Effectiveness of a heat exchanger in a heat pump clothes dryer

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Abstract. This paper deals with study on a heat pump clothes dryer coupled with a heat exchanger. The objective is to explore the effects of the heat exchanger on the performance of the heat pump dryer. The heat pump dryer consists of a vapor compression cycle and integrated with a drying room with volume 1 m\textsuperscript{3}. The power of compressor is 800 Watt and the refrigerant of the cycle is R22. The heat exchanger is a flat plate type with dimensions of 400 mm \times 400 mm \times 400 mm. The results show the present of the heat exchanger increase the performance of the heat pump dryer. In the present experiment the COP, TP and SMER increase 15.11\%, 4.81\% and 58.62\%, respectively. This is because the heat exchanger provides a better drying condition in the drying room with higher temperature and lower relative humidity in comparison with heat pump dryer without heat exchanger. The effectiveness of the heat exchanger is also high, it is above 50\%. It is suggested to install a heat exchanger in a heat pump dryer.

1. Introduction
Drying is a process to reduce moisture content by evaporating and uses amount of energy to overcome the latent heat evaporation. The drying process are used in several applications such as industrial drying, agricultural product drying, manufacturing drying and clothes drying. One of the biggest drying applications is clothes drier. This application consumes big amount of energy by using several energy sources such as fossil fuel and electricity. Meyers et al. [1] and Yadav and Moon [2] reported that in the USA 71 Terawatt hours (TWh) of electricity per year electricity is consumed for drying clothes. This energy is up to 9\% of electricity consumption in the USA. To the best knowledge of the authors, there is no report on energy consumption of electricity for drying clothes in Indonesia. However, based on survey there is an increasing number of commercial laundry in big cities in Indonesia. These laundries use commercial drying instead of typical natural drying. Several types of clothes drier are found in literature and tumbler rotating drum and flowed by hot air of 40-60\textdegree C is the most used system [3].

One of the most promising artificial clothes drier is vapor compression heat pump drier. Here, the heat from the condenser of vapor compression cycle is used as a heat source for drying process. Minea [4] reported the review on the heat pump drier and system integration. It was shown that a lot of unworkable, unnecessarily complicated or doubtful improved drying heat pump concepts have been proposed. The true challenge is first to make heat pump drier and its combination feasible by providing relevant information about integration, schedules, control strategies, operating parameters and energy performance issues. Braun et al [5] has reported their study on energy efficiency analysis of air cycle heat pump dryers. Two types of typical cloth dryers were compared the first type is conventional tumbler dryer using electric heater and the second one is reversed Brayton cycle. Ameen and Bari [6]
investigated the feasibility of drying clothes using waste heat from a condenser from a typical split-type residential Air-Conditioner (AC) typically used in high rise urban apartments. Three drying methods of clothes were compared, they are commercial dryer using 1 kW electric heater, indoor natural drying, and heat pump dryer. The results showed that the drying rate for the three methods commercial dryer, natural dryer, and heat pump dryer were 0.319 kg/hr, 0.139 kg/hr, and 0.424 kg/hr, respectively. The drying time of the tested methods varied from 120 minutes to 390 minutes. They proposed the parameters energy consumption (SEC) rate in kWh/kg and specific moisture extraction rate (SMER) in kg/kWh to compare the performance of the methods. Since this study, SEC and SMER typically used as a performance comparison in heat pump dryer.

