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Experimental Performance Investigation of a Plate Heat Exchanger as a Condenser for Ground Coupled Air Conditioning System

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ABSTRACT
The condenser, a major part of an air conditioning system, significantly affects the coefficient of performance (COP) of an air conditioning system. Generally available condensers are- air-cooled, evaporative-cooled and water-cooled condensers. The air-cooled condenser is the most commonly used type in split and packaged systems. It especially has the disadvantages of considerable size and noise issues as a fan is required to provide the necessary air flow rate. An evaporative condenser is also problematic in the case of providing an evaporative medium. A better option than these two types is a water-cooled condenser in case of compact design and higher heat transfer coefficients. A plate heat exchanger (PHEX) is used in this study to condense the refrigerant of an air conditioning system, considering ground water as the cooling medium. In this ground-coupled proposed system, groundwater was circulated inside the PHEX to cool the refrigerant, and the initial lowest water temperature was about 23ºC. Three flow rates of water were maintained at the inlet of PHEX, which were 0.07 kg/s, 0.12 kg/s, and 0.15 kg/s, respectively. The highest COP was found at 0.15 kg/s mass flow rate of water. The average COP of the air-conditioning system improved from 1.99 to 2.78 when a ground-coupled plate heat exchanger replaced the air-cooled condenser. The effect of water temperature was investigated, and it was revealed that the COP was highest at low water temperatures of about 24ºC. The highest average heat rejection at PHEX was 4.39 kW for 0.15 kg/s mass flow rate of water. Therefore, considering the overall analysis, the plate heat exchanger as a water-cooled condenser demonstrated superior performance in the air-conditioning system.

Keywords: Plate Heat Exchanger, Ground Water, Water-Cooled Condenser, Ground-Coupled AC.

1. Introduction

In our daily life, heating and cooling are essential for different purposes like comforting human beings, food preservation, drying, preheating boiler feed water, and many more. A vapor compression refrigeration system is primarily used for heating and cooling within buildings, with its key components being a compressor, condenser, expansion (or throttling) valve, and evaporator. An air conditioner moves undesirable heat from a building's inside to the exterior [1]. Air-cooled condensers are used most often in conventional AC systems. Air-cooled condensers require a high rate of airflow for better operation, which occasionally causes a noise issue. On the other hand, a water-cooled condenser works based on the heat exchange between the refrigerant tubes and flowing water. It has a higher heat transfer coefficient and cooling capacity compared to air-cooled condensers [2]. A water-cooled condenser can also function as a waste heat recovery unit. This enables the system to provide both cooling and heating functions by utilizing the recovered heat [3].

Notably, subcooling in the water-cooled condenser enhances both the cooling performance and energy efficiency of an air conditioning or refrigeration system [4]. The impact of water-cooled condenser's subcooling is that COP reaches its maximum due to a balance between growing refrigerating impact and particular compression work [5]. A study by Ansari et. al [6] highlights significant COP improvements in water-cooled condensers with advanced configurations. Another study by Shrivastav et. al [7] outlined that water-cooled condensers surpass air-cooled ones in cooling efficiency, as their performance is less affected by ambient air conditions.

The simplest type of heat exchanger for a water-cooled condenser is plate heat exchanger [8]. The condenser is one of the most significant units of an air conditioning system, which plays a vital role in energy utilization. Plate heat exchanger has wide applications in condensing units [9]. Maheshwari and Ali [10] investigated the performance of air-cooled and water-cooled condensers of the AC Systems focusing on peak power and energy consumption, carried out over the summer in one of Kuwait's leading hospitals for comparative study. For the same cooling output, the water-cooled system's peak power demand and daily power consumption were 45% and 32% lower, respectively, compared to the air-cooled system. Hu and Huang [2] investigated a high-efficiency residential split water-cooled air conditioner that incorporated cellulose sheets as the filling material in the cooling tower. The combination of the water-cooled condenser and cooling tower lowers the compressor's power consumption, leading to significant energy savings.

Different heat exchangers were used as water-cooled condensers in numerical and experimental investigations. However, results showed that plate heat exchangers performed better than the other types. Raveendran and Sekhar [11] conducted an experimental study on the performance of a domestic refrigeration system, utilizing a brazed plate heat exchanger as the condenser and refrigerants like R600a and R134a.

