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Performance Enhancement of Heat Pump Dryer using Heat Recovery

Praphanpong Somsila[1], Eakpoom Boonthum[2], Songsupa Pumchumpol[1], Umphisak Teeboonma[1], Apinunt Namkhat[1,*]

[1] Department of Mechanical Engineering, Faculty of Engineering, Ubon Ratchathani University, Ubon Ratchathani Province, 34190, Thailand
[2] Department of Mechanical Engineering, Faculty of Industrial Technology, Pibulsongkram Rajabhat University, Phitsanulok Province, 65000, Thailand

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ABSTRACT

The purpose of this research was to study on performance of a heat pump dryer using R32 refrigerant by recovering waste heat from an external condenser. Drying was carried out with drying temperatures of 45, 50 and 55 °C and water flow rates in the heat exchanger of 2, 3 and 4 L/min. Criteria for evaluating performance of heat pump dryer include: drying rate (DR), specific moisture extraction rate, specific energy consumption (SEC) and coefficient of performance of heat pump (COP_h). The result shown that the performance of a heat pump dryer with heat recovery is higher than that of a traditional heat pump dryer. It was also found that increasing in drying temperature and water flow rate in heat exchanger resulted in an increase in the drying rate, power of the heat pump dryer and the specific moisture extraction rate. Whereas the specific energy consumption had decreased.

1. Introduction

As electricity demand and prices increase around the world, there are serious concerns about the environmental impact and influence of energy policies of countries around the world [1-3]. For example, the problem of global warming causes the loss of the ozone layer and air pollution, PM2.5, etc. In developed countries, it has been found that the drying process is widely used to create economic prosperity, accounting for 9 - 25% of the country's total energy consumption [4-6]. This is considered to be a process that uses a lot of energy, especially in the fields of food and agriculture [7,8]. Nowadays, energy saving technology is very important to the drying industry. A well-known energy saving device is a heat pump, which is a device that can convert the latent heat of the refrigerant into sensible heat in the condenser [9]. Because of its excellent energy efficiency, wide temperature adjustment range, high drying efficiency, excellent controllability and outstanding drying quality [10-13]. Since heat pump drying is a closed drying system, the pollution problems caused by drying exhaust gases are relatively small [14]. In addition, there are such advantages as effective control of relative humidity and good sanitary conditions. Because it is clean and safe from

* *Corresponding author.*
E-mail address: apinunt.n@ubu.ac.th

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contamination of dried products [15,16]. The disadvantages of heat pump dryers are that they have complicated systems and equipment that require experts to install and take good care of the system. The use of heat pump dryers in industry is found to be mainly used in the drying food industry, such as meat, fish, vegetables, and fruits, etc. Comparing the drying process between drying using an electric heater and a heat pump dryer, it was found that the heat pump dryer has relatively less energy consumption. As a result, the cost of producing dried products is kept low as well. Past studies by researchers have found that there have been several ways to improve the performance of heat pump dryers, such as heat recovery using heat exchangers that use the refrigerant R134a [17]. Study of the effect of different temperatures on drying time on coefficient of performance (COP) and specific moisture extraction rate (SMER) [18]. Study of the performance coefficient of a heat pump dryer with an air bypass pipe compared to a system without an air bypass pipe, which can reduce energy consumption but the air temperature at the bypass pipe is lower than 40◦C [19]. Dual drying system design using twin air compressors [20]. In addition, studies have been conducted to reduce energy consumption, such as using R410a refrigerant in heat pump dryers to reduce energy consumption by as much as 51% and reduce drying time by 69% [21]. A study of heat pump drying using refrigerant R744 combined with a new heat exchange system design can reduce energy use by 7.2% [22]. Studying the design of a new closed air flow pipe and using the refrigerant R134a can reduce electrical energy consumption [23]. It was also found that studies on the use of other types of energy were also studied, including studies of heat pumps combined with the use of solar energy [24-27]. Study of the application of fossil energy [28]. Using infrared with a heat pump dryer [29]. In addition, there found that researchers studied the performance of heat pump dryers related to the selection of refrigerants, including a study of the use of refrigerants CO_2 and R134a in heat pump dryers to increase the specific moisture extraction rate and coefficient of performance were 13% and 8%, respectively [30]. Past research studies have found that most heat pump dryers use refrigerants that cause high global warming problems (Global Warming Potential, GWP), such as R22, R134a, R407C and R410a, which have GWP of 1,810, 1,430, 1,774 and 2,090, respectively [31-34]. From related research, it was found that most heat pump dryers have a method of controlling the temperature of drying chamber by using an external condenser, which wastes heat mostly into the atmosphere. It would be beneficial to use this waste heat to increase the temperature of the drying chamber. Therefore, this research aims to study how to increase the performance of a heat pump dryer using R32 refrigerant by increasing the temperature of the drying room by using heat recovery techniques to increase the temperature of the drying room because of heat recovery can be used to reduce energy consumption in drying. and increase drying efficiency with a heat pump dryer. and compare the performance of heat pump dryers with and without heat recovery.