Deng and Han [7] carried out an experimental study on clothes dryer using rejected heat from split-type residential AC. An experimental rig has been designed and set up to perform the study. The residential AC with specification of 6.4 kW of cooling capacity was used. It is a typical size of AC for a room of up to 30 m² in Hongkong. In the experiments, the initial weight of clothes dried was about 3 kg. Two drying methods were compared, electrical clothes dryer and their proposed method. The electric consumption and drying time from both methods were compared. The results revealed that there was an additional electric use of residential AC, but it was only 1.2% in comparison with AC without dryer. Mahlia et al [8] studied experimentally clothes dryer using heat wasted from split-type residential AC. They proposed a system which consists of a drying room and a residential AC which is moveable. The experimental data were used to compare the effectiveness of the system proposed with a conventional dryer in terms of drying time and specific energy consumption. It was shown that drying time varied from 70 minutes to 420 minutes. The drying rate varied from 0.56 kg/hr to 0.75 kg/hr with residential AC, on the other hand it was 0.13 kg/hr for indoor drying and 0.18 kg/hr for out-door drying. In addition, SMER varied from 0.1809 kg/kWh to 0.2205 kg/kWh. The residential AC clothes dryer is claimed more efficient way to dry clothes. This system results in shorter drying time and high effectiveness. As a note in their study, the increase power due to additional fan was not taken into account. Suntivararakorn et al [9] studied on a clothes dryer using waste heat from split-type residential AC. The results showed that the drying rate was varied between 1.1 kg/hr to 2.26 kg/hr. Based on these rate, it was claimed that the system has a better performance than commercial and natural dryers. Ambarita et al. [10] studied experimental the performance of a clothes dryer by utilizing waste heat from a split-type residential AC. A drying room with a volume of 1 m³ has been designed and fabricated. The waste heat from the condenser of a residential AC with compressor power of 800 W was utilized as a heat source. The tested clothes were made of pure cotton with initial weight varied 3.05 kg, 5.25 kg, 6.21 kg, 8.22 kg, and 10.22 kg. Two different drying methods, single inlet and multi inlets, have been tested. The experiments showed that the drying time varies from 80 minutes to 410 minutes. The experiments with single inlet the averaged drying time, optimum initial weight, optimum drying rate and optimum SMER were 242 minutes, 6.21 kg, 0.868 kg/hr, and 2.345 kg/kWh, respectively. While with multi inlets, those parameters were 222 minutes, 8.22 kg, 0.922 kg/hr, and 2.492 kg/kWh, respectively.

The above reported studies showed that heat pump dryer can be used for drying with two different methods, pure heat pump system [5] and waste heat system [6-10]. However, studies are still needed to improve the effectiveness and the efficiency. Recently, Ambarita et al. [11] reported their study on the performance and characteristics of heat pump clothes dryer. In the study, a heat exchanger was employed in the system. However, the effect of the installed heat exchanger was not explored. In the present study, the effectiveness of the heat exchanger in a heat pump clothes dryer is investigated. The objective is to explore the effect of the heat exchanger to the heat pump dryer and the effectiveness of the heat exchanger. The results are expected to supply the necessary information in developing an efficient and effective artificial drying.
2. Methods

2.1. Experimental Apparatus
In this study, a lab scale model of heat pump drier with overall dimensions of 3000 mm × 1000 mm × 1800 mm has been designed and fabricated. The main components are the compressor, condenser, expansion valve, evaporator, fan, a flat plate heat exchanger, and drying chamber. The drying room has a volume of 1 m³ with dimensions of 1400 mm × 1000 mm × 1080 mm. The heat pump is a modified split-type of residential AC with commercial made by Samsung and the model is AS09TUQX. The specifications of residential AC are shown in Table 1. The power of the fan is 105 W. The heat exchanger is a flat plate type with dimensions of 400 mm × 400 mm × 400 mm. It is made of zinc plate with a thickness of 0.35 mm, the distance between the flat plates is 4 mm, and the number of gap is 92.

Table 1. Specification of heat pump

| Parameter                                      | Value                   |
|------------------------------------------------|-------------------------|
| Compressor Power (Averaged)                    | 800 W                   |
| Cycle                                          | Vapor Compression Cycle (VCC) |
| Input Voltage/Frequency                        | 220 -240 V/50 Hz        |
| Electric Current (Maximum)                     | 4.7 Ampere              |
| Dimension of the Condenser                     | 660 mm × 470 mm × 240 mm |
| Dimension of the Evaporator                    | 820 mm × 283 mm × 210 mm |

Figure 1. Experimental apparatus and data acquisition unit.
In order to perform the experiment, a data acquisition unit is installed on the experimental apparatus. The temperature and the humidity of the drying air are measured using a Portable Thermohygrometer with accuracy 1.0°C and 5.0% RH. The temperature and humidity are measured at five locations. They are located in the drying room, at the inlet of the heat exchanger, at the evaporator entrance, at the exit of the evaporator, and at the heat exchanger exit. The velocity of the drying air is measured using a DT-8880 Hot wire anemometer. The specification of the anemometer are as follows, speed range and accuracy are 0.3 to 30 m/s and ± 3%, respectively. The weight history of the clothes dried is recorded using S-type Load cell with an accuracy of 1.0 gram. The load cell is placed on the top of the drying room. The pressure of the refrigerant is measured using a pressure gauge at three positions, at the compressor suction line, discharge line and the line after condenser. The schematic diagram of the experimental and the data acquisition unit are shown in Figure 1. In the figure, the photograph of the heat exchanger is shown.

