of the whole kernel is accepted) after milling divided by weight of paddy before milling. Whiteness was determined by using a commercial equipment called Kett meter

RESULTS AND DISCUSSION

In this study, there were two drying cases, drying capacity of 2.8 t/h at the bed depth of 10 cm and 3.6 t/h drying capacity at 13.5 cm bed depth. Air flow rate and fraction of air recycled were fixed at 3.5 m^3/s (bed velocity of 2.8 m/s) and 0.8 respectively.

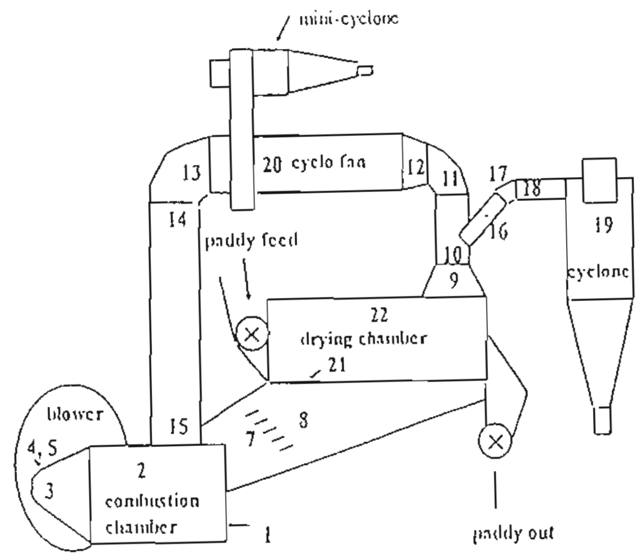
Paddy Moisture Content and Temperature in the Drying System

In the first test (operating time =180 minutes), average inlet drying air temperature was 148 °C. Moisture content of paddy was reduced from 28.5 % to 20.4 %. Temperature of paddy at the dryer exit was 81.1 °C while exit air temperature was 87.6 °C. Residence time was approximately 1.4 minutes. Average ambient air temperature and relative humidity were 26.5 °C and 60 % respectively.

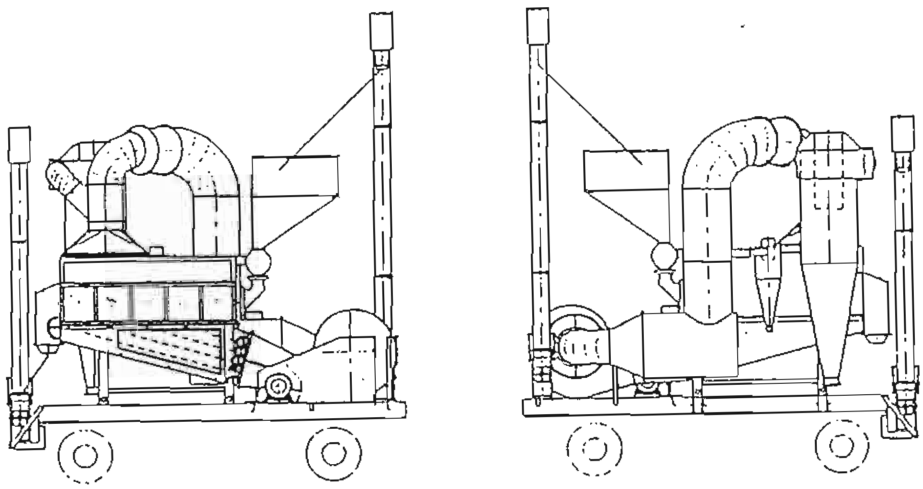
In the second test (operating time = 180 minutes), maximum bed depth of paddy that provided uniform fluidization was investigated. It was recorded at 13.5 cm. Fluidization was not uniform at higher bed depth. Average inlet air temperature was 144 °C. Moisture content of paddy was reduced from 32.6 % to 25 8 % dry-basis. Ambient temperature and relative humidity were 26.5 °C and 58 % respectively. Exit air temperature was 66.3 °C while paddy temperature at the dryer exit was 71 °C. Residence time was 1.3 minutes.

Paddy Quality

For the first test, average head yield of paddy dried by fluidized bed dryer and that dried by ambient air (as reference) were 48.7 % and 49.1 % respectively. Both figures are very close which means that fluidized bed drying does not cause significant breakage to rice kernel. For the second test, average head yield of paddy dried by fluidized bed dryer and that of reference were 53.7 % and 48.9 % respectively. Head yield varies with operating time but the average head yield increases approximately 5 %. This is a significant figure as it affects a lot on selling price. The initial moisture content of paddy of both tests



a. Mobile fluidized bed paddy dryer diagram



front view

rear view

b. drawing

Figure 1 Mobile fluidized bed paddy dryer temperature of 40-100 °C, bed thickness of 5-20 cm and air velocity of 1.5-2.5 m/s. Minimum fluidized bed velocities were 1.2 m/s for low moisture content and 2.0 m/s for moisture content of 30 % dry-basis.

Soponronnarit et al., 1994, reviewed some research and development works on fluidized bed grain drying. They also conducted both experimental and simulated works on fluidized bed paddy drying in batch. The results showed that maximum drying air temperature had to be limited to 115 °C and final moisture content of paddy of 24-25 % dry-basis if product quality in terms of head yield and whiteness was maintained. To maximize drying capacity and minimize energy consumption, air velocity of 4.4 m/s, bed thickness of 9.5 cm (corresponding to specific air flow rate of 0.1 kg/s-kg dry matter of paddy) and fraction of air recycled of 80% should be employed. Specific energy consumption in terms of primary energy which was equal to heat plus 2.6 times electricity was reported at approximately 7.5 MJ/kg-water evaporated.

Soponronnarit et al.,1996, described the development of a cross-flow fluidized bed paddy dryer with a capacity of 200 kg/h. Experimental results showed that final moisture content of paddy should not be lower than 23% dry-basis if quality in terms of both whiteness and head yield was maintained. Drying air temperature was 115 °C. Simulated results indicated that the appropriate operating parameters should be as follows: air speed of 2.3 m/s, bed thickness of 10 cm and fraction of air recycled of 80% At this condition, energy consumption was close to the minimum while drying capacity was near the maximum. In this study, moisture of paddy was reduced from 30% to 24% dry-basis. According to the success of the development of the cross-flow fluidized bed paddy dryer, Rice Engineering Supply Co., Ltd., a private company based in Thailand, showed his interest in the collaboration of the development of a prototype with a capacity of approximately 1 ton per hour (Soponronnarit et al., 1995). It comprised of a drying section, a 7.5 kW backward curved blade centrifugal fan, a diesel fuel oil burner and a cyclone The bed length, width and height of the drying section were 1.7 m, 0.3 m and 1.2 m respectively. Experimental results showed that the unit operated efficiently and yielded high product quality in terms of head yield and whiteness. In reducing the moisture content from 45% to 24% dry-basis using air temperature of 100-120 °C, fraction of air recycled of 0.66, specific air flow rate of 0.05 kg/s-kg dry matter, superficial air velocity of 3.2 m/s, bed depth of 0.1 m, total primary energy consumption was 1.86 MJ/kg-water evaporated of which 0.36 was primary energy from electricity (electrical energy multiplied by 2.6) and 1.5 was primary energy in terms of heat.

According to the success of the prototype, commercial fluidized bed paddy dryers with capacity of 5 tons/h and 10 tons/h are now available. More than 80 units have been sold in Thailand, Taiwan, the Philippines, Indonesia and Malaysia since the beginning of 1995 (as of September 1997). The range of drying air temperature used in these commercial units is from 120 to 150 °C. Specific energy consumption in terms of primary energy for reducing moisture content from 26-30 % to 21-23 % dry-basis is 2.5-4.0 MJ/kg water evaporated.

In order to make the fluidized bed paddy dryer more convenient to use, especially in the harvesting area where electricity is not available and is far away from rice mills, a project on development of mobile fluidized bed dryer with capacity of 2.5-4.0 tons per hour is proposed.

MATERIAL AND METHOD

The mobile fluidized bed dryer was designed by the research group on drying technology at King Mongkut's Institute of Technology Thonburi and constructed in collaboration with Rice Engineering Supply Co., Ltd. The capacity was 2.5-4.0 t/h. The dryer was installed on a 2x4 m trailer. It comprised of diesel burner, 0.6x2.1x0.8 m drying chamber, paddy hopper, a backward-curved blade centrifugal fan driven by a 11.2 kW motor, 2 bucket elevators, cyclone and cyclo-fan as shown in Figure 1a and b. To start the design work, inlet and outlet moisture content of paddy were specified, and drying time could be determined by a drying kinetic equation (Soponronnarit et al., 1944 and Soponronnarit et al., 1996).

Drying '98 - Proceedings of the 11th International Drying Symposium (IDS '98)
Halkidiki, Greece, August 19-22, 1998, vol. B, pp. 1426-1431

MOBILE FLUIDIZED BED PADDY DRYER

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Keywords : Drying, grain, fluidization

ABSTRACT

The objectives of this research are to design, construct and test a mobile fluidized bed paddy dryer with a drying capacity of 2.5-4.0 t/h. Suitable drying conditions are recommended as follows : drying capacity 3.8 t/h, bed velocity 2.8 m/s, average drying air temperature 144 °C, bed height 13.5 cm, fraction of air recycled 0.8. Residence time of paddy was approximately 1.3 minutes. Test results showed that moisture content of paddy was reduced from 32.6 % dry-basis to 25.8 % dry-basis. Specific primary energy consumption was 4.2 MJ/kg-water evaporated. Cost of paddy drying was 1.48 baht/kg-water evaporated of which 0.53 was fixed cost and 0.95 was energy cost (US$1 = 34 baht).

INTRODUCTION

Thailand produces approximately 20 million tons of paddy each year. Moisture content of freshly harvested paddy is about 21-25 % wet-basis (26.5-33% dry-basis). During the past 8 years, research and development on fluidized bed paddy drying had been conducted in Australia and Thailand, and finally it has been commercialized (Sutherland et al., 1990, Tumumbing et al., 1991, Soponronnarit et al.,1994, Soponronnarit et al , 1996 and Soponronnarit et al., 1995). The dryer has also been commercially applied with corn (Soponronnarit et al., 1997).

Sutherland et al., 1990, investigated fluidized bed paddy drying. Experimental results showed that head yield was 58-61 % when paddy was dried from 22 % to 17 % wet-basis (28 % to 20 % dry-basis) but it was 15-24 % when the final moisture content was 16 % wet-basis (19 % dry-basis). Drying air temperature was 40-90 °C. For higher initial moisture content, 26 % wet-basis (35% dry-basis), head yield was 55-58 % when paddy was dried to 19 % wet-basis (23 % dry-basis). For the latter case, drying air temperature was 60-90 °C. Tumambing et al.,1991, experimentally found that drying rate was affected by drying air temperature and bed thickness. Drying conditions were as follows: drying air

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The operating cost is neglected in this study. When life time of heat pump is 10 years, total annual cost is 27.079 baht/year or 12.8 baht/kg water evap. of which 6.1 is fixed cost, 5.3 is electricity cost and 1.4 is maintenance cost. When life time of heat pump is 5 years, total annual cost is 32,246 baht/year or 15.2 baht/kg water evap. of which 8.5 is fixed cost, 5.3 is electricity cost and 1.4 is maintenance cost.

CONCLUSION

1. Drying rate (water evaporated rate from papaya glace') of heat pump can be operated to 0.686 kg water evap./h
2. Moisture extraction rate from evaporator is 0.78 kg water condensed/h
3. Total drying time of both steps in the experiment is approximately 80 h (40 h for each step)
4. Energy consumption is 9.93 MJ/kg water evap. or in terms of specific moisture extraction rate is 0.63 kg water evap./kW-h at the condition of specific air flow rate 21.4kg dried air/h-kg dried papaya.
5. Coefficient of performance for heat pump (COP_{hp}) varying between 3.71-3.85 indicates that power supplied by heat pump system for cooling at evaporator is 3.7 kW and for heating at condenser 5.04 kW of which 4.74 is heating power at internal condenser and 0.3 is at external condenser. Power supplied to compressor is 1.31 kW.
6. Cost evaluation of this study is found that total operating cost is 12.8 baht/kg water evap. of which 5.3 is energy consumption cost, 1.4 is maintenance cost and 6.1 is fixed cost.
7. Colour of papaya glace' after drying is light reddish-orange (code 34-C from R.H.S Colour chart), lighter than colour of papaya glace' dried by hot air tunnel(Noosuk et al.,1996). This may be due to the effect of drying temperature which is lower than that of the drying in tunnel.

ACKNOWLEDGMENT

The authors would like to thank the Thailand Research Fund for their financial support and to Rice Engineering Supply Co. Ltd. for her help in construction of heat pump dryer.

NOTATION

COP_{hp}	coefficient of performance for heat pump	-
m	mass of water	kg
M	average moisture content of papaya glace'	kg
MER	moisture extraction rate from evaporator	kg water condensed/h
SMER	specific moisture extraction rate	kg water evap./kW-h
T	temperature	°C

Subscripts

a	ambient air
c	condensed at evaporator
ci	inlet at internal condenser
d	before drying
e	evaporated from papaya glace'
ei	inlet at evaporator
eo	outlet at evaporator
f	after drying
ro	outlet at recuperator
xo	outlet at external condenser

Table 1. Experimental drying results

Description	Test No.					
	1/1	1/2	2/1	2/2	3/1	3/2
Ambient condition						
Average temperature (°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'						
Average moisture before drying (%db.)	74.8	40.4	73.8	38.3	74.8	36.7
Average 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 (°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

Heat Pump Performance Analysis

In this study, performance of heat pump is determined by experimental results obtained from both air loop and refrigerant loop (average record data every 2 hours). Analytic results show that error percent is in range of being acceptable. Performance of heat pump expressed in terms of coefficient of performance for heat pump (COP_{hp}) varies between 3.71-3.89.

Papaya Glace' Quality

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

Cost Evaluation

Conditions for evaluation of heat pump in this study are as follows: capacity 132.2 kg/batch, operating time 48 batches /year, average drying time 80 hr/batch, dried papaya glace' quantity 6346 kg/year, fixed cost 59,012 baht (US$ 1 = 34 baht), life time of heat pump 10 years, maintenance cost per year 5% of fixed cost, salvage value 10% of fixed cost, evaporation water ability 44.25 kg water evap./batch, electricity price 1.55 baht/kW-h, electricity used rate 1.89 kW-h and interest rate 18%/year.

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 is found that value of MER is higher than drying rate , as shown in Figures 6 and 7. It is assumed that surrounding humidity can absorb into drying section of heat pump.

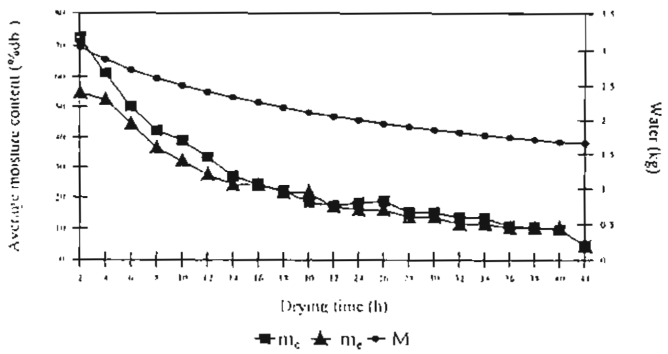


Figure 6. Evolution of average moisture content of papaya glace', water condensed at evaporator and water evaporated from papaya glace' for the 2nd test, 1st stage

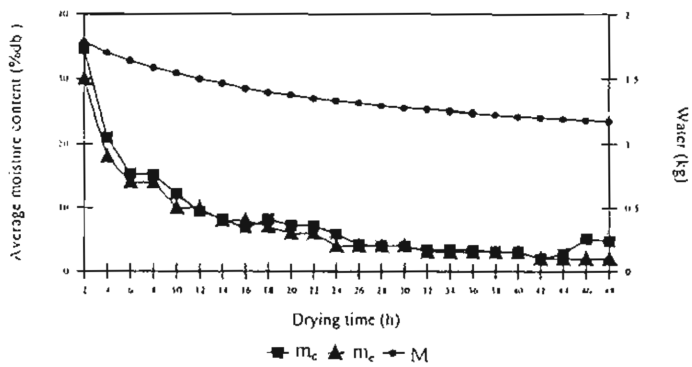


Figure 7. Evolution of average moisture content of papaya glace', water condensed at evaporator and water evaporated from papaya glace' for the 2nd test, 2nd stage

Drying Efficiency Analysis

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

follows: 1) Papaya glace' sample is taken and cut into small pieces. 2) The sample is measured by digital balance (accuracy of 0.01 g). 3) The sample is put into a cabinet dryer at temperature of 103 °C for 72 h. Papaya glace' quality after drying is studied by checking color with R.H.S. color chart.