The results showed that the system with a water-cooled BPHE can significantly reduce energy consumption in a standard refrigeration system. It can save up to 70% of the pull-down time and increase the refrigerator's COP from 52% to 68% when the original air-cooled condenser is replaced with a water-cooled BPHE.

The primary focus of this study is to investigate the performance characteristics of a traditional air-conditioning system and a ground-coupled air-conditioning system that incorporates a plate heat exchanger as the condenser. The effect of water temperature and flow rate on the performance of the ground-coupled air-conditioning system was investigated to compare with that of a traditional air-conditioning system with an air-cooled condenser.

2. Methodology

This experiment establishes a setup in which the conventional air conditioning system is modified by introducing a plate heat exchanger (PHEX) in place of the air-cooled condenser.

2.1 Experimental Setup

An existing air conditioning system consisting of an evaporator, a compressor, an air condenser and a capillary tube has been used in this experiment. A plate heat exchanger (PHEX) was connected to a double-tube ground heat exchanger to reject water heat into the ground, allowing the system to continuously circulate water through a pump and efficiently manage the cooling process. Figure 1 shows the schematic diagram of an air conditioning system with a coupled plate heat exchanger.

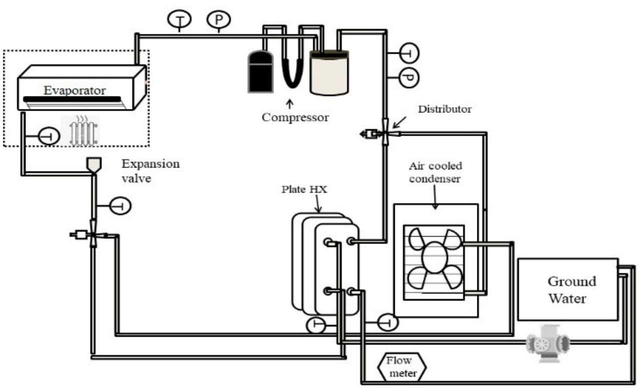


Fig.1 Schematic diagram of an air conditioning system with ground coupled plate heat exchanger.

A copper brazed stainless steel plate heat exchanger (model B3-020-22D-3.0-304) has been used because metal plates are corrugated to improve heat transfer efficiency. The brazed plate heat exchanger has mainly two plates, the front and back cover plate. In the heat exchanger, some adapters are also used to properly fit the water and refrigerant sides to the heat exchanger port. The plate heat exchanger has a cooling capacity of 7.5 kW and consists of 22 plates. Figure 2 shows the photographic view of the plate heat exchanger.

In this experiment, one evaporator (Walton air conditioner having cooling capacity of 3.5 kW and net weight of 8.03 kg with packing dimension of 820x300x270 (mm)), one compressor (Panasonic 2KS206D5AF04 type), one energy meter (1-phase 2-wire, 50 Hz, 230V, 1600 Imp/kWh type), one air condenser (Walton air conditioner WSN-12K-0102-RXXXA model having cooling capacity of 3550W), one clamp meter (FLUKE 381 type having tested range of 999.9 A), two pressure gauges, one water flow sensor (Arduino-based water flow sensor of model YF-S201 having working range of 1 L/min to 30 L/min), one humidity meter (model Lutron HT-3009 having resolution of 0.01% RH for humidity reading, resolution of 0.01 degrees for temperature reading and 2% RH humidity accuracy), one anemometer (model LUTRON AM-4202 with a velocity probe having accuracy of ± (2% + 1d) for air velocity and 0.8°C for temperature measurement), T-type and K-type thermocouples (T-type having accuracy of ± 0.5°C and K-type having accuracy of ± 1.1°C), data logger (GRAPHTEC type), one capillary tube, and one pump of 0.37 kW capacity have all been used. Figure 3 illustrates the experimental setup incorporating a ground water-cooled plate heat exchanger.

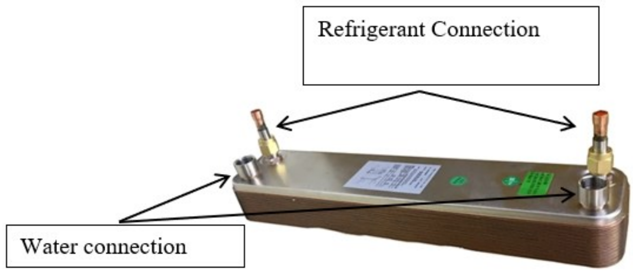


Fig.2 Photographic view of B3-020-22D-3.0-304 plate heat exchanger.

