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Experimental Study on Heat Recovery of Air Dryer from Waste Heat Energy of Condensing Unit from VCRS Air Conditioner

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ABSTRACT

Heating, Ventilating, and Air Conditioning (HVAC) is a system to condition indoor air by cooling or heating to achieve thermal comfort for a human being. The HVAC system operates based on the refrigeration cycle, where heat is dissipated from the condensing unit in the warm air arrangement. This represents an ironic foundation of heat that might be recovered for further schemes or applications. In this paper, experimental work was developed to validate the proposed heat recovery system using heated air released from the condenser unit of the HVAC system as a source for the air dryer for the drying rack. Four different output parameters are to be observed in this research: the dry-bulb temperature of the air exit from the condenser unit, the dry-bulb temperature of the air inflowing the dryer, and the drying time and the relative humidity of the air leaving the dryer. These experimental works were conducted using a domestic application of a 1.0 hp air conditioning (AC) system with R-22 refrigerant gas and based on the following factors: The three-variant mass of wet clothes, the three-stage of mechanical fan speed for releasing warm air from the condenser, and the effect of variable ambient or surrounding air dry-bulb temperature were studied. A physical prototype of the dryer was constructed for proof-of-concept purposes. The experimental output was then analyzed to obtain precision and accurate data. To determine the system behavior, a refrigeration cycle analysis was conducted. It has been shown that an AC system of 1.0 hp can cover wet clothes drying of weights 1950 g, 4255 g, and 6350 g at 55, 80, and 110 min with a constant air velocity of 0.34 $m^{-3}.s^{-1}$ in an ambient temperature of 33°C. The significant contribution of this research is the proposed heat-recovery-based air dryer system with the capability to increase the Coefficient of Performance (COP) of the AC unit from 2.36 to 2.70. Hence, the energy-saving was received using the heat-recovered-based air dryer instead of a commercial electric air dryer system that uses high power consumption from their heater element.

INTRODUCTION

Nowadays, free energy sources are wasted due to inefficient technological ability. This includes heat energy waste from electrical appliances, which consume ambient temperature rise, especially in the city area. In 2016, the Paris Agreement stated that the temperature of pre-industrial levels rises to 2°C, which required further actions to edge the temperature rise not more than 1.5°C (Analytics 2016). To decrease the temperature and increase any system operation, waste heat generated from the system must be recycled for useful applications. For example, waste heat can be recouped from multiple sources, including the automotive system (internal combustion engine) (Song et al. 2020), industrial system (boiler) (Kim et al. 2020), and residential system (split type AC). For instance, in an internal combustion engine widely used in rail transport, vehicle, marine, and decentralized power generation, the fuel energy in an internal combustion engine is transformed into sound mechanical work output is only 30% to 40%. The rest is a waste of heat energy (Badescu et al. 2017). It is critical to minimize the waste produced to ensure sustainable processes can be achieved. Several waste heat recovery methods have been explored to optimize energy consumption proficiency. Thakar et al. (2018) highlighted that exhaust vapors from a diesel machine can be recovered. Apart from that, the special heat exchanger design placement adjacent to the inlet and outlet vessel of the engine to facilitate the unused energy from the exhaust can be used to warm up the air passed to the engine. In China, ordinary gas-fired boilers were traditionally used to substitute coal-fired boilers due to their fairly low emissions and opportune fuel delivery system (Hou et al. 2018).

Meanwhile, Suntivarakorn & Treedet (2016) researched the enhancement of boiler effectiveness using heat recovery for 9 tons.hr^{-1} fire tube boilers, which belonged to an engineering facility in Thailand. The experimental result shows that fuel moisture content can be reduced by 3%, and the boiler efficiency increases by 0.41% when applying the heat recovery to parch the fuel and put on it to warm up the air before inflowing the burning compartment. A previous study determined that the HVAC system contributes to the major peak energy consumption for residential, commercial, and industrial buildings (Wang et al. 2020, Wei 2019). Fig. 1 illustrates the energy consumption breakdown for a building based on typical services, and AC shows the highest energy consumption with 34%.