RESULTS AND DISCUSSION

Experimental Results

Considering air temperature variation from the experimental results, it is found that differences of inlet and outlet air temperature of each subcomponent of heat pump system are : internal condenser 10 °C, evaporator between 20 °C, recuperator between 3-4 °C and cabinet dryer between 1-5 °C, as shown in Figures 4 and 5. Outlet air temperature at external condenser varied up and down, which is effected from temperature controlling by solenoid valve. For hot air temperature distribution in trolley, it is found that air temperature of the tray on top part, middle part and bottom part of the trolley is slightly different (temperature of top tray is higher than that of bottom tray).

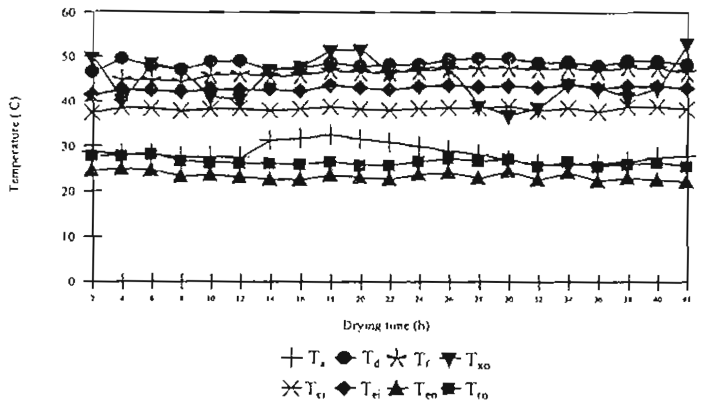


Figure 4. Evolution of temperature in air loop of the 2nd test, 1st stage

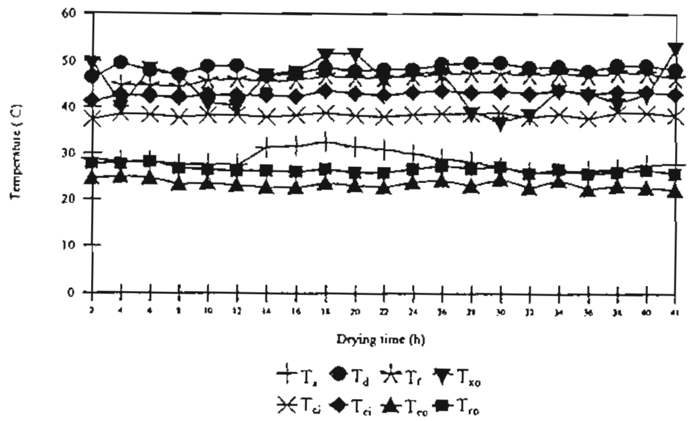
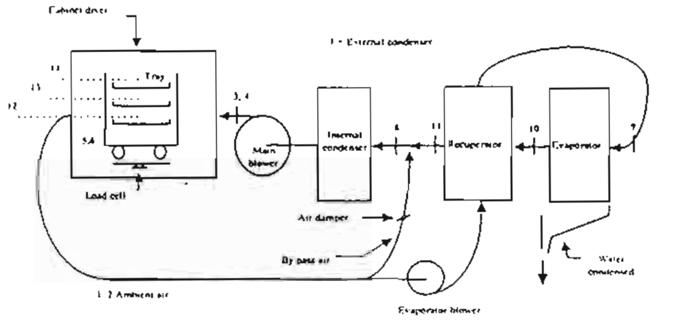


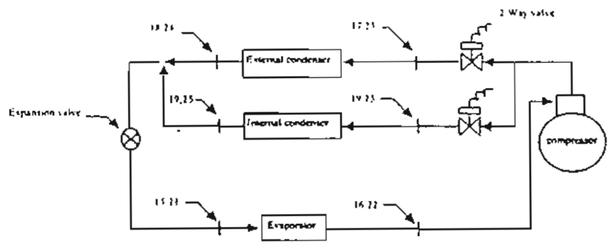
Figure 5. Evolution of temperature in air loop of the 2nd test, 2nd stage

and initial moisture content of 74% dry basis is dried (experiments 1/1, 2/1, and 3/1). Second step, papaya glace' dried from the first step is cut into dimension of 0.98x0.98x0.98 cm^3 and dried to final moisture content of 23 % dry basis (experiments 1/2, 2/2, and 3/2). Air velocity in recycled duct is measured by hot wire anemometer. Temperature of air loop in Figure 2 and temperature of refrigerant loop in Figure 3 are measured by Chromel-Alumel type k thermocouple connected to data logger (accuracy ± 1 °C).



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

Figure 2. Temperature measurement for air loop



For temperature	For pressure
15,16 = inlet and outlet of evaporator	21,22 = inlet and outlet of evaporator
17,18 = inlet and outlet of external condenser	23,24 = inlet and outlet of external condenser
19,20 = inlet and outlet of internal condenser	25,26 = inlet and outlet of internal condenser

Figure 3. Temperature and pressure measurements for refrigerant loop

Budong gauge is used to measure pressure in refrigerant loop. A load cell with accuracy of 50 g is used to measure weight of material in cabinet dryer. Maximum weight measured is 150 kg. Condensed water from evaporator is measured by a load cell with accuracy of 0.01 g. Maximum weight measured is 3 kg. Kilowatt-hour meter and Clamp-on meter are used to measure energy consumption in the system. The values measured are as follows: dry-bulb temperature, wet-bulb temperature, weight of papaya glace', weight of condensed water from moisture air in evaporator and energy consumption. The measurement is conducted every two hours. Initial moisture content of papaya glace' is measured by the methods as

From the past research (Nousook et al.,1996, Chou et al.,1993, Clement et al.,1993, Pendyala et al., 1990, Rossi et al.,1992, Young et al.,1995 and Strommen et al.,1994), it showed that there were three types of heat pump dryer: fixed tray dryer, continuous dryer and fluidized bed dryer, and two models of air system : close-loop system (air was recycled in the system) and open-loop system (dried air was rejected to surrounding). Drying temperature depended on refrigerant and it could be increased by adding heater into the system. However, the heater caused COP reduce. Heat pump dryer performance could be increased by selecting suitable ratio of air entering to 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 are to design, construct, evaluate performance and conduct cost analysis of heat pump fruit dryer. Papaya glace' was selected as drying product.

MATERIALS AND METHODS

Heat pump dryer in this research is a close-loop system as shown in Figure 1. It consists of 0.90x0.80x0.75 cm^3 drying cabinet, 12 drying trays with area of 0.63x0.72 cm^2 each, 1.3 kW two piston compressor, 4.5 kW internal and external condensers (4x13 rows and 14 fins per inch), 3.66 kW evaporator (3x8 rows and 14 fins per inch), 2 cycles of capillary tube throttling valve with dimension of 100x0.164 cm, 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 0.4-0.8 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.

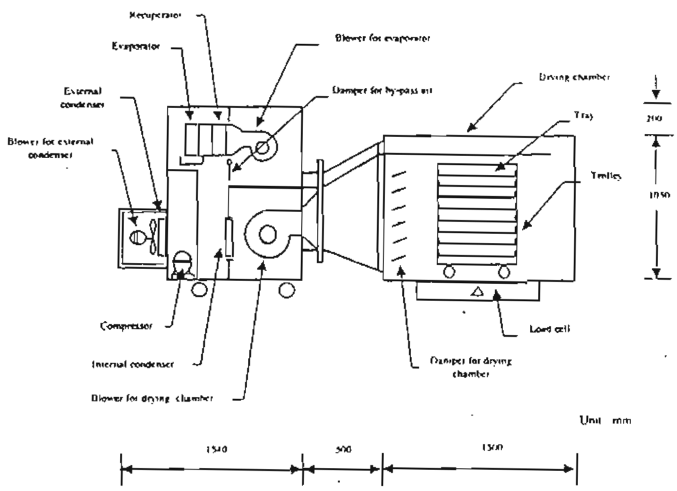


Figure 1. Heat pump fruit dryer

Experimental fruit in this research is papaya glace'. Papaya glace' is spread on trays which are put on a trolley. This fruit drying is a batchwise drying. There are three experiments of the drying. The conditions for the experiment are as follows: 1) Drying is a close loop system. 2) Air used for drying is controlled at 50 °C. 3) Air mass flow rate is constant at 0.45 kg/s and ratio of by pass air is 63 % (air mass flow rate through evaporator is 0.17 kg/s). 4) Papaya glace' quantity is varied between 70-132 kg. The experiment is divided into two steps. First step, papaya glace' with dimension of 6.35x15x2.54 cm^3

Drying '98 - Proceedings of the 11th International Drying Symposium (IDS '98)
Halkidiki, Greece, August 19-22, 1998, vol. B, pp. 1373-1380

PAPAYA GLACE' DRYING USING HEAT PUMP

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Key words : Fruit drying, heat pump, papaya glace'

ABSTRACT

The purposes of this research are to design, construct, evaluate performance and conduct cost analysis of heat pump fruit dryer. The dryer consists of cabinet dryer and heat pump. Product capacity of the cabinet dryer is 100-132 kg with 12 trays and capacity of heat pump is 1 ton refrigeration. In this experiment, papaya glace' is dried in close loop air with drying temperature of 50°C, air flow rate of 0.45 kg/s and by pass air of 63 %. Drying operation is divided into two steps. The results are as follows: drying rate 0.686 kg water evaporation/h, moisture extraction rate from evaporator 0.78 kg water evaporation/h and drying time of the two steps approximately 80. Energy consumption is 9.93 MJ/kW-h or SMER 0.363 kg water evaporation/kW-h at specific air flow rate of 21.42 kg dry air/h-kg dry papaya glace'. The coefficient of performance for heat pump varies between 3.71-3.85. For the quality of papaya glace' after drying in terms of color, it is found that color of papaya glace' is light reddish-orange. For cost evaluation from this experiment, it is found that cost of papaya glace' drying is 12.8 bath/kg water evaporation of which 5.3 is energy cost, 1.4 is maintenance cost and 6.1 is fixed cost (US$ 1 = 34 baht).

INTRODUCTION

Dried fruit is a type of agricultural modified product which is in high requirement in both domestic and international markets. Drying process is an important step of production process which uses high cost for operating. 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. Product quality in terms of color and smell is limited changed and is accepted by consumer.

CONCLUSION

1. Fluidized bed corn dryer is suitable for high initial moisture corn because of low energy consumption. Energy consumption increases with decreasing initial moisture content.

2. Evaporation rate increases according to the increase of drying temperature. Drying at too high temperature and low moisture content causes stress crack and breakage of corn kernel. The suitable drying temperature is in range of 150-160 °C.

3. Too high corn bed causes reduction of fluidization and ununiform final moisture content .

ACKNOWLEDGMENT

The authors would like to thank the Thailand Research Fund and Australian Centre for International Agricultural Research for their financial support.

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Corn Kernel Quality

Table 2 shows quality change of corn kernel. When corn was dried, percentage of breakage was high compared with reference sample. However, in some case, it was less than reference sample because some piece of corn was small as compared with complete corn kernel. The small piece of corn was blown out from drying chamber and collected by cyclone except in experiment 8. In this experiment, corn was dried at temperature of 188 °C. The results of this experiment found that percentage of breakage increased because corn kernel was broken as pop corn.

Table 2 Quality of corn

test no.	drying air temp. (°C)	final moisture content (% db.)	colour change: reference a	colour change: reference b	colour change: after drying a	colour change: after drying b	breakage (%): reference	breakage (%): after drying	stress crack (%): reference	stress crack (%): after drying
1	119	31.1	10.85	22.87	11.26	23.85	3.8	2.9	-	-
2	131	27.1	13.34	27.35	12.85	28.28	2.4	2.4	-	-
3	145	19.2	9.87	26.65	10.63	25.46	4.6	5.9	-	-
4	152	26.3	10.80	28.85	12.09	25.93	2.0	2.8	-	-
5	156	19.4	9.55	23.24	10.42	22.92	1.7	1.5	1.6	10.0
6	168	19.0	10.90	26.92	11.41	29.34	1.3	1.0	1.7	30.4
7	172	17.8	11.64	26.13	13.62	23.55	1.8	2.2	2.4	38.8
8	188	15.7	10.77	20.42	12.87	18.44	2.1	4.6	4.1	49.1
9	156	18.1	11.32	18.60	12.40	23.52	2.0	2.1	3.6	19.7
10	168	17.0	9.19	19.77	12.35	21.29	2.5	2.4	3.8	28.7
11	120	19.1	10.23	22.82	11.42	24.52	1.0	1.9	0.2	0.6
12	143	16.7	8.84	21.10	11.13	23.91	1.7	1.8	0.6	1.0
13	156	14.2	7.66	19.86	8.10	21.61	2.4	2.8	0.6	32.7
14	165	18.2	6.98	19.52	7.69	20.22	1.5	1.3	0.8	3.3

Remarks : 1. In experiments 1-4 and 11-14, reference samples were dried by ambient air.
2. In experiments 5-10, corn before drying was used as reference samples.

For percentage of stress crack, it was found that it increased after drying as compared with reference sample. Percentage of stress crack increased according to increasing temperature of drying. These results can be expressed that when corn kernel was dried at high temperature, the water at outer surface of kernel rapidly evaporated thus causing corn kernel hard. When drying zone moved from outer surface to inner surface of kernel, inner surface lost moisture content and it contracted by separating from outer surface.

Regarding the results of color change of kernel, drying process has little effect on change of color. After drying, the value of a (redness) and b (yellowness) slightly increased and it did make any commercially affect.

Experimental results showed that evaporation rates in experiments 1-10 were high and increased with increasing temperature, as shown in Figure 3. In experiments 11-14, corn kernel was dried at low initial moisture content (18-22 % dry-basis). The results showed that evaporation rates were low compared with those of experiments 1-10. It was because most water was still in corn kernel and mass transfer was limited by moisture diffusion in corn kernel.

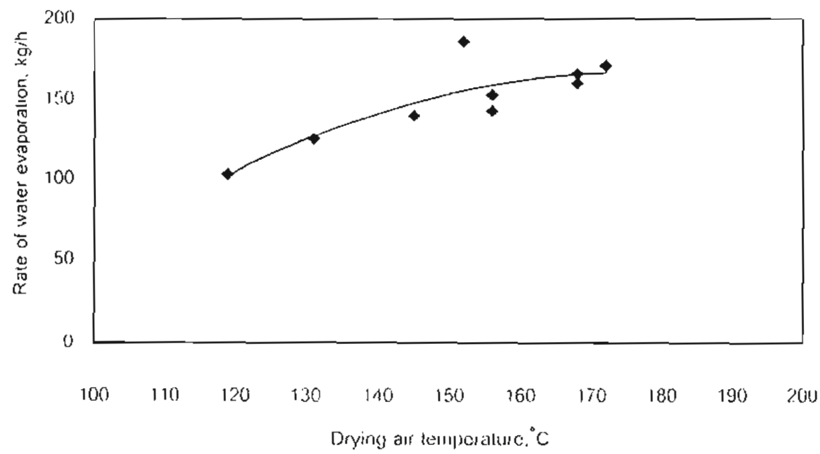

Figure 3 Effect of drying air temperature on water evaporation

Energy Consumption

Energy consumption increased according to increasing temperature but specific energy consumption was not depend on temperature. The specific energy consumption was depend on average moisture content of corn kernel as shown in Figure 4. At high initial moisture content, specific heat and electricity consumption were 4.7-6.9 and 0.32-0.61 MJ/kg-water evaporated respectively. At low initial moisture content, specific energy heat and electricity consumption were in range of 10.0-27.4 and 0.65-2.03 MJ/kg-water evaporated respectively. In experiments 9 and 10 residence time and bed height of corn kernel were increased. The results showed that evaporation rate was fairly high but final moisture content was ununiform compared with those of experiments 1-8. This was because the power of blower was not adequate to produce complete fluidization.

