Heat Pump Dryers Using HCFC 22 and HFC 134a as Refrigerants

Umphisak Teeboonma, Somchart Soponronnarit, Jirawan Tiasuwan, Warunee Tia, and Warraboon Kaewassadorn
School of Energy and Materials
King Mongkut's University of Technology Thonburi
Suksawat 48 Rd., Bangkok 10140
THAILAND

ABSTRACT

The performance of heat pump dryers using single circuit of HCFC 22 refrigerant and double circuits of HFC 134a refrigerant were investigated. Evaporating temperatures range from 0-20°C and condensing temperatures from 45-60°C were considered as operating conditions in the theoretical analysis. The theoretical results showed that the heating effect, pressure ratio, and coefficient of performance of heat pump using HFC 134a refrigerant are close to those of heat pump using HCFC 22 refrigerant when the evaporating temperature is increased or the condensing temperature is decreased. In the experiments, bean sprout and bananas were dried by using both heat pump dryers. To maintain the physical properties of the products, the drying air temperature should be controlled. The heat pump dryer using double circuits of HFC 134a refrigerant showed a good potential to reduce input energy especially during the period when drying air temperature is higher than a setting point.

1. INTRODUCTION

Agricultural products are generally dried by using conventional hot air dryers. The conventional hot air drying typically uses high drying air temperature, causing low product quality. Moreover, the humid air of the conventional hot air drying is vented to atmosphere which results in the loss of both sensible and latent heat. The heat pump dryer offers many advantages when compared to conventional hot air dryers, such as high product quality, environmentally friendly, and energy efficiency. Heat pump drying can use low drying air temperature due to the dehumidification effect at the evaporator, providing high product quality. It is energy efficient because both sensible heat and latent heat of air leaving the drying chamber are recovered.

In previous research studies, the authors found that the qualities of agricultural products dried by heat pumps were better, in terms of color and smell, than the qualities of those dried by conventional hot air dryers [1]. Meyer and Greyvenstein [2] studied the economics of using a heat pump, an electric heater and a fuel burner to dry grain. The authors found that the heat pump dryer was more economical than the other systems. However, its initial cost was higher than the other two systems. Fluidized bed using a heat pump was studied by Strommen [3]. The working fluid used in heat pump was HCFC 22. Shrimp and fish were selected as test materials. The author found that the product quality, in terms of mass and color, was slightly changed and the energy consumption of fluidized bed using a heat pump was lower as compared with other dryers. Prasertsan and Sean-saby [4] studied heat pump drying of agricultural products compared with conventional dryers. The authors concluded that the heat pump dryer required the lowest operating cost but the highest initial cost. Continuous drying of rubber by using heat pump with CFC 12 as working fluid was studied by Clement, et al. [5]. They found that the condition giving maximum specific moisture extraction rate did not correspond to the condition for maximum coefficient of performance of heat pump. The authors suggested that evaporator bypass air ratio of 60-70% and air mass flow rate of 0.63 kg/s should be used. Achariyaviriya, et al.[6] developed a mathematical model of heat pump dryer using HCFC 22 as working fluid. The authors recommended that the specific air mass flow rate of 10.3 kg-dry air/h-kg dry papaya and the evaporator bypass air ratio of 85% was the best condition.

The working fluids used in heat pump should be non-flammable, non-toxic, with zero ozone depletion potential (ODP) and low or zero global warming potential (GWP). They should operate at suitable condensing and evaporating pressures. Furthermore, the critical temperature should be above the operating temperature. The ODP and GWP of HCFC 22 are 0.05 and 0.35, respectively, with respect to CFC11 [7], whereas HFC 134a has zero ozone depletion potential and low global warming potential when compared to HCFC 22. For this reason, HFC 134a is now widely used in commercial refrigerators.

The objectives of this work were to compare the theoretical performance of heat pump using HFC 134a and HCFC 22 as a refrigerant and to evaluate the experimental performance of heat pump dryer using double circuits of HFC 134a refrigerant and single circuit of HCFC 22 refrigerant. In the experiments, bananas and bean sprout were chosen as test materials. The double circuits of HFC 134a refrigerant were compulsory because the size of the compressor available in domestic market was small.

2. MATERIALS AND METHODS

In the theoretical analysis, temperature range from 0-20°C at the evaporator and from 45-60°C at the condenser were considered as the operating parameters. Figure 1 shows the pressure-enthalpy diagram of vapor compression heat pump cycle, which is based on the following assumptions:

- The refrigerant at outlet of evaporator and condenser are saturated vapor and saturated liquid, respectively.
- The compression and the expansion of the refrigerant vapor are an isentropic and an isenthalpic process, respectively.
- The pressure drop of pipe system is neglected.