Most research is conducted to uncover heat waste in an AC system derived from the second law of thermodynamics. Borri et al. (2017) did a simulation of absorption chiller integration to recover waste heat from the compression stage of the liquefaction sequence and used that heat to drive the absorption sequence. The results show a decrease in specific consumption of about 10% (537 kWh.t^{-1} to 478 kWh.t^{-1}) and a rise in energy efficiency of approximately 11.5%. Recently, many researchers investigated the drying process through waste heat recovery, especially using an AC system (Kane et al. 2016, Husainy 2017, Nelwan et al. 2018). In the frame of this paper, a new recovery technology system for air dryers is suggested. The idea relies on recovering the heated air from the condenser unit of an AC system to supply an air dryer. Four different output parameters to be considered in this research are the dry-bulb temperature of the air exit from the condenser unit, the dry-bulb temperature of the air inflowing the dryer, the drying time, and the relative humidity of the air leaving the dryer. To validate the code, experimental works were conducted using a domestic application of a 1.0 hp AC system with R-22 refrigerant gas. Experimental shown based on the following factors: 1) the three-variant mass of a wet object, 2) the three-stage of the mechanical fan speed for releasing warm air from the condenser, and 3) the effect of variable ambient or surrounding air dry-bulb temperature. As far as the review is concerned, no prior study focuses on investigating the use of air dryers based on heat recovery from an HVAC system taking into account ambient temperature, the mass of the wet object, and airflow rate capacity. Therefore, the findings of this study may systematically reveal the interaction of essential variables in increasing the performance of the heat-recovered-based air dryer. This paper was organized as follows, starting with Section 2 illustrates the fundamental of the vapor compression cycle system. Section 3 describes the past studies of air dryers from AC units. Section 4 defines the new proposed air dryer system. Section 5 describes the procedure for setting up the experimental works. Section 6 describes three parametric study's critical parameters with the results and discussion. The final section illustrates the conclusion of this paper.

Vapor Compression Cycle System

In an HVAC system, the AC operates using a vapor compression cycle consisting of four basic components (Shaban et al. 2020): compressor, condenser, expansion valve, and evaporator, as shown in Fig. 2.

First, process the compression of refrigerant gas through the compressor and leave it as high-pressure and high-temperature gas. In the second stage, the refrigerant

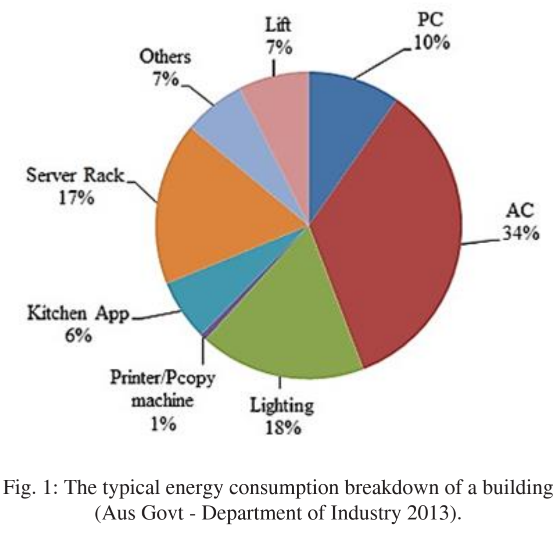


Fig. 1: The typical energy consumption breakdown of a building (Aus Govt - Department of Industry 2013).

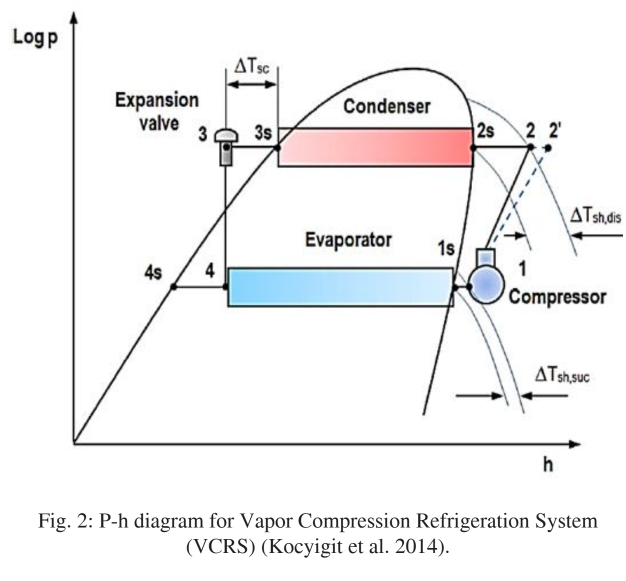


Fig. 2: P-h diagram for Vapor Compression Refrigeration System (VCRS) (Kocyigit et al. 2014).