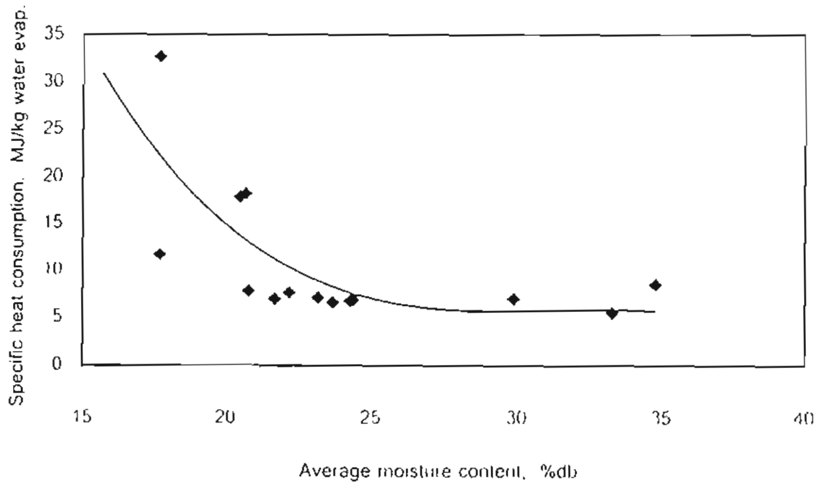

Figure 4 Effect of average moisture content on specific heat consumption (range of drying air temperature 119-188 ^{O}C)

RESULTS AND DISCUSSION

Rate of Evaporation

Table 1 shows the results of performance testing of fluidized bed corn dryer. In experiments 1-10 and 11-14 corn was dried at high initial moisture content (26-40 % dry-basis) and low initial moisture content (21-23 % dry-basis) respectively at temperature of 119-188 °C.

Table 1 Experimental results of performance of fluidized bed corn dryer

test no.	temperature (°C)	air recycled (%)	bed height (cm)	feed rate (kg/h)	residence time (min)	initial moisture content (% db.)	final moisture content (% db.)
1	119	78.2	13	2000	3.44	38.2	31.2
2	131	78.2	13	3000	2.29	32.7	27.1
3	145	78.2	17	2000	4.50	28.2	19.2
4	152	78.2	15	1860	4.27	40.3	26.3
5	156	80.4	15	1980	4.01	29.4	19.4
6	168	80.4	15	2016	3.94	29.7	19.0
7	172	80.4	15	1980	4.01	28.6	17.8
8	188	80.4	15	2160	3.68	26.1	15.7
9	156	80.4	20	2160	4.90	26.5	18.1
10	168	80.4	20	2160	4.90	26.4	17.0
11	120	84.4	17	1860	4.84	22.2	19.1
12	143	84.4	17	1860	4.84	18.6	16.7
13	156	84.4	19	1600	6.28	21.1	14.2
14	165	84.4	17	1860	4.48	22.8	18.2

Table 1 (continued)

test no.	rate of water evaporation (kg /h)	energy consumption from diesel (MJ/h)	electricity consumption (MJ/h)	specific heat consumption (MJ/kg water evap.)	specific electricity consumption (MJ/kg water evap.)
1	103.1	710.7	64.0	6.9	0.61
2	125.5	728.1	58.7	5.8	0.47
3	140.3	771.9	58.7	5.5	0.42
4	185.6	875.8	58.7	4.7	0.32
5	153.0	894.0	59.7	5.8	0.41
6	165.8	967.1	59.7	5.8	0.37
7	170.8	1058.1	59.7	6.2	0.35
8	178.2	1238.1	59.7	6.9	0.35
9	143.5	901.3	59.7	6.3	0.41
10	159.9	957.6	59.7	6.0	0.37
11	47.3	713.0	58.7	15.1	1.22
12	28.7	786.2	58.7	27.4	2.03
13	92.3	925.6	58.7	10.0	0.65
14	69.4	1090.0	58.7	15.7	0.85

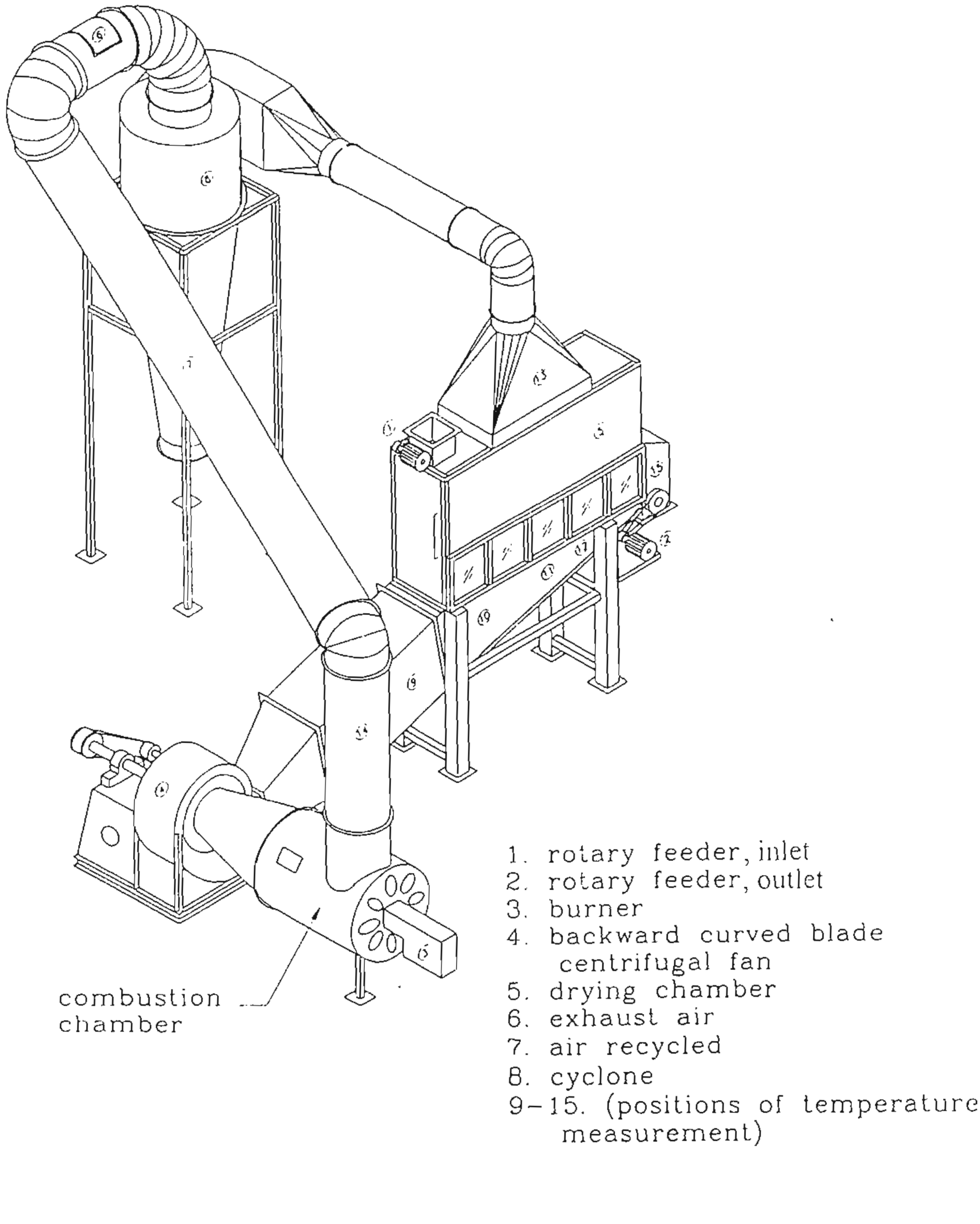

Figure 2 Fluidized bed dryer

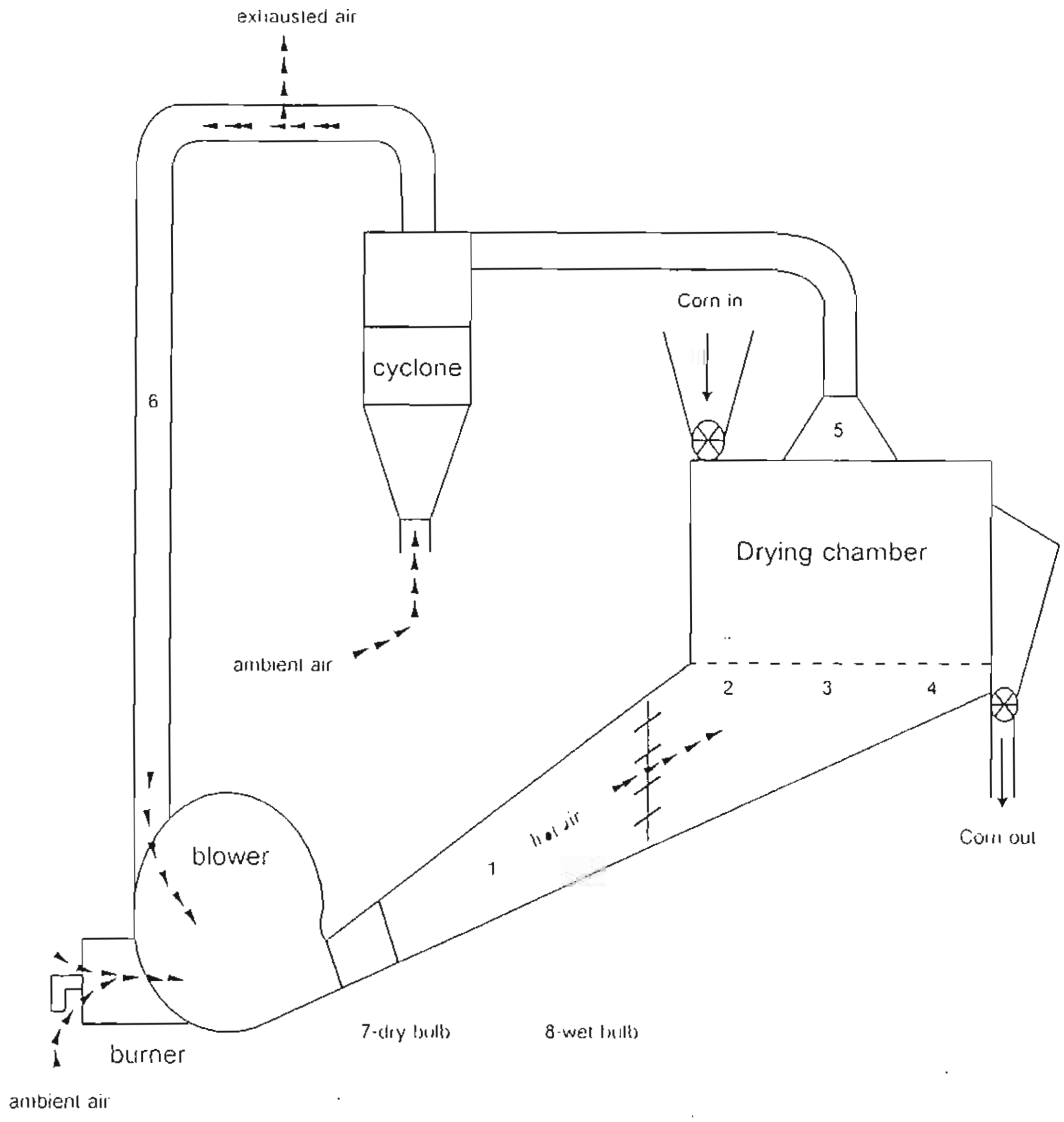

Figure 1 Diagram of fluidized-bed corn dryer (Numbers indicate where temperature measurements were taken)

Satayaprasert and Vanishsriwatana (1992) studied batch fluidized bed corn drying at temperature of 60-90 °C, air velocity of 2.7-4.2 m/s and bed height of 3-12 cm. It was found that parameters that highly affected drying rate were air temperature and bed height respectively. The quality of product in terms of lysine was decreased when corn kernel was dried at high temperature. Pongtornkulpanich (1996) studied parameters affecting drying rate and quality, in batch fluidized bed corn drying at drying temperature of 15-200 °C, air velocity of 2.2-4.0 m/s and bed height of 4-12 cm. The parameters which affected drying rate were drying air temperature and specific air flow rate. When moisture content of corn was decreased from 43 % dry-basis to 24 % dry-basis at temperature of 150-170 °C, stress crack of corn kernel was less than 5 percent and there was no grain breakage. Color change of grain can be expressed by kinetic theory in form of reaction rate that assumed to be zero order.

The objective of this research is to study the parameters which affect drying rate, energy consumption and quality of grain after drying by using industrial scale fluidized bed dryer.

MATERIALS AND METHODS

Figure 1 shows the diagram of fluidized bed corn dryer. The process of drying is as follows: corn from hopper is fed into drying chamber by rotary feeder. The hot air flows through drying chamber and the bed thickness is controlled by a weir. Heat and mass transfer between corn and drying air decreases moisture content of corn kernel but increases its temperature. Dried corn is fed out from drying chamber by rotary discharger and exit drying air is cleaned by cyclone. Some part of drying air is recycled to reduce energy consumption . Details of fluidized bed dryer is shown in Figure 2.

Experimental corn drying using continuous fluidized bed technique has capacity of 1.8-3.0 tons per hour. High speed diesel is used as fuel for producing hot air. Backward curved blade centrifugal fan and motor (25 hp.) are used to produce hot air which blows out at constant velocity of 2.9 m/s. In this experiment, corn kernel is dried with the conditions as follows: initial moisture content of 18-40 % dry-basis, bed height of 13-20 cm, feed rate of 1600-3000 kg/h, recycled air of 78-84 % and drying temperature of 119-188 °C. Air velocity is measured by hot wire anemometer and temperature is measured by type K thermocouple connecting to data logger. Temperature can be read from data logger with accuracy of ± 1 °C. After drying, corn kernel is put in the insulation storage to measure the temperature by a thermometer. Samples of corn are taken every 20 minutes to determine moisture content, quality in terms of stress crack, breakage and change of color.

Sample of corn, approximately 30 gram, is taken before and after drying every 20 minutes and put in a hot air oven at temperature of 103 °C for 72 hours. Then, its weight is measured to determine moisture content.

Color of corn is determined by using a measuring instrument, Minolta CR-3000. The results shown are : l (lightness), a (redness) and b (yellowness)

Percentage of stress crack and breakage by weight of corn is determined with sample of corn , approximately 150 gram, by visual inspection under light.

Proc. 13th CIGR, Rabat, Morocco, 2-6 Feb, 1998, Vol. 6, Processing, pp.307-314

Performance Testing of Industrial-Scale Fluidized Bed Corn Dryer

Somchart Soponronnarit[1], Somboon Wetchacama[1], Thanit Swasdisevi[1], Komkrit Kittiporn[2], and Shotiwoot Vitsutdipat[3]

ABSTRACT

Fluidized bed paddy dryer is commercially successful at present. The dryer has been applied with corn grain, another important crop in Thailand. The objective of this research is to investigate performance of industrial-scale fluidized bed corn dryer. Parameters affecting drying rate, energy consumption and product quality were considered. Experimental results showed that rate of water evaporation increased with initial moisture content of corn and drying air temperature while specific energy consumption increased when initial moisture content decreased. Corn quality in terms of breakage and stress crack increased when drying air temperature increased or final moisture content decreased.