2. Methodology

2.1 Experiment Setup

The heat pump dryer used in the experiment can be shown as shown in Figure 1 and a diagram showing the equipment and working cycle of the heat pump dryer system is shown in Figure 2, which can explain the components and working principles as follows.

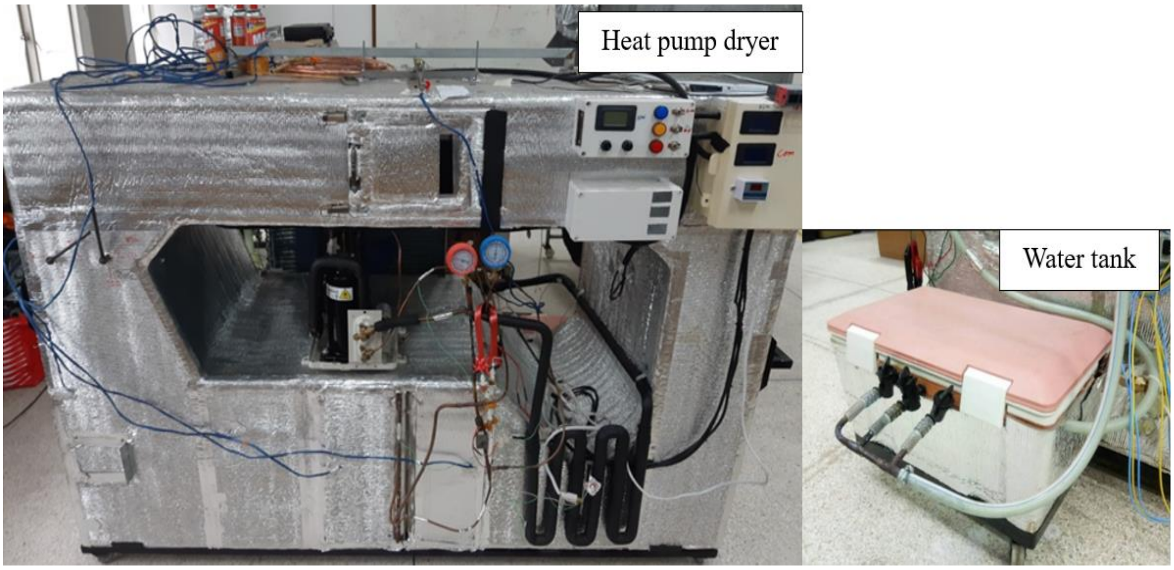

Fig. 1. Heat pump dryer

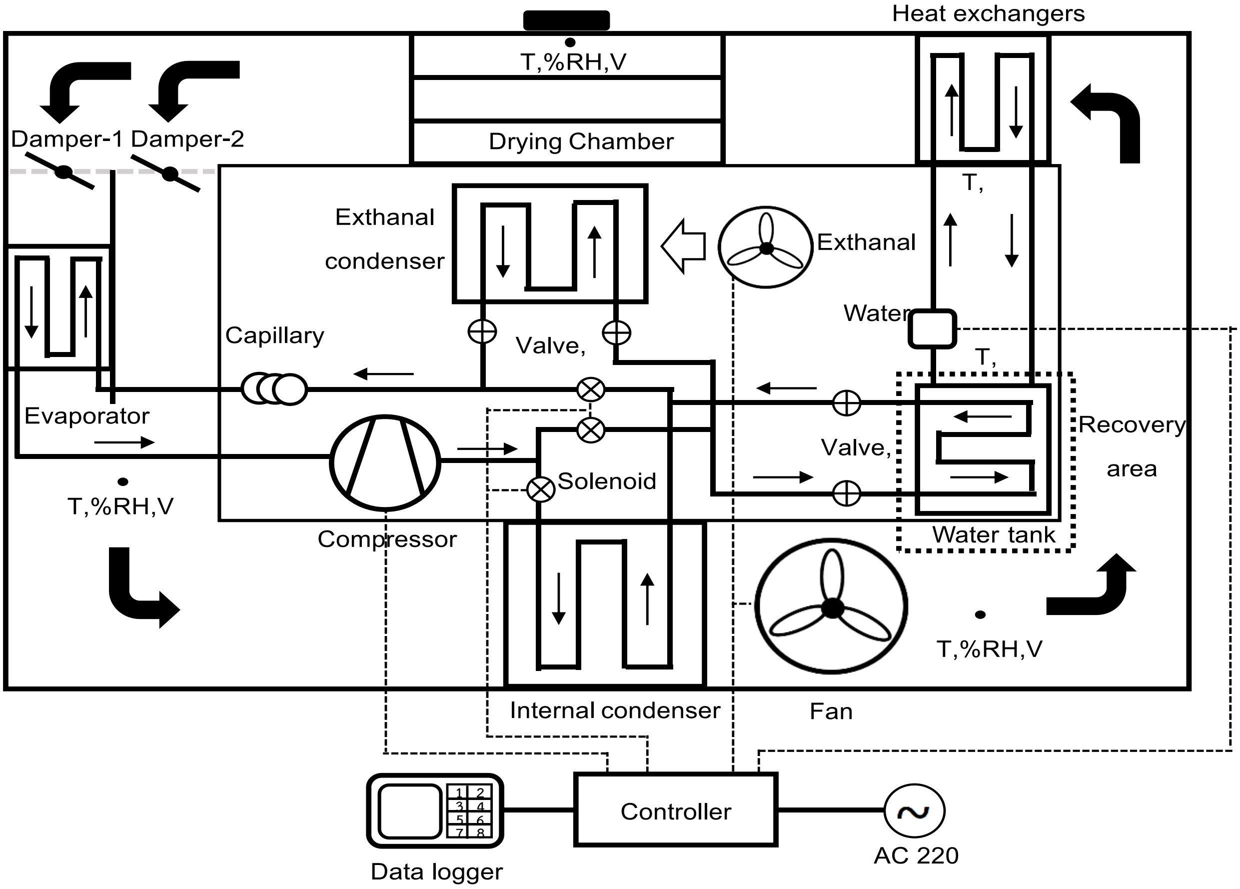

Fig. 2. Schematic diagram of heat pump dryer and instruments

The heat pump dryer used in this study for experiments under normal drying conditions consists of a 0.75 kW compressor, a 4.35 kW internal condenser, a 4.35 kW external condenser, an expansion device, a 3.50 kW evaporator, air circulation fan, drying chamber size 35 x 70 x 30 cm and maximum capacity of drying chamber 15 kg**.** For the experimental conditions, various equipment was added, consisting of a water tank measuring 30 x 58 x 36cm, first heat exchanger made of pipe with a diameter of 3.14 cm and a length of 335 cm contained within the water tank and second heat exchanger, sizing of 28 cm width and 79 cm height. It was made from pipe with 2.10 cm diameter and 890 cm length, placed at the entrance of drying chamber. The installation of the instrumentation and control equipment is shown in Figure 2.