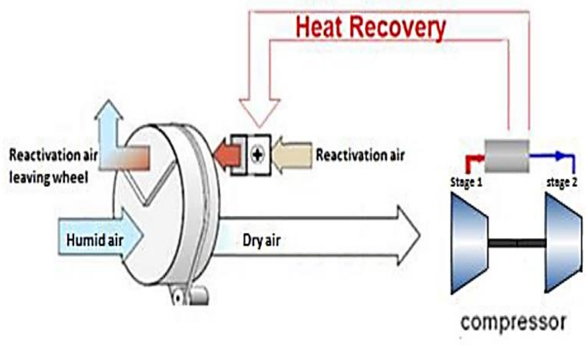


Fig. 3: Heat recovery for drying ambient air (Goodarzia et al. 2017).

gas passes through the condenser unit, which uses an air-cooled or water-cooled heat exchanger to dissipate the heat. During this process, the hot refrigerant gas is cooled by a condenser and becomes a warm liquid form. In the third stage, the warm refrigerant was regulated in an expansion valve or capillary tube to become a low-pressure and low-temperature refrigerant. Lastly, the refrigerant gas flowed into the evaporator, absorbing heat in the specified area. This stage will be affected by the increasing temperature of the refrigerant gas (Wang 2001). Finally, the refrigerant gas returns to the compressor, and the cycle is repeated in the operational mode of the AC system.

Past Studies of Air Dryers from the AC Unit

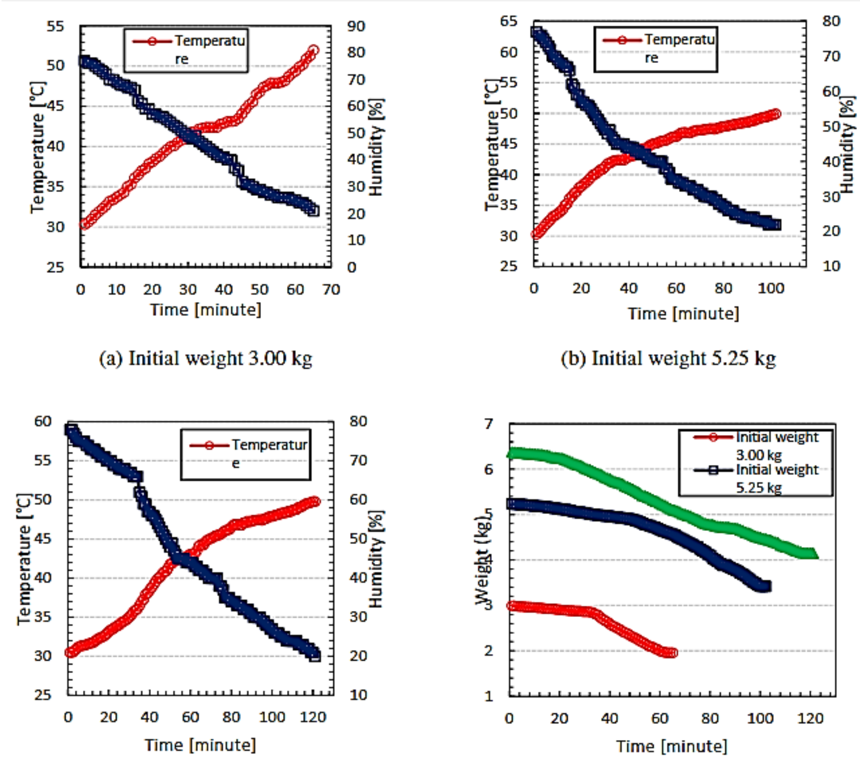
In a VCRS, the condensing unit rejects heat from a refrigerant in the condensing process. It produces a lot of waste heat, about 1.15 to 1.25 times the cooling effect on the evaporator side (Bhatia 2012). This percentage is more significant due to the heat of compression added into the system. The real proportion that arises is subject to the discharge and suction temperatures. High discharge and/or low suction temperature will increase the percentage. In recent years, there has been a growing amount of literature on discovering energy-efficient and industrial technology using heat recovery from the condensing unit. This is widely reported and extensively explored in the previous literature conducted to produce a recovery heat dryer system. Energy-saving for residential or industrial applications is the main issue recently focused on by researchers. Due to that issue, some researchers perform investigation and experimental work to recover waste heat from any resources to be integrated with an application to reduce energy consumption (Ramadan et al. 2017). Every residential or industrial may use AC for thermal comfort and to ensure indoor air quality (Wu et al. 2020). Some of the users may use the AC system for their cleanroom area. Waste heat generated from the compressor of AC can be recycled in many ways, including drying. Goodarzia et al. (2017) studied the effectiveness of drying the ambient air with the coupled air from the compressor and solid desiccant wheel. The first stage of the air compressor recovered to reactivate the desiccant wheel and remove the moisture in ambient air, as shown in Fig. 3.