The parameters used to study the heat pump system, based on theory, were heating effect (HE), pressure ratio (PR) and theoretical coefficient of performance of heat pump ($COP_{h,th}$). Referring to Fig. 1, the parameters can be calculated by using Eqns. (1), (2), and (3).

$$HE = h_2 - h_3 \tag{1}$$

$$PR = P_{co}/P_{ev} \tag{2}$$

$$COP_{h,th} = (h_2 - h_3)/(h_2 - h_1) \tag{3}$$

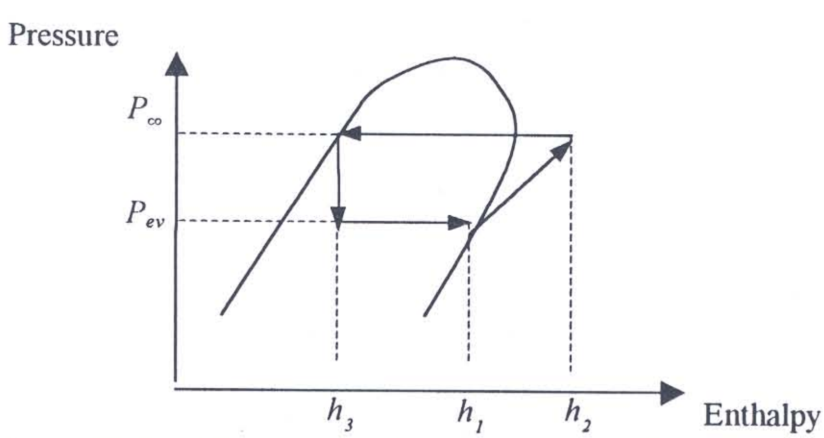

Fig. 1. Pressure-enthalpy diagram of vapor compression heat pump cycle.

Where, h_1, h_2 and h_3 are the enthalpy of refrigerant at compressor inlet, compressor outlet or condenser inlet and condenser outlet, respectively. P_{co} is the saturated pressure at condensing temperature and P_{ev} is the saturated pressure at evaporating temperature.

The criteria for evaluating the experimental performance of heat pump dryers were drying rate (DR), specific moisture extraction rate (SMER), and experimental coefficient of performance of heat pump ($COP_{h,exp}$).

In the experiments, the refrigerant temperatures at evaporator and condenser, compressor power (P_{comp}), and cooling load of evaporator (Q_{ev}) were measured. The average refrigerant temperatures at evaporator and condenser were used for estimating their saturated pressures. Consequently, the vapor compression heat pump cycle as seen in Fig. 1 was depicted on the pressure-enthalpy chart of the refrigerant. The theoretical and experimental coefficient of performance of heat pump can be computed by using Eqs. (3) and (4), respectively.

$$COP_{h,exp} = (P_{comp} + Q_{ev}) / P_{comp} \quad (4)$$

Figure 2 presents the schematic diagram of the heat pump dryer using single circuit of HCFC 22 refrigerant. It comprises of a drying chamber, 1.3 kW reciprocating compressor, 3.7 kW evaporator, a forward-curved-blade centrifugal blower driven by a 0.75 kW motor, 4.6 kW internal condenser and 2.2 kW external condenser. The evaporator bypass air ratio was fixed at 78%.

Figure 3 shows the schematic diagram of the heat pump dryer using double circuits of HFC 134a refrigerant. Each circuit consists of 0.5 kW reciprocating compressor, a forward-curved-blade centrifugal blower driven by a 0.75 kW motor, 1 kW evaporator and 1.8 kW internal condenser. The external condenser of 1.1 kW was installed in single unit. The evaporator bypass air ratio was fixed at 52%.

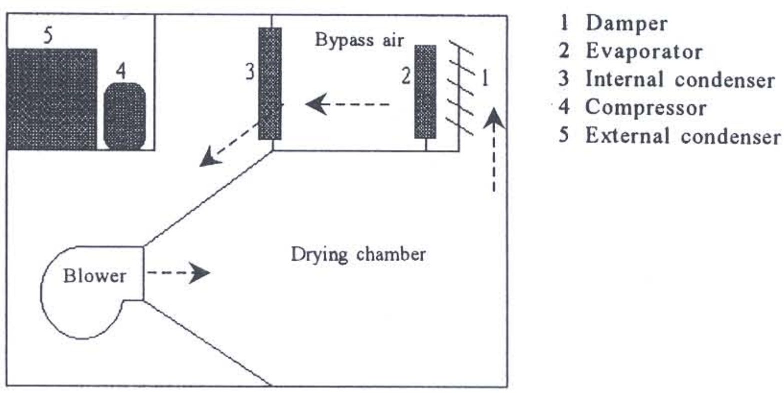

Fig. 2. The schematic diagram of the single-circuit system using HCFC 22 refrigerant.