Drying air flows into the drying room at point 1 and absorbs moisture from clothes. The air that contains high moisture content at point 2 is then directed past the heat exchanger (2 to 3) and then across the evaporator coil (3 to 4). Heat exchanger works as a heat recovery to air at 4 to 5 points. During the dehumidification process (the humidity) from point 3 to point 4, the first time the air conditioning cooled the sensible until the dew point (dew point). The cooling process will produce condensation of water vapor contained in the air dryer. Latent heat of evaporation of water is then absorbed by the evaporator to boil the refrigerant. Heat is recovered will be pumped to the condenser. The air cooled and lowered the humidity will absorb the heat that is released condenser from point 5 to point 1 as heating sensible to raise the temperature of the drying air.

2.2. Performance Parameters

During the experiments, the temperatures history, weights history, and air velocity in the drying room will be measured and recorded by the data acquisition system. In the vapor compression cycle, the voltage, electric current, and the pressure of refrigeration line will be measured. These measured data will be used to analyse the performance parameters. The performance parameters that used in the present study are explained as follows.

The first drying performance is specific moisture extraction rate (SMER). This parameter is defined as the ratio of moisture removed from the clothes to energy consumption by the system. In the present system, the energy consumption for removing the moist from the clothes consists of heat released from the condenser and the energy rate to run the auxiliary fan ($W_f$). Since the heat released from the condenser is the heat of vapor compression cycle as a byproduct of the system, the input power of compressor ($W_c$) will be used to calculate the SMER [10]. Thus, SMER [kg/kWh] is given by the following equation:

$$\text{SMER} = \frac{\dot{m}_d}{W_c + W_f}$$  \hspace{1cm} (1)

Where $\dot{m}_d$ [kg/hr] is the drying rate of the clothes dried and it is calculated by the following equation:

$$\dot{m}_d = \frac{m_o - m_d}{\Delta t}$$  \hspace{1cm} (2)

where $m_o$, $m_d$ and $\Delta t$ are the mass of the clothes at initial time (wet) and when it is dry and drying time, respectively. In the analysis, non-dimensional (MR) weigh of the clothes is used. It is modeled using the below equation.

$$MR = \frac{m - m_d}{m_o - m_d}$$  \hspace{1cm} (3)

Heat pump dryer performance expressed in total achievement (TP), which is calculated by the below equation:
The effectiveness of the heat exchanger is defined as the ratio of the actual heat transfer rate to the possible maximum heat transfer rate.

\[ e = \frac{\dot{Q}}{\dot{Q}_{\text{max}}} \]

As a note, the present heat exchanger is categorized a flat plate and cross flow type heat exchanger where the hot and cold fluids are unmixed. To the best knowledge of the author there is no empirical correlation of effectiveness can be found in the literature. Thus, the experimental measurement will be used to make the analysis.

The experimental method is explained in brief as follows. In the beginning the heat pump drier will be operated without any drying load or empty drying room for 30 minutes. This is known as idle operation time. After the idle operation time, the wet clothes which are pre-dried using washing machine are loaded to the drying room. The wet clothes are hanging inside the drying room using typical clothes hanger. The experiment is then started, and all of the temperatures, weight, current, and hot air velocity were measured and recorded using the data acquisition unit. In this study, the dryer load is the clothes made of pure cotton with initial weight of 245 gr.

3. Results and Discussions

The experiments have been carried out for the case heat pump drier without heat exchanger and the case where the heat pump drier with heat exchanger. The results will be discussed in the following sections.

3.1. Temperature history

Figure 2 shows the temperature history in the drying room and at several drying air lines. The temperature history only shown during the drying time only, it is about 20 minutes. The annotations refer to the positions as shown in figure 1. For instance, T1 shows temperature in the drying room and T2 shows temperature of the drying air leaving the drying room and entering the heat exchanger as a hot fluid. As expected, the figure shows that temperature in the drying room is higher than in all lines. The function of the system is to make temperature in the drying room is high and has low humidity. This condition is a perfect drying force for drying clothes. In the drying room, the moist is evaporated into vapor and it needs amount of heat to overcome the heat evaporation of water. The heat evaporation is provided by hot drying air. In other word, the temperature of the drying air when it is leaving the drying chamber will decrease. In the figure, temperature of the drying air leaving the drying room, named as T2, is lower than temperature in the drying room. This temperature difference provide energy to the drying process. In the figure, it can be seen clearly the temperature difference increase with increasing time. The reason for this is that at a high temperature, the heat loss to the surrounding increasing. Temperature of the drying air leaving the heat exchanger (shown by T3) is lower than T2. This because temperature of the cold fluid entering the heat exchanger (T4) cools the hot air. The trend
of the temperature of the hot drying air leaving the heat exchanger and cold air entering the heat exchanger is similar. This fact reveals that the heat pump dryer can provide a good drying condition in the drying room.