Other than drying the ambient air, another study is about the drying characteristics and the heat pump's performance for the clothes drying process (Goodarzia et al. 2017). They construct a small-scale prototype using the necessary heat pump components and accessories of a 1-meter cube drying chamber of 1400 mm x 1000mm x 1080mm. The heat pump capacity in this model is 800 watts with an R-22 refrigerant set-up. The clothes are moistened and initially dried via the conventional spinner for about 3 min. Three samples of clothes are taken in this experiment. The first sample clothes weight when dry is 1.96 kg and when wet is 3.00 kg, the second sample clothes weight when dry is 3.42 kg and when wet is 5.25 kg, and the last sample clothes weight when dry is 4.15 kg and when wet is 6.38kg. The initial weights to be dried will be taken based on weight after passing through the spinner.

The results in Fig. 4 show that the clothes for sample 3.0 kg will be dried in 65 min, sample 5.25 kg will be dried in 102 min, and sample 6.38 kg will be dried in 121 min. The summary of the graph proves that the highest temperature inside the drying chamber, the faster the clothes are dried. The recent literature review shows no methods exist for replacing the air dryer chamber with an open space concept. The minimum space required for the air dryer chamber in the previous study is a 1-meter cube, not including the other fittings and accessories, which is not suitable if this technology is provided for residential usage. In this research, experimental works were conducted to study the effectiveness of replacing the air dryer chamber with an open space chamber concept. If future works to use the waste heat recovery technology of VCRS are applicable, much saving of energy consumption can be done; hence the performance of the VCRS also be improved.

Proposed New Air Dryer System

This research presents an improved air dryer application technology to recover the waste heat from the condenser unit from the AC system. The initial stage is to identify the critical elements involved in the waste heat recovery process for the air dryer system. The critical elements were selected based on the previous results conducted by other researchers. To gain useful results for the proposed system, critical elements are the main factors that contribute to system performance and efficiency. The parameters required to find the drying time of the proposed system are shown in Fig. 5. Meanwhile,



(a) Initial weight 3.00 kg (b) Initial weight 5.25 kg

(c) Initial weight 6.38 kg (d) Weight loss clothes

Fig. 4: Typical temperatures and weight loss of the clothes dried in the drying chamber (Goodarzia et al. 2017).

the schematic of the proposed air dryer system is shown in Fig. 6. The ambient air will pass through the condensing unit and become the hot air temperature, which is then used in the air dryer system to dry and return to the surrounding area.

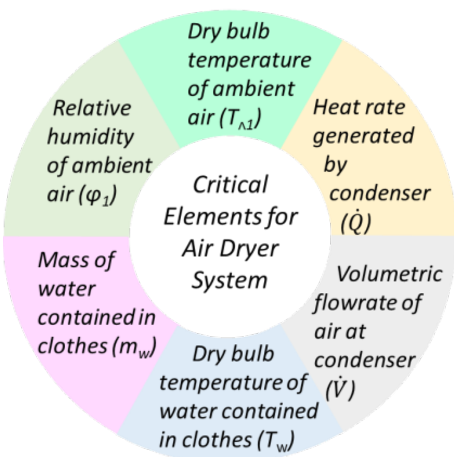


Fig. 5: Critical elements for air dryer system.

MATERIALS AND METHODS

Fig. 7 depicts a research flowchart on developing a new proposed air dryer to identify product performance. The first step involves several phases to determine the standard performance condition. Correspondingly, it is necessary to consider the preliminary design for this project to give users the best product. It is an excellent way to detect functionality and discover better ways and combinations of the achieved functionality. The next stage is to choose several design alternatives for the best choices of products. Examples of requirements are dryer size, AC type, and size. After all, criteria have been determined; fabrication is done to produce the product. Subsequently, testing this product operationally is done to find the coefficient of performance of this product. Note that this process must meet the criteria of this project to ensure that this product has a suitable performance to benefit users in terms of energy saving. This process goes to the preceding stages if it fails to meet its requirements. The final step is to collect data and analyze the performance of the new proposed air dryer system.