Key words : Fluidized bed, drying, grain

INTRODUCTION

Corn is an important economic crop second to rice. There is high production of corn from middle of June to October while consumption of corn is needed all year. Therefore, storage of corn after harvesting is necessary. Corn should be stored at moisture content of 14 % wet-basis to prevent growth of microbes and fungus thus causing corn damage. Moisture content of freshly harvested corn is between 20-30 % wet-basis which should be reduced before storage. At present, dryer has played an important role. Fluidized bed dryer is one among dryers which uses high air temperature for drying. Drying air and grain are mixed throughout in drying chamber. Moisture content is decreased in a very short time and the final moisture content is uniform throughout the product. However, too high temperature causes corn kernel crack. Therefore, a suitable operating drying condition is needed to increase dryer performance and quality of product.

Abid et al. (1990) studied heat and mass transfer occurred in corn kernel drying by fluidized bed technique. It was found that air temperature and residence time highly affected drying rate while drying air velocity, size of corn kernel and moisture content slightly affected drying rate. Dayanghirang et al. (1991) studied the effect of heat on quality of corn kernel, in terms of germination, when dried by fluidized bed technique. The experiment was conducted with initial moisture content of 24.5 % wet-basis, drying temperature of 40-80 °C and air flow rate of 0.03 kg/s. The results showed that drying corn in range of temperature 40-55 °C, germination rate was normal while drying at temperature higher than 55 °C, germination rate was decreased.

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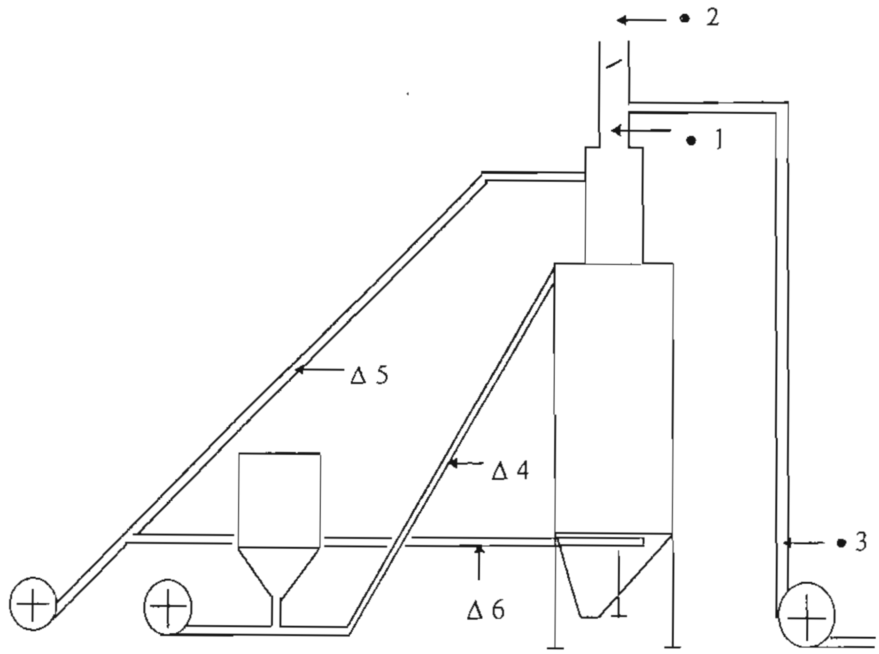

Figure 2. Position for measuring temperatures and air speed

- • Temperature (1,2,3)
- Δ Air speed (4,5,6)

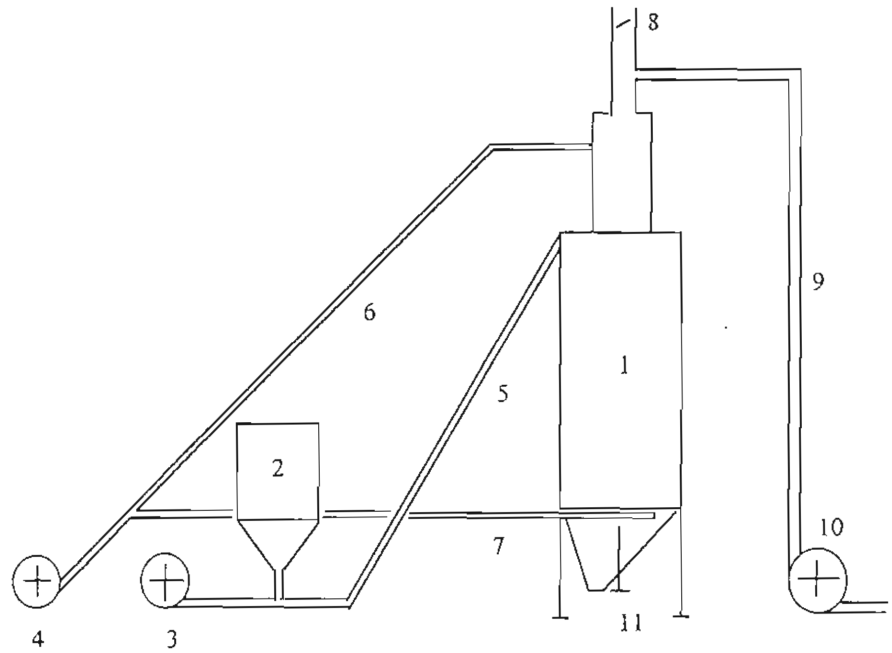

Figure 1. Schematic diagram of the rice husk furnace showing the principal components. (1) combustion chamber; (2) rice husk tank hopper; (3) conveying fan of rice husk feeding system; (4) conveying fan of air feeding system; (5) primary air; (6) secondary air; (7) tertiary air; (8) butterfly valve; (9) exit air duct; (10) suction blower; (11) screw conveyor.

Table 1. Experimental results on thermal efficiency

Height of ash (cm)	Start up time (min)	Feed rate of rice husk (kg/h)	Ambient temp. (°C)	Average air temp. at blower inlet (°C)	Average. air temp. at furnace exit (°C)	Eff. of system (%)	Eff. of furnace (%)
30	10	127	34	293	-	64	-
45	13	133	34	296	-	62	-
50	10	126	33	296	-	65	-
60	15	143	32	297	504	58	59

Table 2. Experimental results on carbon conversion efficiency

Height of ash	Flue gas after combustion				Unburnt carbon	Ash	Carbon conversion Eff.
	CO	NO_x	SO_x	O_2			
(cm)	(ppm)	(ppm)	(ppm)	(%)	(%)	(kg)	(%)
30	1,300-1,600	50-60	9-11	18	19.3	101.0	-
45	1,700-1,800	40-50	10-20	18	12.6	93.0	-
50	1,600-1,900	40-60	6-10	18	24.8	102.5	-
60	1,000-1,800	30-60	3-5	18	14.9	108.0	90

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Power consumption of rice husk furnace

Power used in the furnace is electricity and rates of power consumption of each devices are as follows: conveying fan of primary air 1.25 kW, conveying fan of secondary air 1.18 kW, suction blower 8.36 kW(This can be reduced by using larger air duct, the air velocity in this study is about 25 m/s.), motor of ash paddle 1.79 kW, motor of feeding rice husk system 0.66 kW, screw conveyor 0.72 kW. Total power consumption of the furnace is 13.96 kW.

Conclusion

The rice husk furnace is constructed for connecting to fluidized bed paddy dryer with capacity of 10 tons/h. Thermal efficiencies of the furnace system and the furnace(at height of ash 60 cm) are approximately 58 % and 59 % respectively. Carbon conversion efficiency is 90 % (at height of ash 60 cm). Total power consumption (electricity) is 13.97 kW. Air flow rate before entering to suction blower is 1.16 kg/s and average air temperature is in range of 293-297 °C.

Recommendation

Upper part of the furnace should be cover with insulation in order to reduce heat loss. CO_2 in flue gases should be measured in order to facilitate the analysis of carbon conversion efficiency. Temperature before entering exit air duct should be also measured.

Acknowledgment

The authors would like to thank the Thailand Research Fund and Australian Centre for International Agriculture Research for supporting this project. Thanks are also due to Rice Engineering Supply Co. Ltd. for supporting fabrication and installation and to Department of Agriculture, Division of Storage and Processing section for providing experimental site and technical support.

Thermal efficiency of furnace

Equation 1 was used to determine the efficiency of the furnace. Air temperature at the furnace exit was measured. At height of ash 60 cm, the thermal efficiency of furnace was higher than the thermal efficiency of furnace system because in furnace system there was heat loss between furnace exit and suction blower.

Carbon conversion efficiency of furnace

Carbon conversion efficiency was determined from mass balance of carbon in rice husk, ash and flue gases after combustion.

Results and Discussion

There are four experiments in the test of the furnace. The height of ash is varied in each experiment. Amount of rice husk used in each experiment is 450 kg and air temperature before entering to suction blower is set at 319 °C. Average temperature of air exit furnace (at height of ash 60 cm) is 504 °C with air flow rate of 0.63 kg/s. Average temperature of air before entering suction blower(at height of ash 30, 45, 50 and 60 cm) are in range of 293-297 °C with air flow rate of 1.16 kg/s. Ambient air temperature is in range of 32-34 °C. Gas analyser is used to measure flue gases left from the furnace and ash is collected for determining unburnt carbon. The results of thermal efficiency and carbon conversion efficiency (at height of ash 60 cm) are as follows: 1) Thermal efficiencies of furnace and furnace system are 59 and 58 respectively. 2) Carbon conversion efficiency is 90 %. Average air temperature before entering to suction blower is approximately 293-297 °C (variation of 10 °C).

Analysis of rice husk and ash

Composition of substance in rice husk before combustion are as follows: carbon 36.8 %, hydrogen 5.8 %, oxygen 37.4 %, nitrogen 0.14 %, sulfur 0.1 %, moisture 7.8 % and gross heat of combustion 13.84 MJ/kg. After combustion, the composition of substances are shown in Table2. This experiment shows that the combustion is not completely.

opened to aid ignition of rice husk while valve of secondary air is closed. When rice husk burns, valve of secondary air and controller system are switched on. Wet bulb and dry bulb temperature is measured by using column thermometer. Humidity is measured by using hygrometer and flue gases (CO, NO_x, SO_x) which exit from combustion chamber are measured by using gas analyser. The height and weight of ash after combustion are also measured. Samples of ash are collected after each experiment and sent to laboratory for determination of unburnt carbon. Air speed in ducts was measured by a Pitot-static tube. Temperature in the furnace was measured by thermocouple type K Schematic diagram of the rice husk furnace is shown in Figure 1 and positions for measuring temperatures and air speed in ducts are shown in Figure 2.

Thermal efficiency of furnace system

Tests were conducted at four heights of ash (30 cm , 45 cm , 50 cm , and 60 cm). Air temperature was measured at a pipe before entering to the suction blower. The thermal efficiency of the furnace system was determined by using the equation:

$$\text{Thermal efficiency of the furnace system} = (H_s / H_a) \times 100 \qquad (1)$$

and

$$H_s = \Delta H \times (M_a / v_a)$$

$$H_a = (M_r \times HHV)/3600$$

where

H_s = Heat supplied, kJ/kg
H_a = Heat available, kJ/kg
ΔH = Enthalpy change between ambient air and exit air, kJ/kg
M_a = Air flow rate, m^3/s
v_a = Specific volume of exit air, m^3/kg
M_r = Rice husk feed rate, kg/h
HHV = High heating value, kJ/kg

Materials and Methods

Rice husk furnace in this research is direct heat furnace. The furnace consists of combustion chamber, rice husk feeding system, air feeding system, controller system and air suction blower. Combustion chamber is made of steel in cylindrical shape. Materials inside the combustion chamber at lower part from inner layer to outer layer are the following: fire brick with thickness of 115 mm, steel with thickness of 4.5 mm , glass fiber with thickness of 50 mm and steel with thickness of 2 mm. At upper part of chamber is made of steel with thickness of 4.5 mm with inner diameter 800 mm. The combustion chamber is 2.75 m high and inner diameter is 1.37 m with a gate for putting rice husk, ash paddle and air pipe of tertiary air at the lower part. Ash paddle and tertiary air will support complete combustion in the combustion chamber. The air pipe of tertiary air with diameter of 5 cm is connected to the air feeding system. Upper part of combustion chamber is connected to three pipes as follows: a pipe from air feeding system with diameter of 10 cm (secondary air), a pipe from rice husk feeding system with diameter of 15 cm (primary air) and a pipe to a suction blower with diameter of 25 cm. A butterfly valve used to adjust inlet fresh air into the chamber is installed at the top of the combustion chamber. Rice husk feeding system consists of a rice husk hopper, a screw motor, pneumatic conveyor and conveying fan. Rice husks from the hopper enter to the pneumatic conveyor by using screw motor. Primary air and rice husks from pneumatic conveyor are fed into the combustion chamber in tangential direction with vortex rotation. Rice husks are forced to the bottom of the chamber and burn when they fall to the bottom of the chamber. Air feeding system consists of pneumatic conveyors of secondary air and tertiary air, and conveying fan. Secondary air creates another vortex in the upper part of the chamber to precipitate ash. Rice husk feeding rate and motor of ash paddle are controlled automatically by controller system which switches on or off screw motor, conveying fan of rice husk feeding system and motor of ash paddle when temperature of combusted air differs from set point. Combusted air is mixed with inlet fresh air at the upper part and left from the chamber by suction blower with air flow rate of 1.16 kg/s. Ash of rice husk is left from the chamber by screw conveyor installed at the bottom of the chamber. This research uses rice husk of 450 kg in each experiment. Temperature before entering to the suction blower is controlled at 319 °C. Height of ash is varied as follows: 30 cm , 45 cm , 50 cm and 60 cm.

To start the experiment, rice husk is measured weight and taken a sample in order to analyse the components, then fed into the furnace via a gate at the lower part of furnace. Rice husk is ignited by burning diesel or paper as fuel. Air feeding system and suction blower are switched on. Valve of tertiary air is

Introduction

Rice husks are obtained as by-product during rice production. The rice husks are widely used as a heat source for paddy drying because of low price and easy to find in agricultural countries. Most of rice husk-furnaces in Thailand (in Ayuthaya and Suphanburi province) are heat exchanger rice husk-furnace. The problems of this type of rice husk-furnace are as follows: 1) heat is not constant during combustion in furnace and 2) ash is difficult to be taken out from husk furnace. The rice husk furnace in this research is a cyclonic rice husk furnace. The advantages of the rice husk furnace are as follows: 1) oxygen can spread throughout the furnace therefore the combustion can occur completely, 2) controlling combustion temperature is available and gas from combustion is clean enough. To apply rice husk furnace to fluidized bed paddy dryer can decrease operating cost for drying because burner which uses diesel as fuel for combustion will be replaced by the rice husk furnace.

Xuan et al.(1995) investigated two types of husk furnace in Vietnam. The first one was a furnace with inclined grate and cylindrical combustion chamber. Rice husk consumption was 20-25 kg/h and furnace efficiency was 70 %. There was no ash and sparks escape from the furnace exit. The second one was a pneumatic-fed furnace. The combustion chamber was a vortex-type. Rice husk consumption and furnace efficiency were 10-12 kg/h and 75 % respectively. Control of husk feed rate and air temperature were automatic. Singh et al.(1980) designed a cyclonic furnace for drying 1 ton of paddy. Moisture content of paddy was reduced from 35 % to 14 % dry basis. Efficiencies of the furnace were different at various rice husk feed rate and air flow rate. The highest efficiency was 80 % with rice husk feed rate 20 kg/h and air flow rate 168 m^3/h. Ritsuya et al.(1978) investigated energy source from biomass. Rice husk was a valuable biomass using as heat source in the furnace. A problem of the furnace used in Japan was dust pollution. Therefore, the furnace be designed as a cyclonic furnace in order to precipitate dust.