2.2 Experimental Method

The R32 refrigerant was used for heat pump dryer. The first case, heat pump dryer operated as traditional. The experiment was conducted under the drying temperature of 45, 50 and 55°C, drying chamber air velocity of 1, 1.5 and 2 m/s. The second case, heat pump dryer operated by recovering heat. The experiment was conducted under the drying temperature of 45, 50, and 55 °C and water flow rate in the heat exchanger of 2, 3 and 4 L/m, respectively. Pork was selected for drying product. Pork was cut lengthwise to a thickness of approximately 0.1 cm, a length of approximately 12 cm, and initial weight of 1,000 grams a batch with average initial moisture content of 275% d.b. which is then dried until the final moisture remains approximately 112% d.b. The moisture determination according to AOAC [35] standard was used.

Various values were measured and recorded during the experiment including drying air temperature, refrigerant temperature, water temperature, refrigerant pressure, product weight changes throughout drying period, electrical power and electrical energy consumption, etc. The quality of the product is not determined, thus in further study this aspect should be considered.

2.3 Analysis

The analysis of the experimental results includes moisture content, drying rate, specific moisture extraction rate and specific energy consumption. The details of the analysis are as follows.

Moisture content, MC, was carried out by preparing some products to dry in an electric oven at 103°C for 72 hours according to AOAC (2019) standard. The equation calculates moisture content at each time period as shown in Eq. (1).

$$MC = \frac{w - d}{d} \tag{1}$$

where MC is a moisture content at each time period (d.b.), w is a wet mass of sample product at each time interval (g), d is a dried mass of sample product (g).

Drying rate, DR, is a variable indicating the value of moisture that can evaporate per unit of time. The relationship is as shown in Eq. (2) [36,37].

$$DR = \frac{\Delta w}{\Delta t} \tag{2}$$

where DR is drying rate (g/min), Δw is water evaporates (g), Δt is time (minutes).

Specific moisture extraction rate, SMER, is the amount of water that evaporates from the product per energy used. The relationship equation can be written as Eq. (3) [38,39].

$$SMER = \frac{w_i - w_f}{E} \tag{3}$$

where SMER is specific moisture extraction rate (kg/kWh), w_i is wet mass before drying (kg), w_f is wet mass after drying (kg), E is electrical energy consumption (kWh).

Specific energy consumption, SEC, is a value that indicates the efficiency of energy consumption. which has a relationship as in Eq. (4) [40,41].

$$SEC = \frac{3.6E}{w_i - w_f} \tag{4}$$

where SEC is specific energy consumption (MJ/kg), w_i is wet mass before drying (kg), w_f is wet mass after drying (kg), E is electrical energy consumption (kWh).

The coefficient of performance of heat pump, COP_h, is defined as the ratio of the heat transfer rate at the internal condenser to the electrical energy used by the compressor, as in Eq. (5) [42].

$$COP_h = \frac{Q_c}{P_c} \tag{5}$$

where COP_h is coefficient of performance of heat pump (decimal), Q_c is a heat rate at condenser (kW), P_c is power of compressor (kW).

3. Results

Figure 3 and Figure 4 show the moisture ratio of the product in the case of experiments under traditional heat pump dryer conditions and heat recovery conditions, respectively. It was found that the product moisture decreased rapidly during the first 35 minutes for the case of normal drying and the first 25 minutes for the case of heat recovery. Thereafter the product moisture will have a slower rate of decrease and similarly the product temperature will increase with increasing drying time. It was found that an increase in the drying temperature, hot air velocity and water flow rate in the heat exchanger would result in a decrease in the drying time. It was also found that in the case of increasing the drying temperature and water flow rate resulting in increased heat transfer, the amount of moisture evaporation from the product increases [18,24]. Similarly, in the case of increasing hot air velocity, resulting in an increase in the convection coefficient, which results in an increase in heat transfer as well, resulting in a reduction in the drying time. Comparing the moisture ratio, it was found that the drying time of heat recovery conditions are higher than the traditional heat pump dryer condition in all experimental conditions, with an average of 13.89 minutes or 12.64%. The minimum drying time at 85 minutes occurred under the condition of drying temperature at 55°C and water flow rate 4 L/min and maximum drying time at 120 minutes occurs in drying temperature at 45°C and hot air velocity 1 m/s.