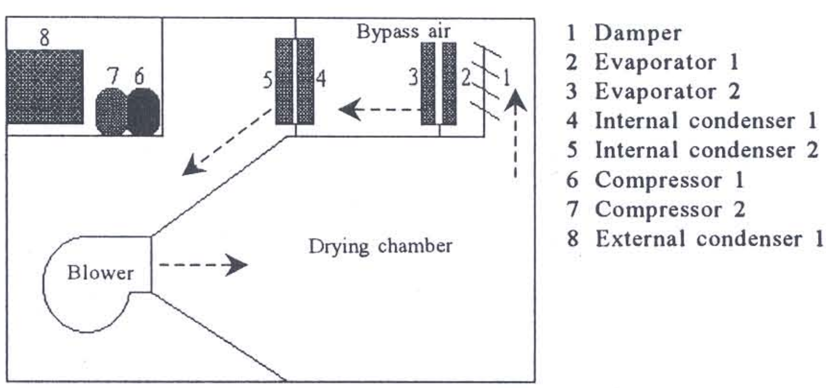

Fig. 3. The schematic diagram of the double-circuit system using HFC 134a refrigerant.

The heat pump dryers operated with closed-loop system. The maximum drying air temperature and air flow rate were fixed at 55°C and 0.54 m^3/s, respectively, for all experiments. There were mechanisms of each system to control the drying air temperature when it would rise beyond the setting point. For the double-circuit system using HFC 134a refrigerant, the excess heat was rejected at the external condenser of an active circuit while another circuit was switched off to reduce input energy in terms of the compressor work. While for the single-circuit system using HFC 22 refrigerant, the solenoid valve was opened to bypass the refrigerant so as to reject excess heat at the external condenser when the drying air temperature would rise beyond the setting temperature.

In the experiments, bean sprout and bananas were selected as drying products. The moisture content of the products was determined by the air oven method at 103°C for 72 hours. Both weight of materials and water condensation were measured by a balance with an accuracy of ±0.01 gram. The temperatures of the drying air and the refrigerant at various points in the system were measured by type-K thermocouples, which were connected to a data logger with an accuracy of ±1°C. Air velocity was also measured by using a hot wire anemometer with an accuracy of ±4%. In addition, electrical energy consumption of compressor and blower were measured by both kilowatt-hour meter and a clamp-on meter with an accuracy of ±0.5%. Finally, the refrigerant pressures at inlet and outlet of heat pump components were monitored by using the bourdon gages.

For economic analysis in this study, it was assumed that the lifetime was 5 years, salvage value at the end of the lifetime was 10% of capital cost, interest rate was 8%, maintenance cost was 5% of capital cost, and electricity price was Baht 3 per unit (US$ 1 = Baht 43). The number of batches per year of bean sprout and banana drying were 336 and 96 batches, respectively. The capital cost of heat pump dryers using double circuits of HFC 314a refrigerant and single circuit of HCFC 22 refrigerant were Baht 69,000 and Baht 64,800, respectively.

3. RESULTS AND DISCUSSIONS

In the theoretical analysis, the heating effect, pressure ratio and coefficient of performance of heat pump are discussed. In order to investigate the performance of the systems, bean sprout and bananas are dried by using both heat pump dryers. The experimental results are summarized in Tables 1 and 2.

3.1. Theoretical Results

Based on the same conditions, $COP_{h,th}$ (Fig. 4) and heating effect of heat pump using HCFC 22 are approximately 1% and 8% higher than that using HFC 134a while the pressure ratio of heat pump using HFC 134a is about 7% higher. It was also found that the heating effect, pressure ratio, and coefficient of performance of heat pump using HFC 134a are close to those of heat pump using HCFC 22 when the evaporating temperature is increased or the condensing temperature is decreased.

3.2 Experimental Results

The experimental results are summarized in Tables 1 and 2. The temperature gradient along the horizontal direction of the drying chamber decreases with drying time. The variations of air temperature and the air velocity along the vertical direction of drying chamber are relatively small. Consequently, the average moisture gradient throughout the drying chamber is also relatively small.

Energy is supplied to the system continuously in the form of work of compressor and blower, which causes continuous increment in the drying air temperature of the system because heat pump dryer operates with closed-loop system. To maintain the physical properties of products, the drying air

Table 1 The experimental results of heat pump drying using double circuits of HFC 134a refrigerant.