The objectives of this research are to study, design, construct and test a furnace for fludized bed paddy dryer with capacity of 10 ton/h.

Rice Husk Furnace for Fluidized Bed Paddy Dryer

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Abstract

The objectives of this research are to study, design, construct and test a rice husk furnace for fluidized bed paddy dryer with capacity of 10 tons/h. The husk furnace is cylindrical in shape with inner diameter of 1.37 m, height of 2.75 m, husk feed rate of 120-150 kg/h and air flow rate before entering suction blower of 1.16 kg/s. Air and rice husk are fed in combustion chamber in tangential direction with vortex rotation. Average temperature of air exit furnace (at height of ash 60 cm) and before entering suction blower(at height of ash 30, 45, 50 and 60 cm) are 504 °C and 293-297 °C respectively. Ambient air temperature is 32-34 °C. Thermal efficiencies of the rice husk furnace and the furnace system are approximately 59 % and 58 % (at height of ash 60 cm) respectively. Carbon conversion efficiency is 90 % (at height of ash 60 cm). The research also studies the effect of gases (CO, CO_2, N_2 and NO_2) from combustion in husk furnace on environment and ash (by-product from combustion).

Key words : Cyclonic furnace, Biomass, Rice husk

Proc. 2nd ASEAN Renewable Energy Conference, Phuket, Thailand.
6-9 Nov. 1997

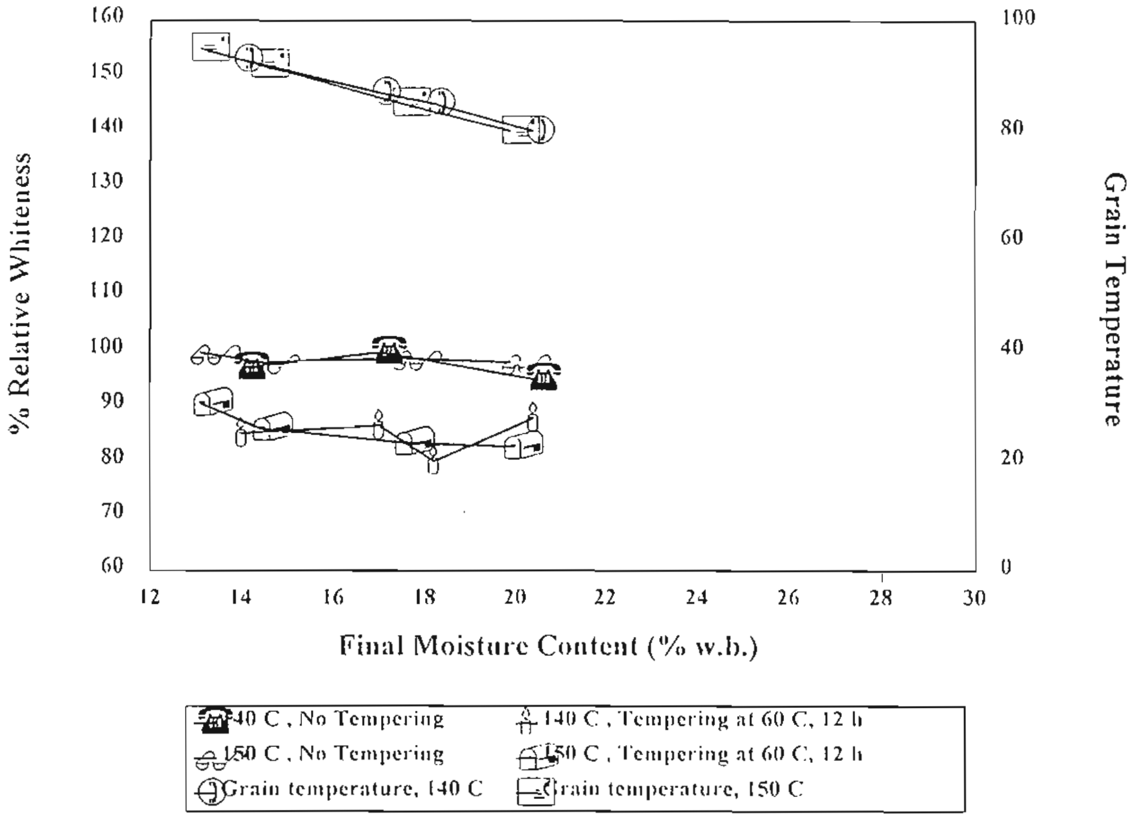

Figure 7 Relative whiteness at different heating process : initial moisture content = 23.8 %w.b., reference whiteness = 45.1

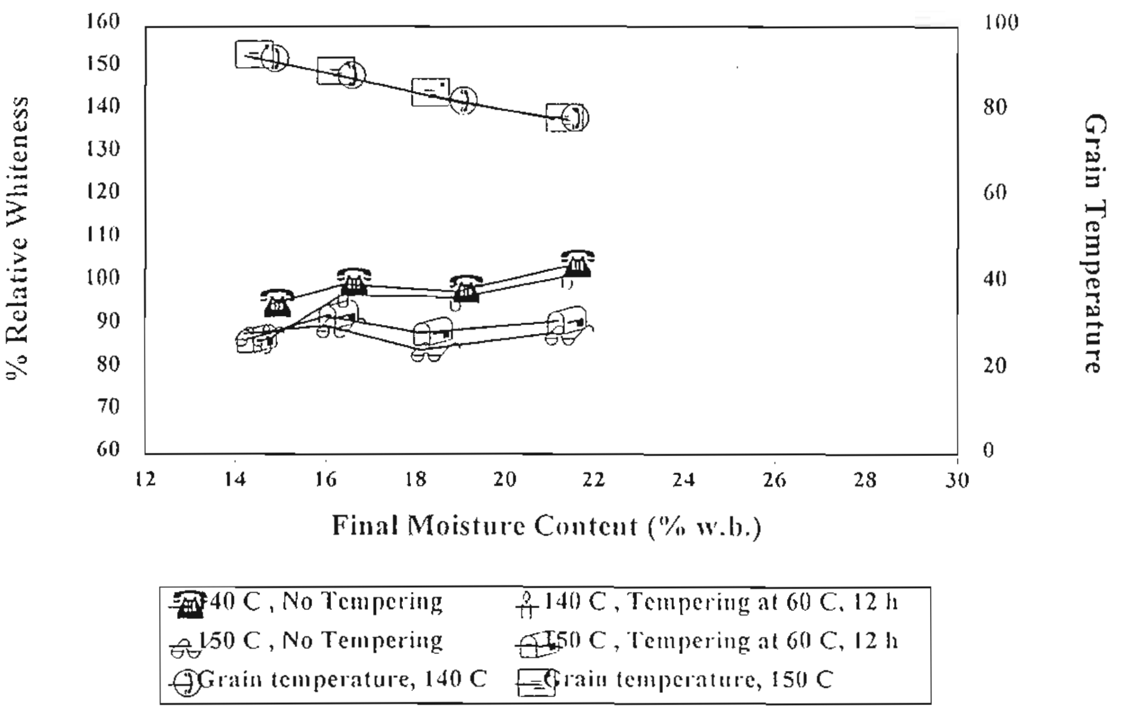

Figure 8 Relative whiteness at different heating process : initial moisture content = 23.1 %w.b., reference whiteness = 46.2

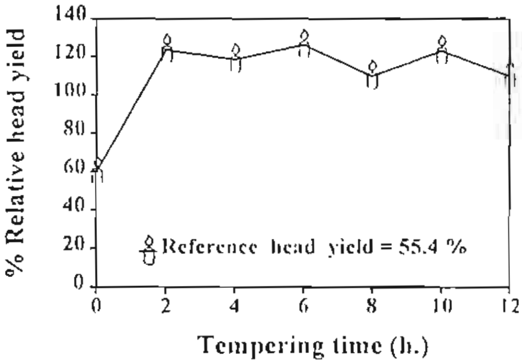

Figure 9 Relative head yield at different tempering time : initial moisture content = 24.6 % w.b., final moisture content = 18.5 % w.b., drying air temperature = 140 °C, tempering temperature = 60 °C

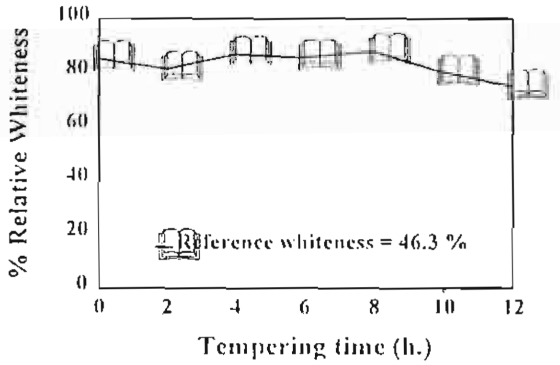

Figure 10 Relative whiteness at different tempering time : initial moisture content = 24.6 % w.b., final moisture content = 18.5 % w.b., drying air temperature = 140 °C, tempering temperature = 60 °C

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Proceedings of the International Agricultural Engineering Conference
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SIMULATION OF HEAT PUMP DRYER

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Keywords : simulation ; heat pump dryer ; modeling

ABSTRACT

A mathematical model of a heat pump dryer was developed to study the performance of an open loop, a closed loop and a partially closed loop heat pump dryers. The criteria for evaluating the performance were specific moisture extraction rate and drying rate. The effects on the performance of ambient conditions, the fraction of evaporator bypass air, specific air flow rate, and drying air temperature were described. It was found that ambient conditions and the fraction of evaporator bypass air slightly affected the performance of the open loop and the partially closed loop heat pump dryers. Specific air flow rate and drying air temperature affected significantly the performance of all heat pump dryers. The results from the simulation of papaya glace' drying using closed loop heat pump dryer were close to the experimental results. From this simulating data, the best conditions were specific air flow rate of 4.3 kg-dry air/h- kg dry papaya and the fraction of evaporator bypass air of 75%. The specific moisture extraction rate was 0.42 kg-water/kW-h.

1. INTRODUCTION

Drying of fruits has been found in various applications. Basically, conventional hot air dryers are used for drying. The main problem is that the conventional hot air dryer results in low product quality due to high drying air temperature. Drying using a heat pump dryer can use lower drying air temperature since moist air leaving the drying chamber can be dehumidified and recirculated.

Chou et al. (1994) developed a mathematical model of a heat-pump-assisted dryer to study the performance of a heat-pump-assisted dryer assuming the coefficient of performance of 8, the effectiveness of outdoor air preheat of 0.7, generator heat losses of 60 %, and transmission losses of 20 %. Jolly et al. (1990) reported a meticulous mathematical model of a heat-pump-assisted continuous dryer. This model was used by Jia et al. (1990) to investigate the performance of a heat-pump-assisted continuous dryer. The criteria were specific moisture extraction rate, coefficient of performance, and product throughput. Parameters which affected the performance were the fraction of evaporator bypass air, the heat transfer area of evaporator and condenser, compressor speed, total air mass flow rate and vented air mass flow rate. Clements et al. (1993) used the model developed by Jolly et al. (1990) to predict the performance of a heat-pump-assisted continuous dryer. The results showed that specific moisture extraction rate increased when air relative humidity was increased. Moreover, the optimum total air mass flow rate of 0.63 kg/s and the optimum fraction of evaporator bypass air of 60-70 % were found. Prasertsan et al. (1996) developed a detailed mathematical model. This model was used by Prasertsan et al. (1997). The simulated results showed that specific moisture extraction rate and moisture extraction rate varied with the ambient conditions and dryer efficiency. A closed loop heat pump dryer was not suitable for high drying rate process. Prasertsan and Saen-saby (1998) reported experimental results of drying of rubber wood and bananas. It was found that the moisture extraction rate of wood and banana drying decreased rapidly, but the compressor power was relatively constant.

The objectives of this study are to develop a mathematical model of heat pump dryers and to simulate the performance of an open loop dryer, a closed loop dryer and a partially closed loop dryer. The effects on the performance of ambient conditions, the fraction of evaporator bypass air, specific air flow rate and drying air temperature will be described.

2. MATHEMATICAL MODELING

A mathematical model of a heat pump dryer consists of two parts: heat pump models and drying models. The details are as follows:

2.1 HEAT PUMP MODEL

In the heat pump models, there are three major models, namely, compressor model, evaporator model and condenser model. The compressor model and the evaporator model, which are empirical models, are constructed from performance data. They are given by equations (1) and (2).

$$P = a_1+a_2T_{er}+a_3T_{cr}+a_4T^2_{er}+a_5T^2_{cr}+a_6T_{er}T_{cr}+a_7T^2_{er}T_{cr}+a_8T_{er}T^2_{cr}+a_9T^2_{er}T^2_{cr} \quad (1)$$

$$Q_e = b_1+b_2T_{er}+b_3T_{cr}+b_4T^2_{er}+b_5T^2_{cr}+b_6T_{er}T_{cr}+b_7T^2_{er}T_{cr}+b_8T_{er}T^2_{cr}+b_9T^2_{er}T^2_{cr} \quad (2)$$

Where a_1= 236.5102: a_2= -11.7410: a_3= 28.60982: a_4= -0.019889
a_5=-0.192508: a_6= 0.432783: a_7= -0.014498: a_8= 0.00321
a_9= 0.00169: b_1=5949.677: b_2=239.8593: b_3= -65.3618
b_4= 2.168339: b_5= 0.07299: b_6= -1.27928 : b_7= 0.031682
b_8= -0.007877: b_9= -0.000677,

and where P and Q are power consumption in the compressor and heat transfer rate in the evaporator, and T_{er} and T_{cr} are refrigerant temperature at the evaporator and refrigerant temperature at the condenser, respectively.

The condenser model is constructed from heat balance, total heat transfer rate in the condenser (internal condenser and external condenser) equal the heat transfer rate in the evaporator plus the power consumption in the compressor. It is written as

$$Q_c = Q_e+P \quad (3)$$

In addition, there are several minor models which are derived from heat and mass balance.

2.2 DRYING MODEL

The drying models used in this study are developed for drying papaya glace. The details of the drying model are as follows:

2.2.1 CALCULATION OF MOISTURE CONTENT

The calculation of papaya glace' moisture content is base on the drying rate equations developed by Achariyaviriya and Soponronnarit(1990). They are given by equations (4) to (7).

$$MR=(8/\pi^2)^3[\exp\{-3\pi^2Dt/l^2\}+(3/9)\exp\{-11\pi^2Dt/l^2\}\}+(3/25)\exp\{-27\pi^2Dt/l^2\}] \quad (4)$$

$$M_{eq} = C_m M_m RH_{di}/\{1+C_m RH_{di}-2RH_{di}-C_m RH_{di}^2-RH_{di}^2\} \quad (5)$$

$$C_m = 163.15\exp(-0.0647T_{di}) \quad (6)$$

$$M_m = 3.1987+0.14077T_{di} \quad (7)$$

Where MR is moisture ratio, M_{eq} is moisture equilibrium content, RH_{di} is the relative humidity of air entering drying chamber, T_{di} is the temperature of air entering drying chamber, D is diffusion coefficient, l is papaya glace' size and t is drying time.

2.2.2 CALCULATION OF MOIST AIR PROPERTIES

From mass conservation, the increase of the moist air is equal to the decrease of moisture content in the product. It can be written as

$$\Delta t\, m_d(W_{do}-W_{di}) = m_p(M_i-M_f) \quad (8)$$

Where Δt is time interval, m_d is dry air flow rate, W_{do} is the humidity ratio of air leaving drying chamber, W_{di} is the humidity ratio of air entering drying chamber, M_i is moisture content before drying, M_f is moisture content after drying and m_p is the dry mass of papaya glace'.