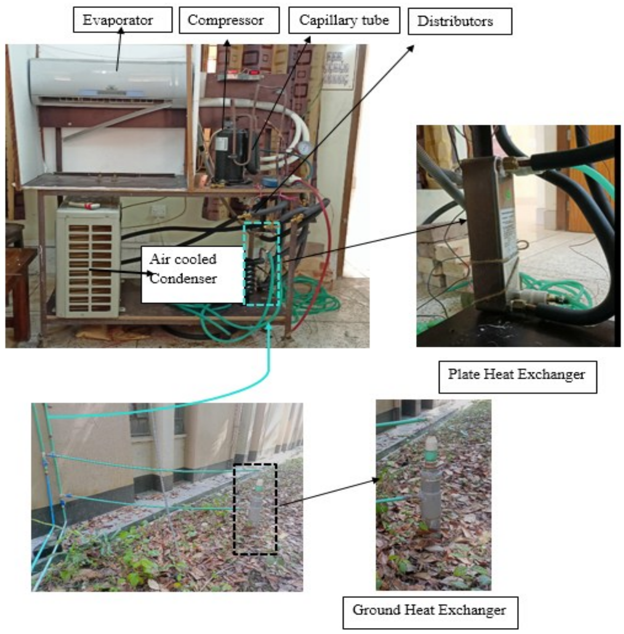


Fig.3 Photographic view of the experimental setup with ground water cooled plate heat exchanger.

2.2 Working Procedure

A split-type air conditioner working with R-22 refrigerant was placed inside a compact, insulated area. Over the course of three days, the room temperature typically fluctuated between 23°C and 26°C, influencing the internal environment of the air conditioner. The air conditioning temperature was set to 19°C because the outside temperature was not very high. A heater was also utilized, and the interior temperature was kept at or near 25°C. Data were measured for around 50 minutes each day. A 5-minute interval was used between two successive readings.

Two distributors were employed at the expansion valve inlet and compressor outlet to connect the plate heat exchanger and air-cooled condenser. The distribution valve system closed the plate heat exchanger line when refrigerant could travel through the air-cooled condenser pipe and vice versa. After completing the setup, the air-cooled condenser was first turned on, and the measurement devices were connected to the system. The data were observed through data logger and pressure gauges. At the starting point of the air conditioner, the discharge pressure initially began to rise, and once it stabilized, the data were recorded.

The water-cooled heat exchanger was then turned on after closing the valve for the air-cooled condenser. Cold water and hot vapour refrigerant entered the plate heat exchanger when the pump was switched on, and the AC was turned on. Via other ports, liquid refrigerant entered the capillary tube, and heated water circulated back to the ground to reject heat, thus creating the cooling impact of the air conditioning system. During this experiment, three distinct water flow rates (0.07 kg/s, 0.12 kg/s, and 0.15 kg/s) were kept constant to monitor the system's cooling capability and COP. Once the system had stabilized, the following measurements were taken: evaporator temperature, relative humidity, and volume flow rate of both the returned and supply air; compressor pressure and temperature at both the inlet and outlet; air-cooled condenser temperature at the inlet and outlet; PHEX temperature at the water inlet, water outlet, refrigerant inlet, and refrigerant outlet; and the voltage and current of the compressor.

2.3 Data Reduction

Performance parameters were calculated using the measured data to compare performance of the water-cooled plate heat exchanger and the conventional air-cooled condenser.

2.3.1 Heat transfer

Flow rates, temperatures, and the specific heat of the water are used to calculate the heat transfer rate in PHEX. Heat transfer occurs between refrigerant vapour and water in the plate heat exchanger. The heat lost by the hot vapor refrigerant will be equal to the heat gained by the cold water. Using energy balance, the following equation can be obtained-

$$\dot{m}_c\, c_{pc}(T_{co} - T_{ci}) = \dot{m}_h\, c_{ph}(T_{ho} - T_{hi}) \tag{2.1}$$