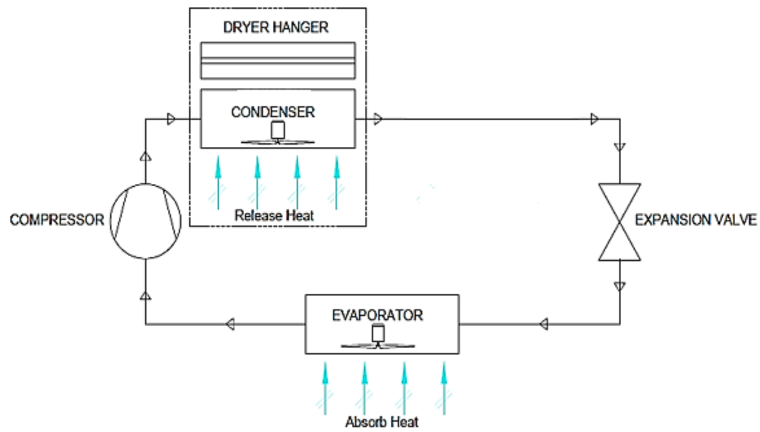


Fig. 6: The proposed schematic of the air dryer system.

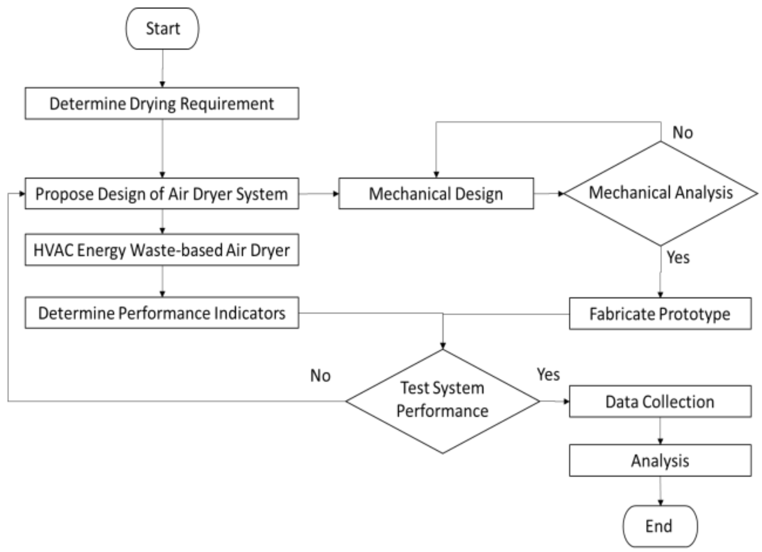


Fig. 7: Flowchart of the research procedure.

The fabrication process must follow the schematic design of the product as selected during the design stage. This experiment was conducted using a 1.0 hp AC system with R-22 refrigerant gas. The domestic user commonly uses the AC capacity of 1.0hp due to this capacity at the house, and easy to study the effectiveness of the proposed system compared to the commercial system. The specification of the AC system is shown in Table 1.

The proposed air dryer system was constructed based on five main components: a drying clothes hanger rack, condenser, capillary tube, evaporator, and compressor. The air dryer design constructs with axes to hold the clothes. Two temperature sensors are placed on the drying hanger (upstream and downstream of the clothes) to measure the dry-bulb temperature of condensing air passed through the clothes. The dry-bulb temperature detected by the temperature sensor placed before clothes are equivalent to the dry-bulb temperature of the air released from the condenser unit. To identify the mass of the wet clothes, an EBalance 1501 electronic digital scale weight balance with an accuracy of 0.01 decimal places is placed at the drying hanger axes. Apart from that, the mechanical fan from the 860W fan motor has three speeds low (0.14 $m^3.s^{-1}$), medium (0.24 $m^3.s^{-1}$), and high (0.34 $m^3.s^{-1}$), which will be placed at the upper hanger to blow hot air from the condenser coil to pass through wet clothes. Clothes will be hanging on the axes with the staggered configuration.

Table 1: Technical specification of the selected AC system.

Item	Specification
Brand	MEC
Refrigerant type	R-22
Nominal cooling capacity [Btu.hr^{-1}. kW^{-1}]	10,000/2.93
Nominal running current for cooling [A]	4.38
Power source [V.Ph^{-1}.Hz^{-1}]	220 – 240/1/50
Indoor air flowrate, Low/Medium/High (cfm)	225/282/342
Condenser tube material	Copper
Condenser tube diameter [mm]	7.00
Condenser fin material	Aluminium
Condenser fin face area [m^2]	0.29
Compressor-rated running current [A]	3.99
Condenser fan motor power [Watt]	860
Custom condenser air flowrate, Low / Medium / High [m^3.s^{-1}]	0.14 / 0.24 / 0.34

RESULTS AND DISCUSSION

Parametric Study

This research aims to formulate the time required for drying based on the following factors: The three-variant mass of wet clothes, three stages of a mechanical fan speed for releasing hot air from the primary condenser, and the effect of variable ambient or surrounding air dry-bulb temperature. Table 2 shows the critical research factors with the scenarios in this research.