From energy conservation, it is assumed that moist air and product are in thermal equilibrium. The equation can be derived from the first law of thermodynamics. It is given by equation (9).

$$m_d[C_aT_{di}+W_{di}(h_{fg}+C_vT_{di})-C_aT_{do}-W_{do}(h_{fg}+C_vT_{do})] = 0 \quad (9)$$

where T_{di} and T_{do} are the drying air temperature of air entering drying chamber and the drying air temperature of air leaving drying chamber, and C_a and C_v are the specific heat capacities of air and vapor, respectively. Furthermore, there are a few minor models derived from physical properties of moist air.

3. SIMULATION PROCEDURE

A computer program including the mathematical models introduced in the previous section has been developed to investigate the effects of some operating conditions on the performance of heat pump dryers. This simulation program can be solved by using numerical method. Figure 1 shows simulation flow chart. The inputs are as follows: the initial moisture content of papaya glace', specific air flow rate, drying air temperature, the fraction of evaporator bypass air, the fraction of air recycled and other constants. The humidity ratio of air entering drying chamber is the guess value. The steps of the calculation are as follows: drying models and heat pump models are calculated, and then the humidity ratio of air entering drying chamber is checked. If it is not equal to the guess value, the new guess value is calculated by using Newton-Raphson technique, and the system model is calculated again. The calculation continues until the guess value is relatively equal to the new one. The next step is to check the relative humidity of air leaving drying chamber whether it is feasible. If it is higher than 1, the moisture condensation is calculated, and then the variables are recalculated. Finally, the performance of heat pump dryer is calculated. Moisture content of papaya glace' after drying is checked. If it is higher than the desired value, moisture content before drying is replaced by moisture content after drying, and then the time step is advanced. The calculation continues until the moisture content of papaya glace' is less than or equal to the desired value.

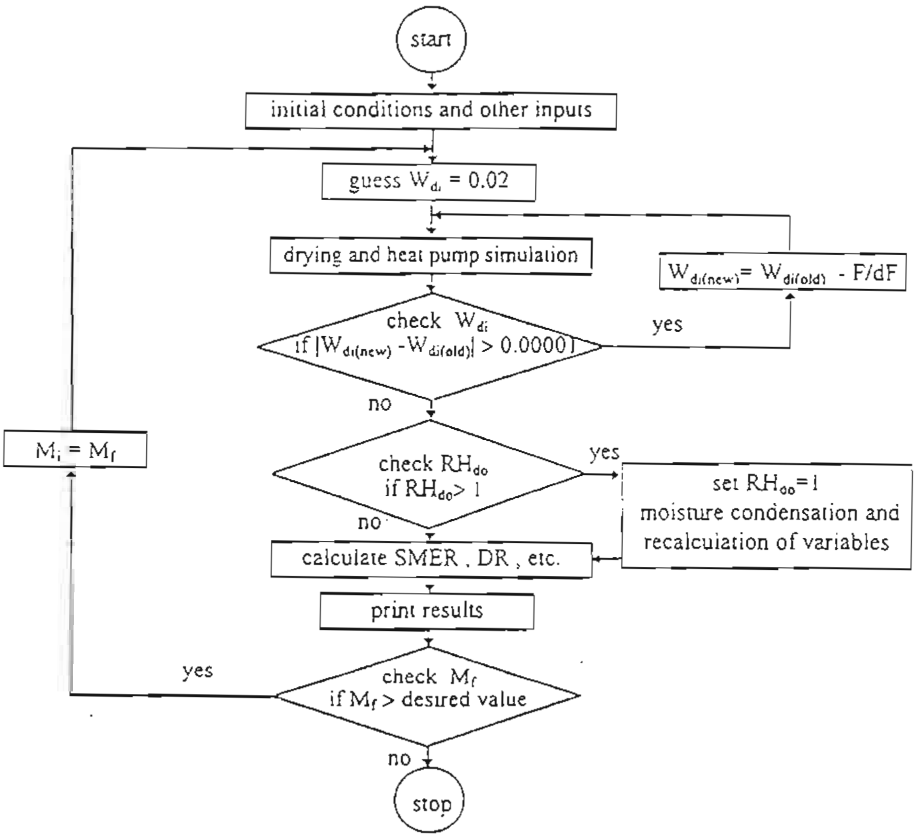

Figure 1. Simulation flow chart.

4. RESULTS AND DISCUSSION

The experimental results of papaya glace' using closed loop heat pump dryer compare with simulated results are shown in Figures 2 and 3. The drying conditions are drying air temperature of 50 °C, product dimension of 1.1x1.2x1.3 cm, specific air flow rate of 29.8 kg/h-kg dry product, the fraction of evaporator bypass air of 0.63 and initial and final moisture content of 38.3 and 23.6 % db, respectively. From Figure 2, the simulated moisture content is slightly higher than experimental results. From Figure 3, the simulated refrigerant temperature at the evaporator and the condenser agrees with the experimental one.

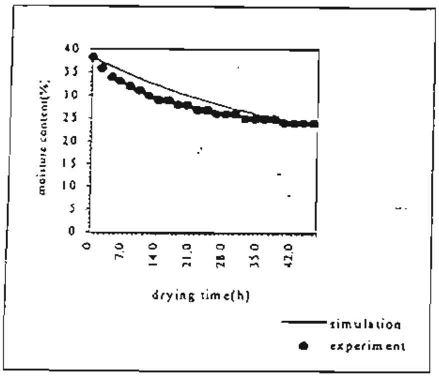

Figure 2. Comparison of moisture content of papaya glace'.

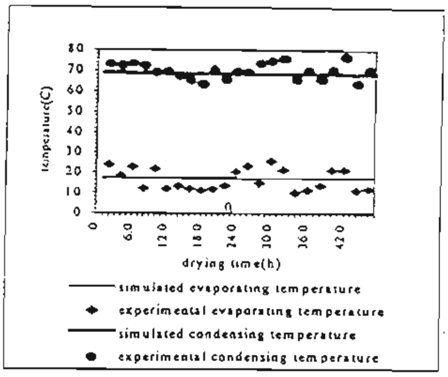

Figure 3. Comparison of working fluid temperature.

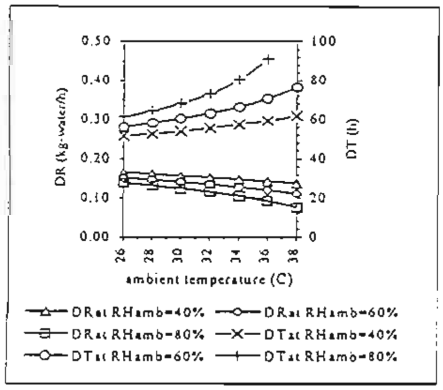

Figure 4. Effect of ambient conditions on DR of open loop system. (DR = drying rate, DT = drying time, RH_{amb} = relative humidity of ambient air)

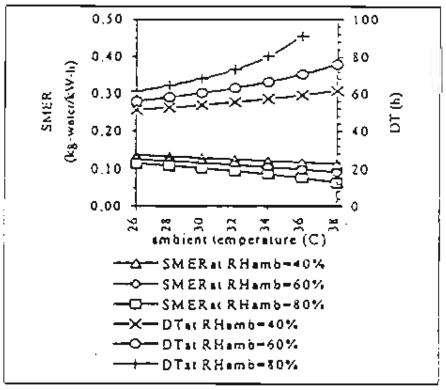

Figure 5. Effect of ambient conditions on SMER of open loop system. (SMER = specific moisture extraction rate, DT = drying time, RH_{amb} = relative humidity of ambient air)

Figures 4 and 5 show the effects of the ambient conditions on DR and SMER of an open loop heat pump dryer, respectively. The simulated drying conditions are drying air temperature of 45 °C and specific air flow rate of 10.3 kg/h-kg dry mass product. Other conditions are the same values as the previous conditions. It is found that DR decreases when relative humidity and/or the temperature of ambient air increase. SMER also decreases when the relative humidity and/or the temperature of ambient air increase. Figures 6 and 7 show the effects of ambient conditions on DR and SMER of a partially closed loop heat pump dryer, respectively. The simulated drying conditions are the same values as the open loop dryer. The behavior of the partially closed loop system on the performance is similar to that of the open loop system. But, the effects of ambient conditions of the partially closed loop system are less than those of the open loop system.

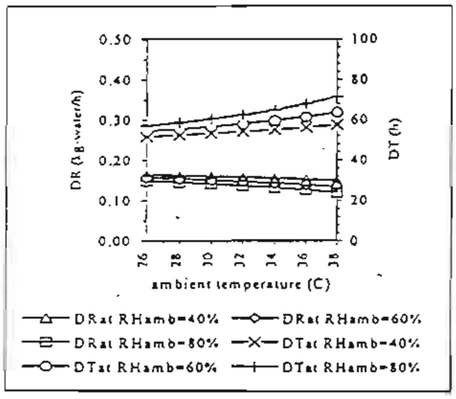

Figure 6 Effect of ambient conditions on DR of partially closed loop system (the fraction of air recycle75%). (DR = drying rate, DT = drying time, RH_{amb} = relative humidity of ambient air)

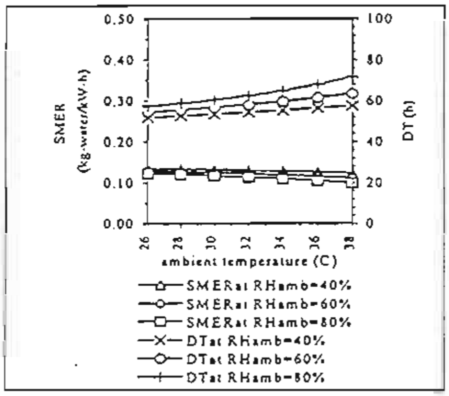

Figure 7 Effect of ambient conditions on SMER of partially closed loop system (the fraction of air recycle75%). (SMER = specific moisture extraction rate, DT = drying time, RH_{amb} = relative humidity of ambient air)

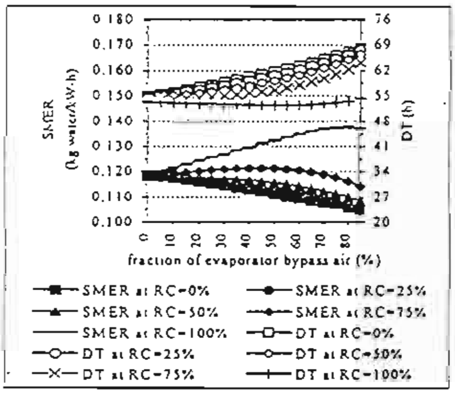

Figure 8. Effect of the fraction of evaporator bypass air on SMER of all heat pump dryers. (SMER = specific moisture extraction rate, DT = drying time, RC = fraction of air recycled)

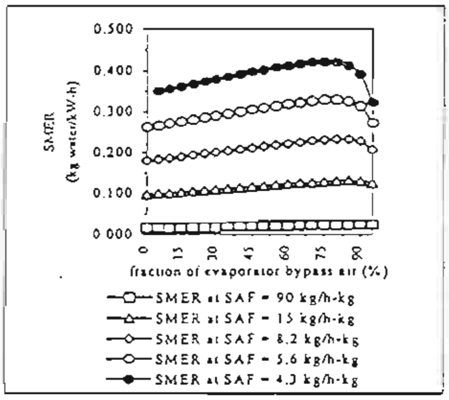

Figure 9. Effect of the fraction of evaporator bypass air on SMER of closed loop dryer for various cases of specific air flow rates. (SMER= specific moisture extraction rate, SAF = specific air flow rate)

Figure 8 shows the effects of the fraction of evaporator bypass air on the SMER of an open loop dryer, a partially closed loop dryer and a closed loop dryer. The ambient conditions are relative humidity of 70 % and temperature of 30 °C. Other conditions are the same values as the previous conditions. Considering the open loop heat pump dryer, it is found that SMER decreases when the fraction of evaporator bypass air increases. For the closed loop heat pump dryer, the simulated results show that SMER increases when the fraction of evaporator bypass air increases in the range of 0-75 %, and SMER decreases when the fraction of evaporator bypass air is more than 80 %. Figure 9 shows the effects of the fraction of evaporator bypass air on SMER for various cases of specific air flow rates of the closed loop system. It is found that SMER increases when the specific air flow rate decreases. From simulated results, the best condition giving the SMER of 0.42 kg-water/kW-h is specific air flow rate of 4.3 kg-dry air/h-kg dry papaya and the fraction of evaporator bypass air of 75 %.

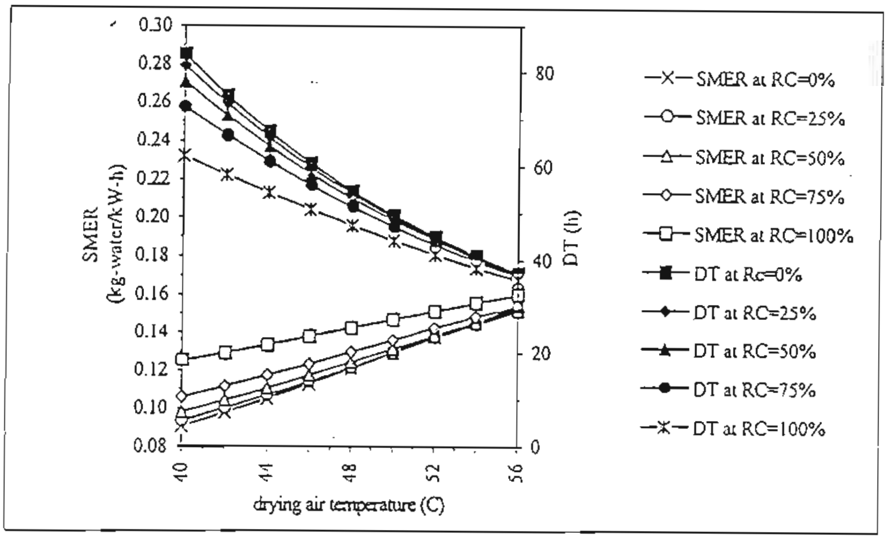

Figure 10. Effect of drying air temperature on SMER for all systems of heat pump dryers.
(SMER = specific moisture extraction rate, DT = drying time, RC = fraction of air recycled)

The effects of drying air temperature on the SMERs of various systems are also investigated. Figure 10 shows SMER versus drying air temperature. It is found that the SMERs of all heat pump models increase when drying air temperature increases.

5. CONCLUSION

A mathematical model of a heat pump dryer developed here is simulated for investigating the performance of heat pump dryers. The refrigerant temperature and the moisture content of papaya glace' are used for the verification of the mathematical model. It is found that the simulated results agree quite well with the experimental results. The effects of the ambient conditions, the fraction of evaporator bypass air, specific air flow rate and drying air temperature on the performance are depicted. It is found that ambient conditions and the fraction of evaporator bypass air slightly affect on the performance of open loop dryer and partially closed loop dryer. Furthermore, specific air flow rate and drying air temperature affect significantly the performance of all heat pump dryers.

ACKNOWLEDGMENT

The authors would like to express their sincere thanks to The Thailand Research Fund for financial support.

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MODELLING OF A LARGE SOLAR DRYING SYSTEM IN THAILAND

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Abstract
A 292 m^2 solar drying system has been constructed at a privately owned food factory in North East Thailand. The performance of the system has been modelled using TRNSYS. Standard subroutines have been used in conjunction with a purpose written crop subroutine to describe the system. The crop dried during the experimental period was sliced green bananas. Hourly collector outlet temperature predictions are, on average, within 3% of measured values. Predictions of solar energy collected over the experimental period are within 7% of the measured amount. When a drying constant (k) of 0.564 hr^{-1} is used in a modified Halsey equation, the predicted values of moisture content are within +/- 4% points of measured values over the drying period. The predicted values of pick-up ratio are within +/- 6% points of measurements. Predictions of auxiliary energy use are within 19% of measured values, if a heat exchanger efficiency of 90% is assumed.