![Figure 2. Temperature history in the experimental apparatus](image)

3.2. Effects of drying medium velocity

In this experiment, three different speeds of drying air are tested. The hot air speed is measured in the condenser with surface area of 0.25 m$^2$. The experiments were carried out at low speed, medium speed and high speed with drying air velocity at condenser surface are 0.23 m/s, 0.41 m/s and 0.64 m/s, respectively. Figure 3 shows temperature in the drying room at different speeds.

![Figure 3. Temperature history in drying room at different hot air speed](image)
The figure shows that higher hot fluid speed results in a higher temperature in the drying room. This is because at high speed results in lower temperature of the cold fluid leaving the evaporator. This will make temperature of the cold fluid entering the heat exchange will be higher. Thus, as a final product temperature of the hot air in the drying chamber will be higher. The higher temperature in the drying room will make drying process faster. This fact shown in figure 4. This is the reason why the temperature history at high speed is lower than temperature history at low speed. This fact suggest that the drying process should be carried out at high drying air speed. However, the effect of different humidity in the drying room is not investigated here. This will be an objective of the further research.

![Figure 4](image)

**Figure 4.** Mass history of clothes at different hot air speed

3.3. *Effect of the heat exchanger to the performance*

![Figure 5](image)

**Figure 5.** MR comparison for the heat pump dryer with and without heat exchanger

The performance of the present heat pump dryer, in term of drying time, with and without heat exchanger is shown in figure 5. In the figure, the non-dimensional weight (MR) in the drying room for heat pump
dryer is shown. It can be seen that the drying rate in the drying room without heat exchanger is lower than the heat pump dryer with the heat exchanger. The gradient of the MR with heat exchanger is higher than without heat exchanger. As a result, the drying time for the heat pump dryer with heat exchanger is 50 minutes and with heat exchanger is only 18 minutes. This fact suggest that the present of the heat exchanger increase the performance of the heat pump dryer significantly. In term of drying time it can reduce the drying time up to 64%.

The reason of higher drying rate in the drying room of the heat pump dryer with the heat exchanger is explored using the temperature and relative humidity in the drying room as shown in Figure 6. In the case without heat exchanger, temperature in the drying room increase from 36°C to a maximum value of 47°C. In the same time, the RH decrease from 40% to a minimum value of 27%. For the heat pump with heat exchanger, the temperature in the drying room increase from 36°C to a maximum value of 52.3°C and the RH decrease from 51% to 17%. As a note drying process is effective in a condition with high temperature and low relative humidity. The figure clearly shows that the present of the heat exchanger increases the temperature and decreases the RH in the drying room. This is the reason for high drying rate for the case with heat exchanger.

3.4. Heat Exchanger effectiveness
The effectiveness of the heat exchanger at different drying air speeds have been calculated using the equations shown in the method section. The results are shown in table 2. The table shows that the effectiveness of the present heat exchanger varies from 55.1% to 59.21% and higher at high speed. This suggests that the heat exchanger is very effective in the present application.

| Parameter | Medium air speed |
|-----------|-----------------|
|           | 0.23 m/s       | 0.41 m/s       | 0.64 m/s       |
| Effectiveness | 55.1            | 59.06           | 59.21          |

The comparison of the performance parameter on the heat pump dryer with and without heat exchanger are shown in table 3. The data shows that the present of the heat exchanger in the system increase COP, TP and SMER in order of 15.11%, 4.81% and 58.62%, respectively.
Table 3. Performance comparison of the heat pump dryer with and without heat exchanger

| Heat pump dryer       | Performance parameter | COP  | TP  | SMER |
|-----------------------|-----------------------|------|-----|------|
| Without Heat Exchanger|                       | 3.64 | 5.82| 0.435|
| With Heat Exchanger   |                       | 4.19 | 6.10| 0.695|
| Increase              |                       | 15.11%| 4.81%| 58.62%|

4. Conclusions
The present of a heat exchanger in a heat pump dryer has been investigated experimentally. The drying load is wet clothes made of 100% cotton with initial weigh 245 gr. The results show the present of the heat exchanger increase the performance of the heat pump dryer. In the present experiment the COP, TP and SMER increase 15.11%, 4.81% and 58.62%, respectively. This is because the heat exchanger provides a better drying condition in the drying room with higher temperature and lower relative humidity in comparison with heat pump dryer without heat exchanger. The effectiveness of the heat exchanger is also high, it is above 50%. It is suggested to install a heat exchanger in a heat pump dryer.

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