Description	Bean sprout	Bananas		
		1st	2nd	3rd
Average moisture before drying, % d.b.	1630	251	95	49
Average moisture after drying, % d.b.	24	92.5	47.0	28.7
Initial weight, kg	30	72.7	40.2	30.6
Final weight, kg	2.15	40.00	30.50	26.20
Average drying temperature, °C	47	52	54	54
Average compressor work, kW	1.13	1.16	0.92	0.70
Average power consumption, kW	1.64	1.80	1.55	1.25
Energy consumption, kWh	18.05	27.07	21.77	16.25
Drying time, h	11	15	14	13
Drying rate$_{avg}$ kg of evaporating-water / h	2.53	2.18	0.69	0.34
SMER$_{avg}$, kg of evaporating-water / kWh	1.52	1.21	0.45	0.27
SEC$_{avg}$, MJ / kg of evaporating-water	2.37	2.98	8.00	13.33
Average condensing temperature, °C	52	56	57	57
Average evaporating temperature, °C	19	20	21	20
Average COP$_{h,th}$	7.0	6.7	6.6	6.0
Average COP$_{h,exp}$	4.4	4.3	4.1	4.1

Table 2 The experimental results of heat pump drying using single circuit of HCFC 22 refrigerant.

Description	Bean sprout	Bananas	
		1st	2nd
Average moisture before drying, % d.b.	1872	287.0	186.0
Average moisture after drying, % d.b.	25.3	133.0	57.8
Initial weight, kg	24.6	98.2	59.5
Final weight, kg	1.61	59.30	39.25
Average drying temperature, °C	45	52	55
Average compressor work, kW	1.22	1.39	1.42
Average power consumption, kW	1.78	1.96	1.97
Energy consumption, kWh	30.26	39.1	69.0
Drying time, h	17	20	35
Drying rate$_{avg}$ kg of evaporating-water / h	1.35	1.95	0.58
SMER$_{avg}$, kg of evaporating-water / kWh	0.76	0.99	0.29
SEC$_{avg}$, MJ / kg of evaporating-water	4.73	3.62	12.41
Average condensing temperature, °C	50	56	57
Average evaporating temperature, °C	14	19	16
Average COP$_{h,th}$	6.8	6.1	5.6
Average COP$_{h,exp}$	4.67	4.5	4.3

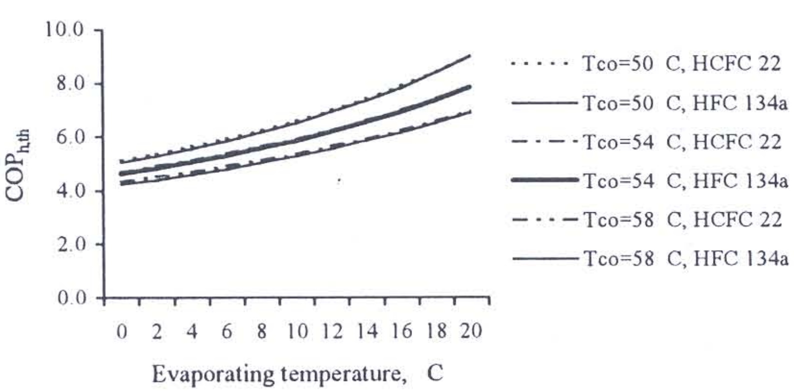

Fig. 4. The relationship between the coefficient of performance of heat pump and the evaporating temperature of working fluids at various condensing temperatures.

temperature must be controlled. Therefore, the excess heat is rejected at the external condenser when the drying air temperature would rise beyond the setting point.

For heat pump dryer using double circuits of HFC 134a refrigerant, the drying air temperature is controlled by switching off one circuit of refrigerant, which is without the external condenser, and rejects the excess heat at the external condenser of the other circuit. As a result of this, half of the compressor work is reduced because one compressor is switched off from the system. Thus, energy and waste heat can be saved. However, this system requires high initial cost.

For heat pump dryer using a single circuit of HCFC 22 refrigerant, there is only one compressor used. To control the drying air temperature, the excess heat is rejected at the external condenser while the input power of compressor is slightly varied. The operating (energy) cost of heat pump dryer therefore remains nearly constant. This is a disadvantage of the dryer using single circuit of working fluid because there is no energy saving. However, this system requires low initial cost compared to the system using double circuits of refrigerant.