1. Introduction

The demand for energy in Thailand is expected to increase greatly in the coming decade. Although fossil fuel resources in the country are limited, there is abundant solar energy. Average annual horizontal global radiation levels are approximately 17 MJ m^{-2}. A solar drying system is currently being trialled at a factory in the village of Khao-kor in North East Thailand. If successful, it is intended that more systems will be constructed at other locations. A validated mathematical model of the system would therefore be a useful tool to assist in the design and optimisation of future systems. This paper describes the mathematical model, and compares model predictions with measured data.

2. System Description

The complete solar drying system consists of four separate drying units. Each of these consists of five main components (**Figure 1**). These are a 73 m^2 solar collector array, ductwork, fan, heat exchanger and drying bed. A central boiler provides supplementary energy to the heat exchanger in each system. A more detailed description of the system has previously been reported (Rakwichian et al., 1998).

3. Model Description

The system has been modelled using the standard subroutines contained within TRNSYS wherever applicable. However, this was not possible for all components of the system. The non-standard sub-routines used in the model are described below.

3.1 Solar Collector

It was not possible to use the standard TRNSYS solar collector subroutine because horizontal solar radiation at the site had not been measured. Solar radiation measurements were made only on the plane of the collector. Therefore the simple model described below was developed to predict collector outlet temperatures.

Collector efficiency can be defined by the following equation

$$\eta = F_R(\tau\alpha)_e - \frac{F_R U_L (T_i - T_a)}{G_T} \ldots\ldots\ldots\ldots\ldots eqn(1)$$

where

F_R = heat removal factor
$(\tau\alpha)_e$ = effective transmittance-absorptance product
U_L = heat loss coefficient ($Wm^{-2}\ K^{-1}$)
T_i = initial fluid temperature (K^{-1})
T_a = ambient air temperature (K^{-1})
G_T = incident solar radiation ($Wm^{-2}\ K^{-1}$)

Collector efficiency can also be defined in terms useful heat collected, Q_u i.e.

$$\eta = \frac{Q_u}{A_c G_T} \ldots\ldots\ldots\ldots\ldots\ldots eqn(2)$$

where

$$Q_u = m\ C_p\ (T_o - T_i) \ldots\ldots\ldots\ldots\ldots eqn(3)$$

By equating equations (1) and (2) and assuming $T_i = T_a$, then the value of T_o can be calculated at each hour, if the collector characteristics, incident solar radiation and the mass flow rate are known. The type of solar collector used at the factory was identical to that tested by Soponronnarit et al. (1990). Experimental data confirmed that flow rates were also similar, justifying the use of the same collector characteristics. Average values of air density and specific heat for air were used in performance predictions.

3.2 Crop

A sub-routine has been written using algorithms and data for sliced banana. The equilibrium moisture content is calculated using a modified Halsey equation suggested by Auchariyaviriya and Soponronnarit (1989). Sankat and Castaigne (1992) report various values of drying constants for untreated banana slices. However, the banana slices used in the present trial were blanched prior to drying, and this increased the drying rate considerably. A "k" value of 0.564 was found to produce acceptable results.

3.3 Duct

The standard TRNSYS sub-routine for modelling the heat losses in the pipework of solar systems has been slightly modified to allow the uninsulated surface area and the volume of air contained within the duct to be entered directly. Sections of ductwork located before and after the auxiliary heater have been modelled.

4.0 Model Validation

Predicted and measured collector outlet temperatures over the six hours of the particular drying trial investigated (June 7 1998) are shown in **Figure 2**. Hourly collector outlet temperature predictions, generated by using measured climatic data, have been compared with the average of the hours' measurements, advanced by 10 minutes. This adjustment was found to be necessary because it was observed that the thermal capacitance of the collector caused a delayed temperature response of approximately 10 minutes. It was found that on average the predictions were within 3% of measured values. The predicted value of solar energy collected was 210 MJ over the experimental period which was 7% less than the measured amount of 225 MJ.

Figures 3 compares measured and predicted values of moisture content of the banana slices. The starting moisture content in the simulation was set at 74% i.e. the measured value. Unfortunately, no moisture content measurement was made at hour 13, but the remaining predicted values of moisture content are within +/- 4% points of the measured values over the drying period.

Figure 4 compares the measured and predicted values of pick-up efficiency, which indicates how efficiently the drying air is utilised. It is the ratio of the actual moisture absorbed by the air after it exits the dryer to its theoretical capacity. The predicted values of pick-up ratio are within +/- 6% points of measurements.

From condensate flow and heat exchanger inlet and outlet temperatures, it was estimated that 704 MJ of supplementary energy was used during the drying period. When a heat exchanger efficiency of 90% is assumed, the model predicts 572 MJ of supplementary energy are required i.e. an under-prediction of 19%. Experimental observations indicate that the steam was not saturated at the heat exchanger inlet. Although the wetness fraction could not be determined, it is concluded that the model would adequately predict supplementary energy use, if the steam delivery system was performing correctly.

5. Conclusions

Although further validation of the model is required for other crops and over a longer time frame, it has been demonstrated that the solar simulation software, TRNSYS, can be adapted readily to make performance predictions of solar drying systems such as those described in this paper. The model can be used for long term predictions of system performance both at Khao-kor and other locations. Design variations can be evaluated, and an optimisation of key components can be carried out. It is believed that the model will be a useful tool in the design of future solar drying systems of this kind in Thailand.

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7. Acknowledgments

Funding for this work has been provided under the University of Melbourne's International Exchange Agreements Collaborative Research Awards Scheme. The assistance of Venus Thadnium in gathering the experimental data, and the assistance of staff, both at SERT and the Khao-kor factory, is duly acknowledged.

Figure 1 Solar Drying System

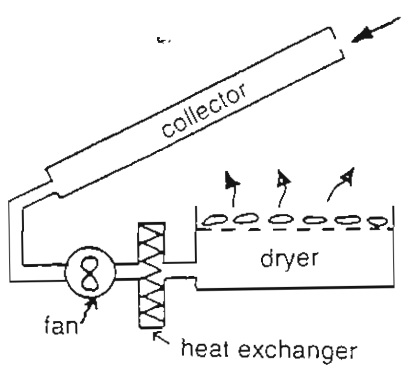


Figure 2 Collector Outlet Temperatures

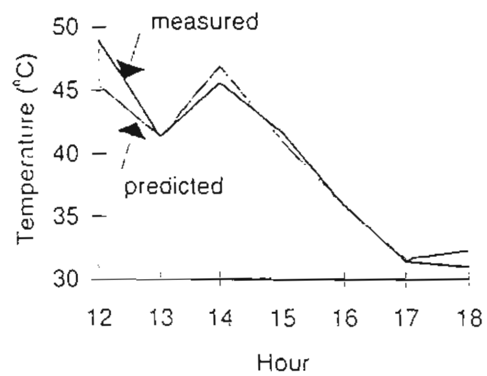


Figure 3 Moisture Content

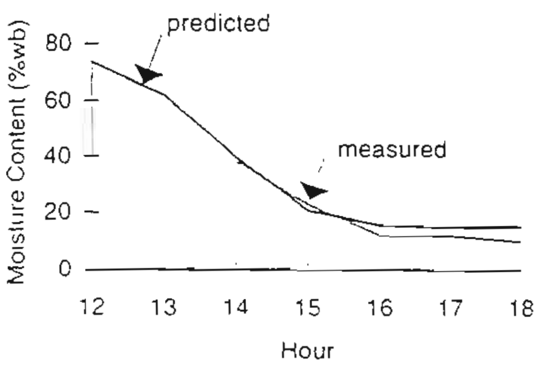
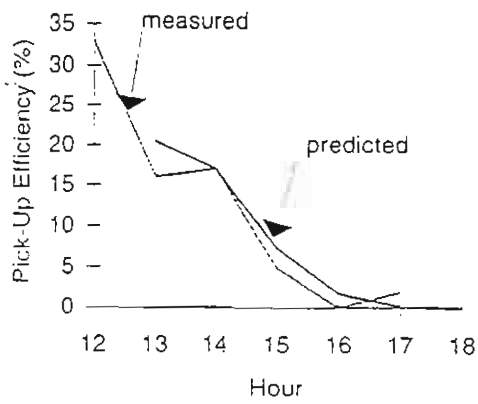


Figure 4 Pick-Up Efficiency



Industrial-Scale Solar Vegetable Drying

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Key words : Solar drying ; Vegetable ; Dryer

ABSTRACT

An industrial-scale solar vegetable dryer with a capacity of 100 kg was designed, constructed and tested at a food factory in the North East of Thailand. The complete solar drying system consists of four dryers. The main parts of a dryer are as follows: a solar collector with an area of 73 m^2, a 2 kW blower, a drying cabinet and an air to steam heat exchanger. The dryer used solar energy and steam as heat resources for drying vegetables such as chopped spring onion, cabbage, ginger, turmeric, green banana, basil and chili. Total area of solar collector was 300 m^2. Steam was used to supplement solar energy at low intensity. A central boiler with capacity of 5 tons/h was used to supply the air to steam heat exchanger. Drying air temperature was controlled at 60°C in each experiment. In operation, air was sucked from the solar collector, heated by air to steam heat exchanger if air temperature was lower than a set value, and blown into the drying cabinet. Vegetable with approximate initial moisture content of 75 - 85 % w.b. was dried to approximate final moisture content of 5 - 10 % w.b. within 4-6 h. Experimental results showed that drying efficiency, efficiency of solar collector and system efficiency were 43 %, 40 % and 17.4 %, respectively.

INTRODUCTION

Drying is one of the most practical methods for preserving agricultural products. Drying with conventional heat sources has been widely used. Solar drying has been studied in many countries in order to reduce cost and substitute conventional energy. Exell(1980) developed a low cost solar dryer made of plastic film. A simple design method was presented. Soponronnarit et al.(1986) showed that most of the solar air heaters developed were the flat plate type and were aimed at agricultural drying purposes. Soponronnarit et al.(1988) concluded that some solar air heaters employed in forced convection solar dryers were made from corrugated galvanized iron sheet normally used in building roofs. Soponronnarit et al.(1992) developed a mathematical model for banana drying using solar energy as supplementary heat. It was found that the results obtained from the model and experiment were in agreement. Drying air temperature should be around 60 °C if product quality was to be maintained.

A project of vegetable drying using solar energy as heat source and supplement with steam was studied. The project has been experimented at Khao-kor in North East Thailand. The objectives of this study were to design, construct and test an industrial-scale solar vegetable dryer using solar energy as heat source and supplement with steam.

MATERIALS AND METHODS

A solar drying system consists of a solar collector with an area of 73 m^2, a 2 kW blower, a drying cabinet and air to steam heat exchanger. There are four dryers in a complete solar drying system. Vegetable of 100-150 kg could be dried in each batch of a dryer. Figure 1. shows the diagram of the solar drying system. In the solar drying system, steam (from a boiler with capacity of 5 tons/h) was used to supplement solar energy at low intensity. In operation, air was sucked from the solar collector, heated by air to steam heat exchanger if air temperature was lower than a set value, and blown into the drying cabinet.

Vegetable was prepared by cutting into small pieces and was then cleaned. Vegetable with high initial moisture content of 75-85 % w.b. was dried to approximate final moisture content of 5-10 % w.b. The vegetables used in this experiment were as follows: basil, tumeric, green banana, chopped spring onion, cabbage, ginger and chili. Temperatures at drying cabinet, solar collector inlet and duct between solar collector and air to steam heat exchanger were measured by Chromel-Alumel type k thermocouples. Thermocouple signals were acquired by a datalogger with an accuracy of ±1 °C. Air velocity in the duct between the solar collector and the steam to air heat exchanger was also measured by hot wire anemometer with an accuracy of 5 %.

RESULTS AND DISCUSSION

Efficiency of a drying cabinet was shown in Table 1. The results showed that the efficiency of a drying cabinet was approximately 35-52 % while the efficiency of solar drying system was 15-25 %. This was due to losses at the solar collector, air duct and steam pipe. Efficiency of solar collector was approximately 30-50 %.

Moisture content of vegetable was reduced from 75- 85 % to 5-10 % w.b. within 4-6 h. Drying air temperature in drying cabinet was controlled at 60°C. Temperature leaving solar collector was approximately 55-65 °C with solar intensity of 650 W/m^2. The temperature depended on solar intensity. Air speed leaving collector was approximately 2.0-2.5 m/s.

In case of basil drying with drying time of 3 h, initial moisture content of 84 % w.b. and final moisture content of 5 % w.b., the system and drying efficiency were 21 % and 49 %, respectively when using solar energy 71 %, steam 18.6 % and electricity 10.4 %. The efficiency of solar collector was 37.6 %. In case of chili drying with drying time of 5.5 h, initial moisture content of 88 % w.b. and final moisture content of 9 % w.b., the system and drying efficiency were 18.5 % and 39.7 %, respectively when using solar energy 53.5 %, steam 38.2 % and electricity 8.3 %. The efficiency of solar collector was 46.4 %. The system efficiency could be increased by reducing heat loss from the system. There are two points where the heat loss from the system occurs: the steam pipeline between boiler and the steam to air heat exchanger, and the air to steam heat exchanger.

CONCLUSION

Efficiencies of the drying cabinet and the solar vegetable drying system are approximately 30-50 % and 15-25 %, respectively. The dryer could reduce initial moisture content of 75-85 % w.b. to final moisture content of 5-10 % w.b. within 4-6 h. Drying air temperature was controlled around 60°C in each experiment.

RECOMMENDATION

Further study is needed to evaluate the economics of the solar vegetable drying system.

ACKNOWLEDGMENT

The authors would like to thank the Thailand Research Fund for financial support.

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Table 1. Efficiency of solar drying system

Experiment	Drying time (h)	initial MC %w.b	final MC %w.b.	Solar Energy (MJ)	Steam (MJ)	Elec. (MJ)	Eff. of dryer (%)	Eff. of system (%)	Eff. of collector (%)
1. basil	4.0	86.8	4.0	258.8	36.8	49.6	47.1	16.1	37.8
2. basil	3.5	84.8	5.7	199.6	87.0	35.6	48.6	16.5	39.0
3. basil	3.0	84.6	5.0	229.8	60.3	33.7	49.2	21.3	37.6
4. basil	4.0	86.8	5.0	297.6	21.0	45.9	46.1	20.0	41.5
5. basil	3.75	84.5	7.0	109.9	177.6	35.7	48.7	17.8	50.0
6. tumeric	5.5	87.5	7.0	128.0	324.3	63.6	57.3	21.5	52.1
7. banana	5.0	78.8	7.7	156.9	24.0	58.0	28.1	10.3	31.4
8. cabbage	6.5	95.0	27.0	185.4	278.6	64.6	27.7	15.5	61.6
9. ginger	4.2	90.5	4.4	230.8	487.8	44.9	50.9	23.8	51.7
10. chili	5.5	88.0	9.0	369.8	263.8	58.0	39.7	19.3	46.4