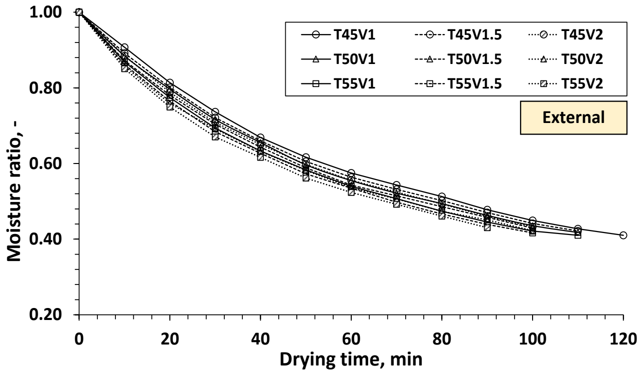

Fig. 3. Moisture ratio in the case of experiment under traditional heat pump dryer conditions in each experimental condition

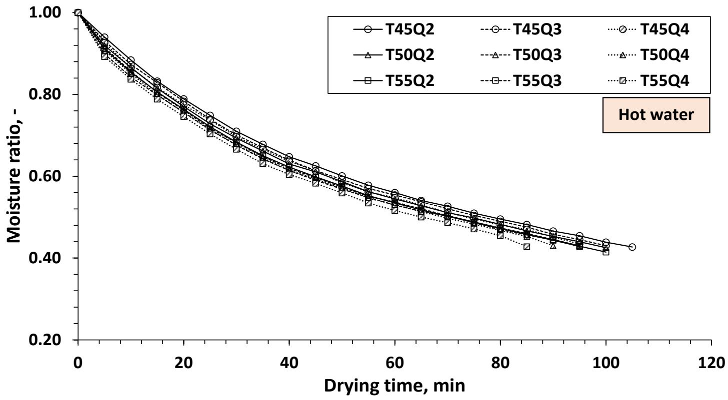

Fig. 4. Moisture ratio in the case of the heat recovery in each experimental condition

Figure 5 shows the drying rate of the product under each experimental condition. It was found that the drying rate in the case of heat recovery was higher than in the case of traditional heat pump dryer condition in all experimental conditions about 6.10g/h or 4.40% of all experimental conditions. It was also found that the highest drying rate occurred in the drying temperature of 55°C and the water flow rate of 4 L/min was 2.63 g/min, and the lowest drying rate of 2.14 g/min occurred in the drying temperature of 45°C and the hot air velocity of 1 m/s. This could be explained with the same reasons as Figure 3 and Figure 4. The use of waste heat results in an increase in the temperature of the hot air and the temperature of the product, causing more heat transfer rate and increasing moisture evaporated from product [15,40]. It causes the drying rate increased.