This parametric study aims to study the behavior of the air dryer system in various conditions.

Knowing that each of the 1hp of domestic AC systems can be delivered, the evaporator capacity is about 9,600 Btu.h^{-1}, the condenser air volumetric flow rate is around 0.34 m^3.s^{-1}, and the recovered hot air temperature is 33°C for outdoor air temperature. The relative humidity is 25°C and 50%, respectively. The size of this AC is being used in this experiment because of the major utilization by domestic and commercial users in Malaysia.

Effect of Cloth Weight

The first factor is to study residential application, which is the most effective drying time depending on the number of people per house. Currently, the number of people in a house varies depending on the size, type of house, and social and geographical regions. Therefore, the number of people was interpreted as the various weight of clothes. Each of the sample weights of cloth included the 100g weight of the hanger to hold the cloth in a staggered method. The details of the configuration weight of clothes are presented in Table 3.

The statistical data for drying time was increased with the weight of clothes since the mass of water to be evaporated increased. Based on Fig. 8, the drying time was increased from 55 min for 1 person to 110 min for 3 persons. When the hot air from the condenser was fully recovered to dry the clothes, the condensing temperature came out is about 70°C. The significant effect of this recovery of condenser air can be observed at the evaporator unit, where the evaporating temperature can drop to 4°C, which raises the cooling capacity created by the AC. The evaporating temperature can achieve at 4°C because the heat at the condenser coil has been fully extracted to the recovery air dryer application. Moreover, when the heat rejection at the condenser site increases, the cooling capacity and heat absorption at the evaporator side will also increase. It can be concluded that the proposed air dryer system can replace a commercial electric air dryer if the 1 hp AC system operates for at least

Table 2: Key research factors for experimental works.

Research Factor	Description	Scenario
Mass of the wet clothes	There are three samples for wet clothes mass which are 1950 g, 4255 g, and 6350 g	The system runs with high airflow capacity and is tested at 33°C of ambient temperature.
Airflow rate capacity	Variable airflow capacity (low, medium, high) with 860watt fan motor	System ran with the mass of 6350g of clothes and tested at 33°C of ambient temperature.
Ambient Temperature	Variable dry bulb temperature, which is 27°C, 30°C, and 33°C	System running with the mass of 6350g of clothes and high airflow capacity

Table 3: The total mass of wet and dry weight for six samples in the function of the number of people.

Sample	Number of people	Description	Dry weight [g]	Wet weight [g]	Water weight [g]	Weight loss [%]
1	1	1 T-shirt, 1 pant, 1 towel	1150	1950	800	41.0
2	2	2 T-shirts, 1 pant, 1 skirt, 2 towels	2450	4255	1805	42.4
3	3	3 T-shirt, 2 pants, 1 skirt, 3 towels	3600	6350	2750	43.3

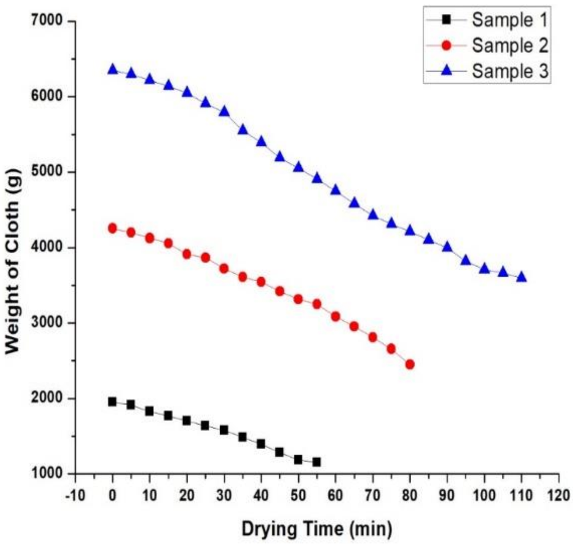


Fig. 8: Effect of cloth weight on drying time.

2 hours to serve 3 persons in each house. Other than that, the side effect of the cooling process of the AC system can be improved.

Effect of Air Flowrate

In domestic AC systems, there are two types of AC systems: non-inverter and inverter. If the proposed new air dryer system was combined with an inverter AC unit, the drying time might differ from the results in Table 1. This happened due to the speed of the condenser fan motor for the inverter AC unit running based on the cooling load cater on the evaporator side. Therefore, when the cooling load decreases in a conditioned room, the condensing unit's air flow rate might decrease and vice versa. Hence, the second parameter in this experiment is to study the effect of drying time when the air flowrate of the condensing system is low (0.14 $m^3.s^{-1}$), medium (0.24 $m^3.s^{-1}$), and high (0.34 $m^3.s^{-1}$). For these cases, the weight of the cloth is fixed to sample 3 in Table 3, and the ambient temperature is 33°C.