The test results of the system using double circuits of HFC 134a refrigerant, as presented in Table 1, show that the first stage of banana drying has the highest energy consumption whereas the third stage of banana drying has the lowest energy consumption. The reduction of energy consumption can be explained by the fact that the initial moisture content of bananas at the first stage is high, thus the system switches on both compressors all the drying time. The moisture content of bananas at the third stage is the lowest, therefore the drying air temperature is increased to the setting point more rapidly than at other stages. Consequently, the system operates single unit at this stage and less energy is needed. Although the drying time of each stage is slightly varied, the energy consumption is significantly reduced. However, the specific energy consumption of the first stage of banana drying is the lowest. This is due to the decrease of moisture content of bananas with time. Therefore, the quantity of moisture removed or drying rate at the next stages is lower than the previous stages. For bean sprout drying, heat pump dryer yields better performance as compared to banana drying. It provides higher drying rate and lower specific energy consumption. This is due to the fact that bean sprout has much higher initial moisture content.

The test results of the system using single circuit of HCFC 22 refrigerant, as presented in Table 2, show that the input power of compressor is nearly constant throughout the drying time; hence, the energy consumption of the system is not reduced. As a result of this, the average power consumption of this system is relatively constant in all stages. Similar to the results obtained from the system using double circuits of HFC 134a, the specific energy consumption of the first stage of banana drying is lower than that of the second stage. For bean sprout drying, the specific energy consumption is slightly higher as compared to the first stage of banana drying.

It should be noted that the effect of pressure drop and the efficiency of compressor are neglected in the theoretical analysis, thereby, the experimental coefficient of performance of heat pump is lower than that obtained by theoretical analysis.

3.3 Cost Evaluation Results

The results of cost evaluation of heat pump dryers using double circuits of HFC 134a refrigerant

Table 3 The Cost Evaluation Results of Heat Pump Drying

Description	Heat pump dryer using HFC 134a		Heat pump dryer using HCFC 22	
	Bean sprout	Bananas	Bean sprout	Bananas
Electricity use rate, unit/h	1.64	1.55	1.78	1.97
Annual total cost, Baht/kg of evaporating-water	4.03	6.03	5.91	8.74
1. Capital cost	1.72	2.54	1.83	2.67
2. Maintenance cost	0.37	0.54	0.39	0.57
3. Energy cost	1.94	2.95	3.69	5.50

and single circuit of HCFC 22 refrigerant are listed in Table 3. The highest annual cost of both heat pump dryers is the energy cost. The annual energy cost of heat pump dryer using double circuits of HFC 134a refrigerant and single circuit of HCFC 22 refrigerant are approximately 48% and 62% of the annual total cost, respectively.

4. CONCLUSIONS

The theoretical results showed that the heating effect and coefficient of performance of heat pump of system operating on HCFC 22 are 8% and 1%, respectively, which are relatively higher than that operating on HFC 134a. The pressure ratio of the system using HFC 134a is approximately 7% higher than that using HCFC 22. The experimental results showed that the coefficients of performance of heat pump dryer using single circuit of HCFC 22 refrigerant and that using double circuits of HFC 134a refrigerant are in range of 4.3 to 4.67 and 4.1 to 4.4, respectively. In addition, the heat pump dryer using double circuits of refrigerant showed a good potential to save input energy especially during the period when drying air temperature is higher than a setting point.

5. ACKNOWLEDGEMENT

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6. REFERENCES

[1] Soponronnarit, S.; Nathakaranakule, A.; Wetchacama, S.; Swasdisevi, T.; and Rukprang, P. 1998. Fruit drying using heat pump. *RERIC International Energy Journal* 20(1): 39-53.

[2] Meyer, J.P. and Greyventein, G.P. 1992. The drying of grain with heat pump in South Africa: A techno-economic analysis. *International Journal of Energy Research* 14: 397-406.

[3] Strommen, I. 1994. New applications of heat pumps in drying processes. *Drying Technology* 12(4): 889-901.

[4] Prasertsan, S. and Saen-Saby, P. 1998. Heat pump drying of agricultural materials. *International Journal of Energy Research* 12: 235-250.

[5] Clement, S.; Jia, X.; and Jolly, P. 1993. Experimental verification of a heat pump assisted continuous dryer simulation model. *International Journal of Energy Research* 17: 19-28.

[6] Achariyaviriya, S.; Soponronnarit, S.; and Terdyothin, A. 2000. Mathematical model development and simulation of heat pump fruit dryer. *Drying Technology* 18: 479-491.

[7] Sand, J.R.; Vineyard, E.A.; and Nowak, R.J. 1990. Experimental performance of ozone-safe alternative refrigerants. *ASHRAE Transaction* 96: 173-182.