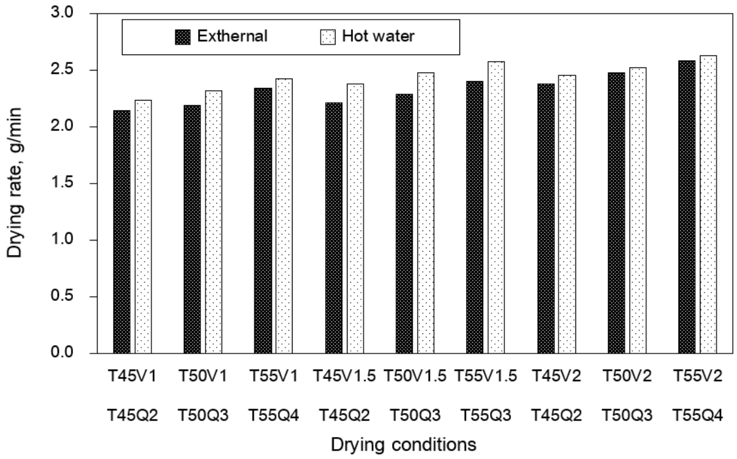

Fig. 5. The drying rate in each experimental condition

Figure 6 shows the power of the heat pump dryer at each experimental condition. It was found that the power of the heat pump dryer in case of traditional heat pump dryer condition and heat recovery conditions was similar in all experimental conditions. It was found that there was an average difference in electrical power about 0.011kW or 0.907% of the case of traditional heat pump dryer condition. It was also found that when increasing the drying temperature by 10%, the power of the heat pump dryer in both conditions increased by 2.90% and 3.10%, respectively. Similarly, if the drying temperature is kept constant in the case of traditional heat pump dryer condition, increasing the flow rate by 50% will increase the heat pump dryer power by an average of 3.44%. In the case of heat recovery drying, increasing the hot air velocity by 50% increases the heat pump dryer power by an average of 3.26%. It was also found that the effect of drying temperature has a greater effect on the power of heat pump dryer than water flow rate and hot air velocity. It could be seen that the power of heat pump dryer increased with increasing the drying temperature, water flow rate and air velocity. This could be explained that increasing the drying temperature would cause the vapor compressor more work to produce a sufficiently high pressure in the refrigerant at desired drying temperature. This process results in an increase in the heat load on the evaporator. As a result, the power of the heat pump dryer increased.

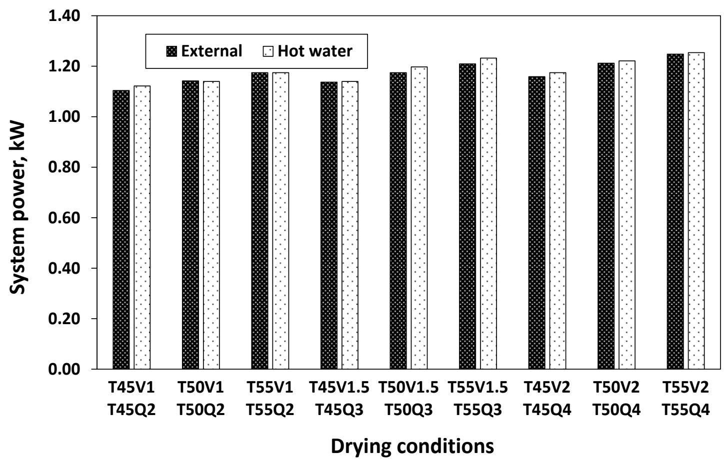

Fig. 6. Electrical power of the heat pump dryer at each experimental condition

Figure 7 shows the specific water withdrawal rate at each experimental condition. This value indicates the efficiency of energy use in the drying process with a heat pump dryer. If the specific moisture extraction rate increases, it means that the drying process with this heat pump dryer has a high level of energy efficiency. It was found that the highest specific moisture extraction rate occurred in the heat recovery drying case of 0.108 kg/kWh under the condition of a drying temperature of 55°C and a water flow rate of 4 L/min. If considering only the power consumption, it would be found that in this condition the heat pump dryer uses the highest power. However, at this condition the drying time is shortest. Considering under the condition that the water evaporates from the product is the same, the condition with a short drying time has a high specific moisture extraction rate and this value is inversely proportional to the specific energy consumption as shown in Figure 8 [15,38]. In addition, it was found that the specific moisture extraction rate in the case of normal drying was between 0.081–0.097 kg/kWh and in the case of heat recovery the value was between 0.091–0.108 kg/kWh. It was found that in all experimental conditions in the case of heat recovery the specific moisture extraction rate was higher than in the case of normal drying.