Based on the data shown in Fig. 9, the drying time varies with the airflow rate of the condenser unit. The drying time increases when the air flow rate is low at 0.14 $m^3.s^{-1}$. While the air flow rate increases, the drying time becomes faster. From this situation, it was clearly shown that the proposed air dryer system might be convenient to use with the inverter AC system because the gap in drying time for low and high airflow rates of the condenser unit is not big. It still can dry the cloth for 3 persons if the AC system operates for at least 3.5 hours.

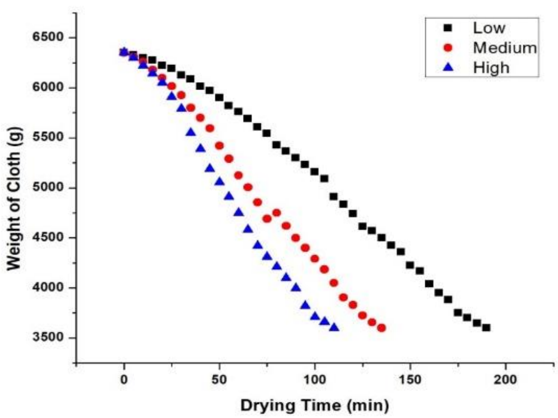


Fig. 9: Graph of effect on airflow rate to drying time.

Effect of Air Flowrate

The climate conditions can change the ambient or surrounding temperature significantly. Thus, it also depends on the geographical zone. When the ambient air change, it might affect the subcooling temperature at condensing unit. To study the consequences of ambient temperature on the performance of the proposed air dryer system, the experimental work was set up with three sample data. The first sample is the set-up system operated within 27°C surrounding temperature, the second within 30°C, and the third within 33°C. For these cases, the weight of the cloth is fixed to sample 3 in Table 2, and the airflow rate of the condenser side is 0.34 $m^3.s^{-1}$.

Fig. 10 shows the drying time results versus the recovered condensing air temperature. It can be shown that the ambient air temperature increment will fasten the time needed to dry the clothes. This is because the evaporation rate depends on the ambient temperature of the air. Besides that, the evaporation process can lower the drying time when the air

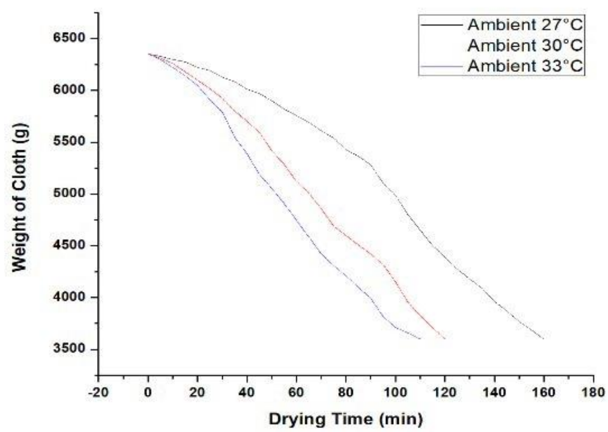


Fig. 10: Effect of ambient Temperature and weight of cloth on drying time.