2.3.2 Cooling capacity

The cooling capacity of a system describes how much heat it can steadily extract from the refrigerant at the evaporator. The refrigeration load is determined by multiplying the change in specific enthalpy of the refrigerant as it passes through the evaporator by the refrigerant's mass flow rate.

$$Q_{evp} = \dot{m}_{ref}(h_1 - h_4) \tag{2.2}$$

The cooling capacity of the air conditioner can also be calculated by leaving air side at the evaporator [12] as following:

$$Q_{air} = \dot{m}_{air}\Delta h_{air} \tag{2.3}$$

Where $\dot{m}_{air}$ can be measured by:

$$\dot{m}_{air} = \rho * A * V \tag{2.4}$$

2.3.3 COP

The coefficient of performance (COP) is the ratio of heat extracted in the evaporator to the work done on the refrigerant.

$$COP = \frac{Heat\ Extracted}{Work\ Done} \tag{2.5}$$

Or

$$COP = \frac{Refrigerating\ Effect}{Compressor\ Work} \tag{2.6}$$

Where compressor work can be determined by:

$$P = V * I = m_{ref}(h_2 - h_1) \tag{2.7}$$

The refrigeration effect can be determined by:

$$Q_r = m_{ref}(h_1 - h_4) \tag{2.8}$$

COP can also be calculated from cooling capacity as:

$$COP = \frac{Q_{air}}{P} \tag{2.9}$$

3. Results and discussion

The experimental performance of a plate heat exchanger for a ground-coupled air conditioning system was investigated, and the comparison between a water-cooled plate heat exchanger and a conventional air-cooled condenser was made using different performance parameters. For all of the observations, the cooling capacity and COP of the AC system with an air-cooled condenser were calculated. Cooling capacity, COP and heat rejection at PHEX for ground-coupled AC system were calculated for three flow rates of water.

3.1 Effect of water flow rate on cooling effect

Figure 4 exhibits the impact of water flow rates on the cooling effect of the system.

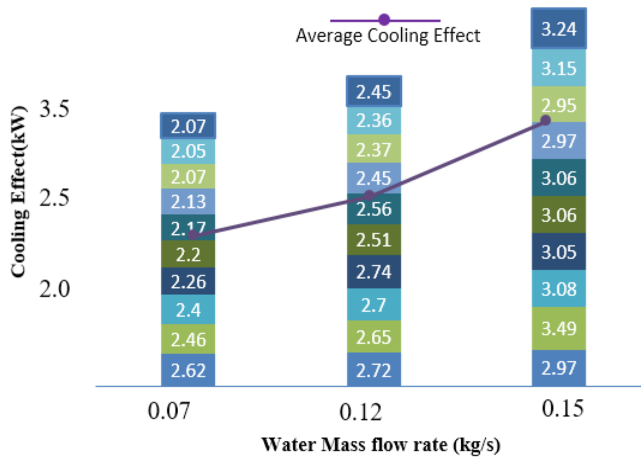


Fig.4 Variation of cooling effect with mass flow rate of water in PHEX.

This work maintained three flow rates: 0.07 kg/s, 0.12 kg/s, and 0.15 kg/s. The figure illustrates that as the water flow rate increased, the cooling effect also increased. At a water flow rate of 0.07 kg/s, the average cooling effect was 2.25 kW. As the flow rate increased to 0.12 kg/s, the cooling effect increased to 2.55 kW, and at 0.15 kg/s, the cooling effect further increased to 3.1 kW. The water flow rate affects the system's cooling effect because as it rises, heat exchange from hot refrigerant to cold water increases, leading to subcooling of the refrigerant and an increase in the cooling effect.

3.2 Effect of water flow rate on COP

Figure 5 demonstrates the impact of the water mass flow rate on the air conditioning system's COP. COP values were also averaged and demonstrated for three different flow rates in this case. It is clear from this graph that COP increased with water flow rate. Due to COP's relationship to the refrigeration effect, COP rose with the water flow rate. The highest COP was discovered at 0.15 kg/s, which is 2.78.