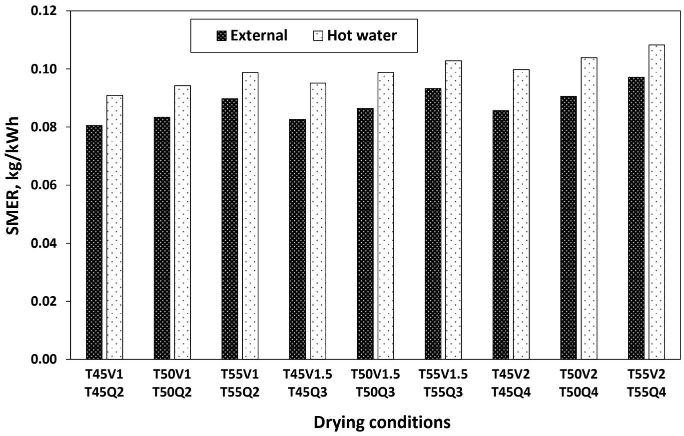

Fig. 7. Specific moisture extraction rates at each experimental condition

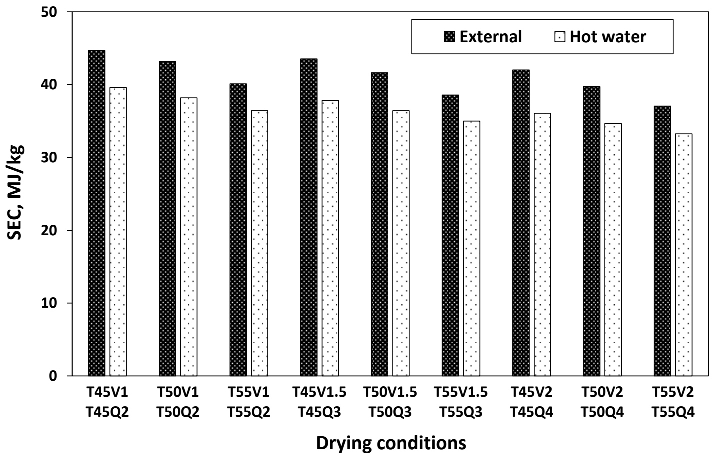

Fig. 8. Specific energy consumption at each experimental condition

Figure 9 shows the coefficient of performance of heat pump in each experimental condition. It was found that the coefficient of performance of heat pump in each experimental condition had very little difference, with an average between 4.34 - 4.42 [17,23,41]. In other words, the difference in the coefficient of performance of heat pump in each experimental condition did not exceed 0.02. As a result, the coefficients of heat pumps in each experimental condition were not significantly different. Therefore, it could be said that the drying temperature, water flow rate and hot air velocity have very little effect on coefficient of performance.