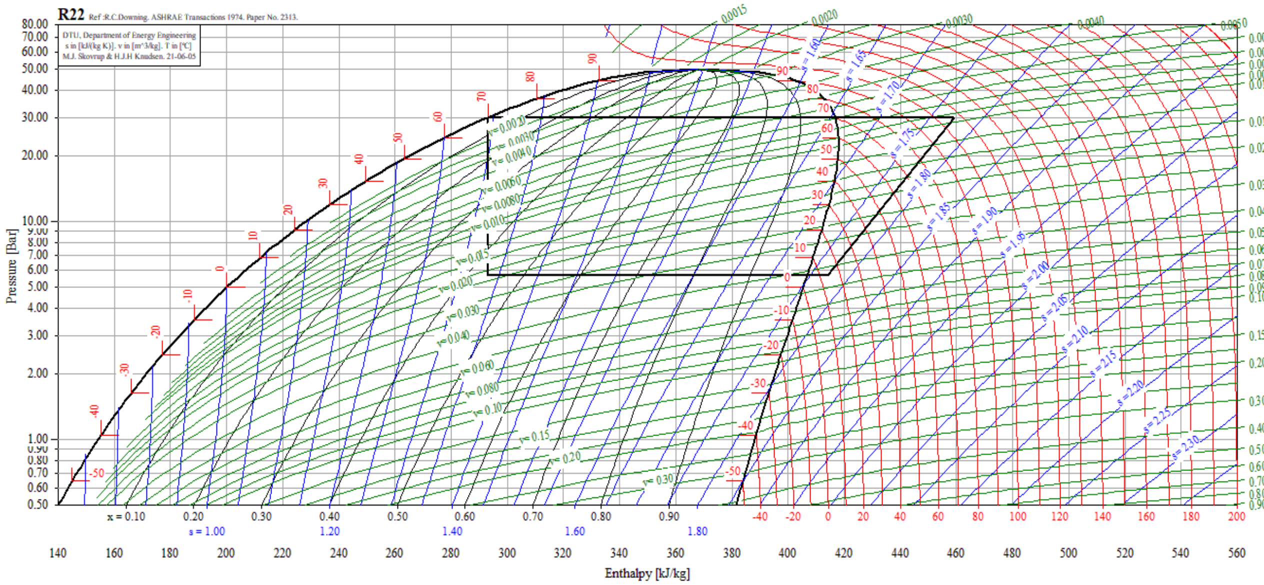


Fig. 11: p-h diagram of the proposed air dryer system.

Table 4: Performance test data generated from Coolpack 1.49.

Parameter	Test data
Evaporator Heat [$kJ.kg^{-1}$]	121.134
Condenser Heat [$kJ.kg^{-1}$]	165.957
Condensing temperature [°C]	70.00
Enthalpy h1 [$kJ.kg^{-1}$]	414.16
Enthalpy h2 [$kJ.kg^{-1}$]	458.98
Enthalpy h3 [$kJ.kg^{-1}$]	293.02
Enthalpy h4 [$kJ.kg^{-1}$]	293.02

temperature increases. The drying time for a 3-person cloth is 160 min when the ambient air temperature is 27°C. Note that the drying time decreases to 110 min for a recovered ambient air temperature of 33°C.

Air Dryer Performance

To clarify the performance of the proposed air dryer system, the data collected was simulated in Coolpack 1.49 version software which can generate an accurate and precise p-h diagram of the system operation. A 1.0hp AC system powers the proposed air dryer system with a specific refrigerant of R-22, Chlorodifluoromethane, which will be phased out by 2030 for developed countries and 2040 for developing countries according to the Montreal Protocol (Abdur et al. 2020). The performance test was conducted with the best air dryer-operated data in the previous experiment. The 3-person weight of cloth, condenser airflow rate at 0.34 $m^3.s^{-1}$, and the recovered ambient temperature at 33°C. While conducting this performance test, the evaporating temperature is 4°C with a superheat value of 10°K. At the condenser site, the heat rejection from the condensing unit is 70°C which consumes the whole condenser heat source of 165.957 $kJ.kg^{-1}$. The p-h diagram representing the behavior of the proposed air dryer system is illustrated in Fig. 11. The Coefficient of Performance (COP) for the AC system was increased from 2.36 to 2.70, respectively. The performance test data is shown in Table 4, and the COP value was derived from the p-h diagram, which can extract the enthalpy data at each point as per Equation 1 (Nurhadi et al. 2021).

$$\boldsymbol{COP} = \frac{h_1 - h_4}{h_2 - h_1}. \quad ...(1)$$

CONCLUSION

To encounter the challenges of speedily growing cooling load demand by users, it is vital to enhance the performance and the efficiency of a VCRS and to reduce the power consumption produced by the speedy surge of cooling load demand. To enhance the performance and efficiency of the VCRS, waste heat from the condensing unit of VCRS must be recycled for other applications, such as the proposed air dryer system. As a result, all experiments have proven that the waste heat energy from the VCRS can be recovered significantly for an air dryer system and can raise the Coefficient Of Performance (COP) of the VCRS from 2.36 to 2.70 concurrently. The AC system of 1.0hp can cover the drying of wet clothes of weights 1950 g, 4255 g, and 6350 g at 55, 80, and 110 min with a constant air velocity of 0.34 $m^3.s^{-1}$ in an ambient temperature of 33°C. For future research, it was recommended to study the effectiveness of the proposed recovery air dryer unit with commercial or industrial AC systems such as chiller and refrigeration systems. As the current industry of the AC system was tried very hard to reduce power consumption and, at the same time to increase the COP of the system, this proposed system might be useful for them to uncover the waste of free energy.

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