Eff. = Efficiency   Elec. = Electricity   MC = Moisture content

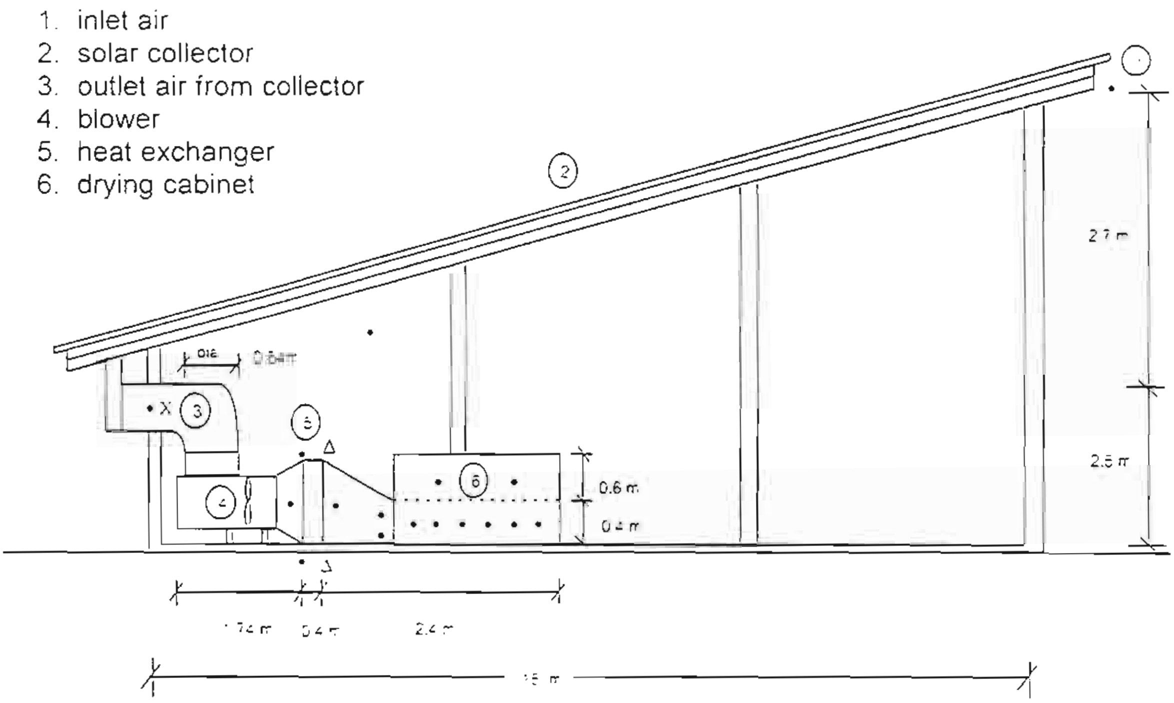

Figure 1. Diagram of a solar system and positions for measuring temperatures and pressure
• Temperature
Δ Pressure
x Air velocity

INDUSTRIAL SCALE HEAT PUMP FRUIT DRYING

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Keywords: Dryer, Heat pump, Papaya glace'

ABSTRACT

An industrial-scale prototype of heat pump dryer (HPD) was designed, constructed and tested. The drying chamber contains four trolleys with product capacity of 600-700 kg. In the experiments, papaya glace' was dried in close system at an average temperature of 55°C, specific air flow rates of 25-32 kg dry air/h-kg dry papaya glace' and the evaporator by-pass air of 81%. The papaya glace' with initial moisture content of 83-86% dry basis was dried in three stages to final moisture content of 12-14% dry basis within approximately 32 hours. No significant final moisture gradient along the vertical and horizontal directions of the dryer was observed due to uniform air distribution within the drying chamber and high enough air flow rate respectively. The experimental results indicate that drying rate decreases rapidly with time, while total power consumption remains nearly constant. At high initial moisture content, the moisture removal is higher than that at low initial moisture content. The maximum average drying rate (DR) and specific moisture extraction rate (SMER) are 9.34 kg water evap./h and 0.732 kg water evap./kWh respectively. The maximum average moisture extraction rate (MER) is 8.59 kg water cond./h and the relative lowest average specific energy consumption (SEC) is about 4.92 MJ/kg water evap. The coefficient of performance of heat pump $(COP_{hp})_{system}$ varies from about 4.1 to 4.7 which is higher than $(COP_{hp})_{used}$ obtained by the internal condenser load which varies from 3.0 to 3.8. This attributes to the excess heat rejected to atmosphere through the external condenser. Operating system on partially open mode does not offer more benefits than close system. The quality of dried papaya glace' in terms of color is acceptable due to low drying temperature. Cost evaluation showed that cost of papaya glace' drying was 6.43 Baht/kg water evaporation of which 2.73 was energy cost, 0.55 was maintenance cost and 3.15 was fixed cost (US$ 1 = 40 Baht). In conclusion, HPD achieves high energy efficiency, and it is feasible to be commercialized, particularly in food drying industry. Latest information shows that the HPD prototype has been sold.

1. INTRODUCTION

Using low drying air temperature of HDP enhances product quality by retaining texture, and reduces the incidence of color degradation. Some of the literature concerning heat pump drying was reported by Soponronnarit et al. [1] which can be summarized as follows: HPD could be operated on close or open systems, drying temperature depended on refrigerant and it could be increased by adding electrical heat into HPD but caused COP to reduce. HPD performance could be increased by selecting suitable ratios of evaporator by-pass air, and using recuperator (Economics of using recuperator is a concern.). Prasertsan et al.[2] conducted computer simulation to study effects of drying rate and ambient condition on the operating modes of HPD in batch drying. The result was in agreement with the previous study as reported by Clements et al. [3] that SMER and MER strongly depended on the relative humidity of outlet air from the drying chamber. It was recommended to run HPD on open system during the stage of high drying rate (early stage of drying) and partially closed system during the stage of low drying rate (final stage of drying). Prasertsan and San-saby [4] studied heat pump drying of agricultural materials. From the economic analysis of HPD and conventional dryers (i.e., an electrically-heated hot air dryer, a direct-fired dryer), it was found that HPD had the lowest operating cost. HPD was operated on both partially closed and open systems. In batch wood drying, the maximum average MER and SMER were 2.854 kg/h and 0.572 kg/kWh respectively. Batch banana drying yielded the highest average MER of 2.710 kg/h and SMER of 0.540 kg/kWh.

In this study. A prototype of industrial-scale HPD was designed, constructed and tested in a food processing factory. Papaya glace' was chosen as test material.

2. MATERIALS AND METHODS

A prototype of industrial-scale HPD which could be operated as a close system or a partially open system was constructed, as shown in Figures 1. In this paper, experiments were carried out on the close system according to test nos. 1, 2 and 3 only by closing dampers A and B and partially open system as test nos. 4. 5 and 6 respectively. The HPD consists of a drying chamber and a heat pump. The drying chamber is 1.0 m wide x 4.0 m long x 1.5 m high, and contains four trolleys. One trolley has 17 trays of 90 cm x 70cm. The main components of the heat pump are a 6.7 kW hermetic reciprocating compressor using R-22 as refrigerant, a 25 kW internal condenser (4 rows x 25 columns, 512 fins per meter), a 10.5 kW external condenser (2 rows x 18 columns, 512 fins per meter), a 25 kW evaporator (551 fins per meter), a thermostatic expansion valve, a forward-curved-blade centrifugal fan equipped with a motor of 5.5 kW corresponding to air volume flow rate of 2.8 m^3/s at 750 kPa and two axial fans equipped with a motor of 200 W each (for the external condenser).

This study was experimentally performed at the fourth Royal Project - Royal Recommended Project Food Processing Section in Burirum province. Papaya glace′ was chosen as the test material to be dried. Its initial mass varied between 600-700 kg. The locations of measuring temperature and pressure for both of the air and refrigerant circuits were shown in Figure 1. For air circuit, the dry bulb and wet bulb temperatures were measured by type k thermocouples. For the refrigerant circuit, temperatures were indirectly measured by inserting type k thermocouples through small copper tubes with their close ends inserted and brazed in to the wall of refrigerant piping. The outputs of temperature sensors were recorded by a data logger with an accuracy of $\pm$ 1°C. The refrigerant pressures were measured by Bourdon-tube-type pressure gauge. The measurement points were located as shown in Figure 1. Air flow rate in the return and by-pass air ducts were measured by a hot wire anemometer. The refrigerant mass flow rate was not directly measured, but determined from the compressor input work by assuming compressor and motor efficiencies. The power consumption was measured by a kilowatt-hour meter and a clip-on-meter. The initial and final mass of papaya glace′ and condensed water were determined by weighing.

Six drying experiments were carried out in batch. The drying process was divided into three stages. At the first stage, papaya glace′ of about 11.5x6.5x1.7 cm^3 with initial moisture content varied from 83 to 86% dry basis was dried, and drying time was about 19 h. At the second stage, the dried papaya glace′ of the first stage was prepared into dimension of about 1.0x1.0x1.0 cm^3. In order to make papaya glace' be cut easily, a small amount of water should be sprayed on it during preparation process. The papaya glace' was dried to moisture content of 17-22% dry basis with approximately 9 h. In the third stage, dried papaya glace' was mixed with icing (sugar) before being dried to final moisture content between 12 and 14% dry basis with approximately 4 h. The total drying time was approximately 32 h. The temperature, pressure, mass of condensed water and power consumption were recorded every 1 h for the 1st stage and ½ h for the 2nd and 3rd stages. To determine the moisture content, the samples were cut into small pieces and weighed by digital balance (accuracy of 0.01g). The samples were dried in an hot air oven at temperature of 103 °C for 72 h. All samples were taken from the middle of trays nos.1, 5, 9,13 and 17 of each trolley. Drying tests were carried out at temperature of 53-55 °C, 45-50 °C for close and partially open system respectively and air flow rate of 2.8 m^3/s. The evaporator by-pass air was set between 70-85%.

The COP_{hp} was analyzed and obtained from measurements made on both the air and refrigerant circuits. In this study, COP_{hp} was classified into 1) $COP_{hp,\ sys}$ obtained from the calculation regarding both internal and external condenser heat loads, and 2) $COP_{hp,\ used}$ obtained from the calculation regarding only internal condenser heat load.

3. RESULTS AND DISCUSSIONS

3.1 Close System

3.1.1 Variations of air temperature and moisture content of papaya glace'

The experimental results of batch papaya glace' drying are presented in Table 1. Temperature gradient along the horizontal direction of the drying chamber decreased with drying time. At the end of each drying stage, air temperature at the entrance and exit of the drying chamber was only slightly different with about 1°C. As a result, the average moisture gradient along the horizontal direction of the drying chamber was relatively small, approximately 5% dry basis during the 1st and 2nd stages and was minimum (1.4% dry basis) at the end of the 3rd stage. Average air temperature along the vertical direction of the drying chamber was not varied as indicated by tray nos. 1, 9 and 17. This was due to the proper function of the air splitter at the right corner as shown in Figure 1. As a consequence, the average moisture gradient along the vertical direction of the drying chamber was quite small, 1.2% dry basis at the end of drying.

3.1.2 HPD performance

The experimental results indicated that the moisture content and MER decreased rapidly with time; that meant the DR was also in the same behavior. However, it was observed that reduction of moisture content or MER was improved during the early period of the 2nd stage as compared to the final period of the 1st stage. This was according to the size reduction of papaya glace′ after the 1st stage.

By comparing the results of the 2nd and 3rd stages of all experiments (Table 1), it was found that an increase in moisture from about 20% to 40% dry basis gave approximate 4 times increase in the water removal of the 2nd stage. Nevertheless, the initial mass of 2nd stage was not substantially higher than that of 3rd stage. This was simply explained that when the papaya glace′ had high moisture content, the surface was nearly saturated with water which consequently increased the moisture diffusion rate. But when the moisture content reduced to relatively low, the moisture diffusion from the inner part to the outer surface became more difficult, and resulted in ineffective drying and low SMER, while SEC increased.

Moreover, it should be noted that SMER defining as the ratio of water evaporated and power consumption were directly proportional to the water removal rate because the power consumption remained nearly constant. By averaging numerical results of all experiments, the HPD achieved a maximum average DR and SMER of 9.34 kg water evap./h and 0.732 kg water evap./kWh, respectively. The average maximum MER was 8.59 kg water cond./h. MER and DR were slightly different due to air leakage through the system . In these experiments, the initial moisture content, initial mass and dimension of papaya glace' were not much different and hence resulted in less difference of SEC and drying time compared to the same stage of each test. SEC of test no.3 was 4.92 MJ/kg water evap. and was considerably lowest compared to others.

Analyzing data from the air circuit showed that $(COP_{hp})_{sys}$ was in the range of 4.1 to 4.7 and $(COP_{hp})_{used}$ obtained by internal condenser varied from 3.0 to 3.8. It was obvious that $(COPhp)_{sys}$ was higher than $(COP)_{used}$. This was because in order to control temperature inside the drying chamber within a certain limit. substantial amount of heat corresponding to compressor and fan work inputs had to be rejected across the external condenser. By using low air temperature. the quality of papaya glace' in terms of color was found to be well acceptable. The color was light reddish-orange (code 34-C from R.H.S. color chart).

3.2 Partially Open System

The experimental results are summarized in Table 1. During test nos. 5 and 6, it rained whole day, thus ambient air was cool and humid. It is obvious that ambient air conditions played an important role on HPD performance even small amount of ambient air was induced to the system such as the 1st stage of test no. 5 which drying temperature could not be raised higer than 45°C. This resulted in less drying potential and SMER as compared to the 1st stage of test nos. 4 and 6. The best results in terms of drying capacity and energy effectiveness done by partially open system were close to that of close system (as compared test nos. 4 and 6 to test nos. 1, 2 and 3). Therefore, to achieve a satisfactory performance. the system can not operate by sustaining a certain amount of ambient air at all time but it has to be varied according to variable ambient air conditions.

3.3 Cost Evaluation

Conditions for cost evaluation of HPD are as follows: holding capacity is 670 kg/batch. drying capacity is 96 batches/year. dried papaya glace' capacity is 34.540

kg/year. average drying time is 31.5 h/batch. cost of HPD construction and cost of stainless steel trolleys and trays are 216,340 and 95,400 Baht respectively (US$ 1=40 Baht), life time was 5 years. salvage value is 24.5 % of system first cost (assuming that trolleys and trays can be further used), maintenance cost per year is 5% of system first cost. evaporation water ability is 267 kg water evap./batch, electricity cost is 2.0 Baht/kWh, electricity use rate is 12.76 kWh/h and interested rate was 18%/year. Other operating costs are neglected in this study. The results of evaluation are as follows.

Total annual cost 181,785 Baht/year or 6.43 Baht/kg water evap. of which 2.73 is energy cost, 0.55 is maintenance cost and 3.15 is fixed cost.

4. CONCLUSION

1. Moisture gradient paralell and perpendicular to the direction of air flow approached to 1.4% and 1.2% dry basis at the final stage respectively. Water removal was very fast at early stage and reduced thereafter when the moisture content were relatively low. similarly to that of MER behavior. Size reduction of papaya glace′ after the 1st stage enhanced DR or MER during the 2nd stage of drying. Power consumption remained nearly constant. whereas the drying process was transient. This attributed to an effort to sustain constant drying air temperature by releasing the excess heat corresponding to compressor and fan work inputs across the external condenser. Consequently, $(COP_{hp})_{used}$ was less than $(COP_{hp})_{sys}$.

2. Water removal from papaya glace′ with relatively low moisture content was extremely difficult compared to that with high moisture content at the same level of initial mass. This resulted in relatively low DR and SMER. The water removal rate was directly related to SMER and SEC. The HPD achieved a maximum average DR and SMER of 9.34 kg water evap./h and 0.732 kg water evap./kWh, respectively. The maximum average MER is 8.59 kg water cond./h. and the relative lowest SEC was about 4.92 MJ/kg water evap. The $(COP_{hp})_{sys}$ varied from about 4.1 to 4.7 and $(COP_{hp})_{used}$ were in range of 3.0 to 3.8. By using low air temperature, it was observed that the quality of papaya glace′ was well acceptable.

3. To run system on partially open mode did not offer more benefits in comparison to close system mode. The ambient conditions had a strong influence on HPD performance. To obtain the best performance, fraction of air recycled has to be varied according to uncertain ambient air conditions. Therefore, it seems that the system is complex and not convenience to user to operate.

4. Cost evaluation showed that total cost was 6.43 Baht/kg water evaporation of which 2.73 was energy cost, 0.55 was maintenance cost and 3.15 was fixed cost. Total cost was less than two times of which previous study reported by Soponronnarit et al. [1] according to the size reduction process which yielded lower drying time and energy consumption.

5. ACKNOWLEDGMENT

The authors would like to thank the Thailand Research Fund for financial support and Rice Engineering Supply Co. Ltd. for supplying facilities for construction of HPD. The fourth Royal Project-Royal Recommended Project Food Processing Section was also thanked for cooperation during the experiment.

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