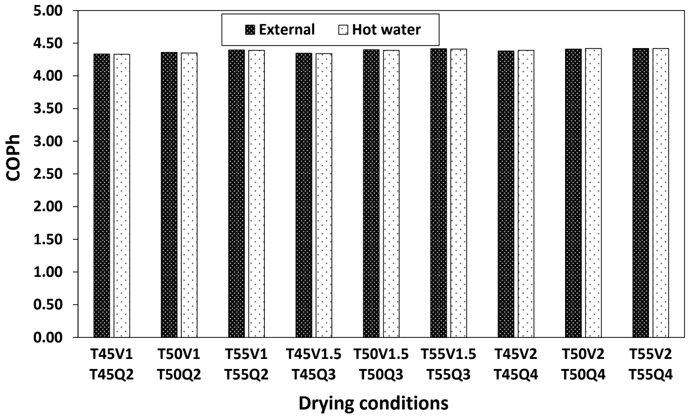

Fig. 9. Heat pump coefficient of performance in each experimental condition

Table 1 and Table 2 show an overview of performance analysis of heat pump dryer in case of traditional heat pump dryer condition and recovery heat conditions, respectively. The summary data is an average from the beginning until the end of the experiment. It was found that, in case of traditional heat pump dryer condition, drying temperature of 55°C and an air velocity of 2 m/s had a drying rate of 153.64 g/h, a specific moisture extraction rate of 0.097 kg/kWh and the highest coefficient of performance was 4.42. this condition gives the lowest specific energy consumption. It was found that, in case of recovery heat conditions, at temperature of 55°C and a water flow rate of 4 L/min, the drying rate was 159.57 g/h, the specific moisture extraction rate was 0.108 kg/kWh, and the highest heat pump coefficient of performance was 4.42. In addition, it is a condition that gives the lowest specific energy consumption. When comparing the overall data of analysing the performance of heat pump dryers in in case of traditional heat pump dryer condition with recovery heat conditions, it was found that in the heat recovery conditions would have higher heat pump performance than in the case of traditional heat pump dryer condition. That is, the drying rate, specific moisture extraction rate and coefficient of performance of heat pump are greater. Including the specific energy consumption is lower as well.

Table 1
Analysis of experimental results in the case of normal drying

Description	Conditions								
	T45 V1	T45 V1.5	T45 V2	T50 V1	T50 V1.5	T50 V2	T55 V1	T55 V1.5	T55 V2
Initial weight, g	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
Initial moisture content, %d.b.	275	275	275	275	275	275	275	275	275
Final moisture content, %d.b.	112	112	112	112	112	112	112	112	112
Drying time, h	1.95	1.90	1.78	1.88	1.82	1.73	1.75	1.68	1.62
Drying rate, g/min	2.14	2.19	2.34	2.21	2.29	2.40	2.38	2.48	2.58
Electrical energy, kWh	3.10	3.02	2.92	3.00	2.89	2.76	2.79	2.68	2.57
Specific moisture extraction rate, kg/kWh	0.081	0.083	0.090	0.083	0.086	0.093	0.086	0.091	0.097
Specific energy consumption, MJ/kg	44.70	43.55	42.02	43.17	41.64	39.73	40.11	38.58	37.06
Heat pump coefficient of performance, COP_h	4.34	4.36	4.40	4.35	4.40	4.42	4.38	4.41	4.42

Table 2
Analysis of experimental results in the case of heat recovery

Description	Conditions								
	T45 Q2	T45 Q3	T45 Q4	T50 Q2	T50 Q3	T50 Q4	T55 Q2	T55 Q3	T55 Q4
Initial weight, g	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
Initial moisture content, %d.b.	275	275	275	275	275	275	275	275	275
Final moisture content, %d.b.	112	112	112	112	112	112	112	112	112
Drying time, h	1.87	1.80	1.72	1.78	1.72	1.65	1.70	1.63	1.57
Drying rate, g/min	2.23	2.31	2.43	2.38	2.48	2.58	2.45	2.53	2.63
Electrical energy, kWh	2.75	2.63	2.50	2.65	2.53	2.41	2.53	2.43	2.31
Specific moisture extraction rate, kg/kWh	0.091	0.095	0.100	0.094	0.099	0.104	0.099	0.103	0.108
Specific energy consumption, MJ/kg	39.61	37.84	36.07	38.19	36.42	34.65	36.42	35.01	33.24
Heat pump coefficient of performance, COP_h	4.33	4.35	4.39	4.34	4.39	4.41	4.39	4.42	4.42

4. Conclusions

This research studied the performance of a heat pump dryer using heat recovery from external condenser to increase drying air temperature. To compare the performance of heat pump dryer in the case of in case of traditional heat pump dryer condition and heat recovery conditions. The results of the study found that an increase in the drying temperature and water flow rate in the heat exchanger in the case of heat recovery conditions will affect the drying rate, power of heat pump dryer and specific moisture extraction rate to be increased. Meanwhile, the specific energy consumption decreased more than in the case of traditional heat pump dryer condition. It was also found that an increase in the drying temperature, water flow rate in the heat exchanger and hot air velocity had a little effect to the coefficient of performance of the heat pump dryer.

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