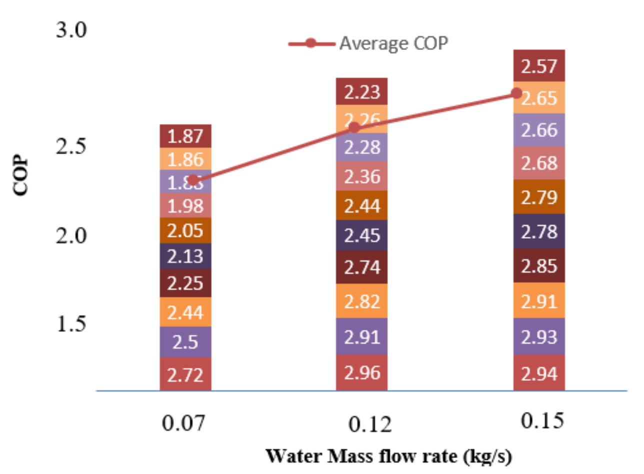
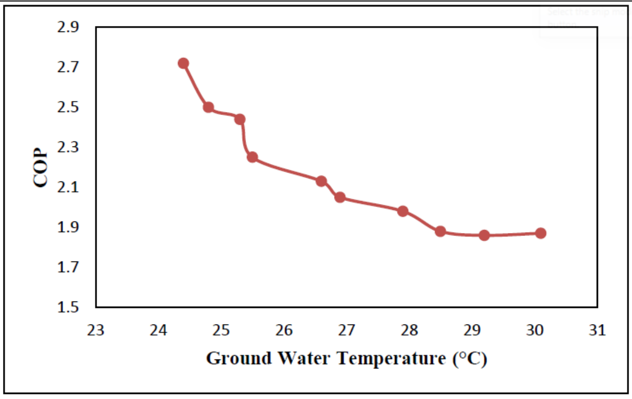


Fig.5 Variation of COP with mass flow rate of water in PHEX.

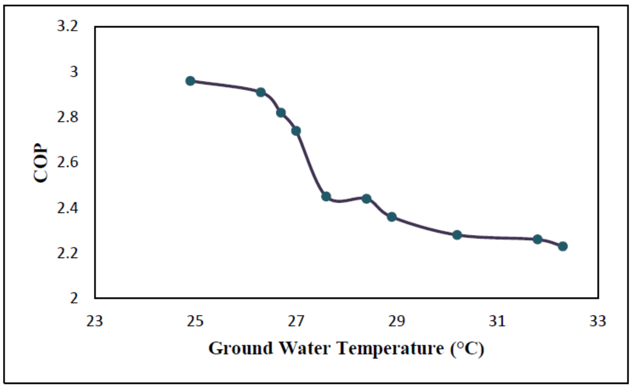
3.3 Effect of water temperature on COP

In this system, the initial groundwater temperature was 23°C. As the system rejected heat into the ground through the heat exchanger, the water temperature gradually increased, reaching up to 35°C. Figure 6 exhibits the effect of water temperature on the COP of the ground-coupled AC system with PHEX.

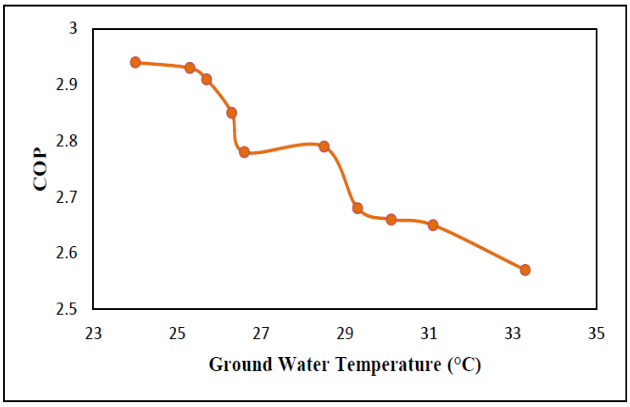
In Figure 6, when the water temperature rose, COP slightly dropped. This is because COP rises as the cooling effect does. Here, the cooling effect increased because of lower water temperature (lowering water temperature means lowering the condensing temperature). Since the plate heat exchanger received water at a lower temperature, subcooling was aided, improving the COP. This figure signifies that at lower water temperature, heat rejection increases along with COP.



(a)



(b)



(c)

Fig.6 Effect of water temperature on COP for water flow rate of (a) 0.07 kg/s, (b) 0.12 kg/s and (c) 0.15 kg/s.

3.4 Effect of water flow rate on heat rejection at PHEX

Figure 7 illustrates the impact of water flow rate on heat rejection (energy taken from a refrigerant during the condensing process) in PHEX.

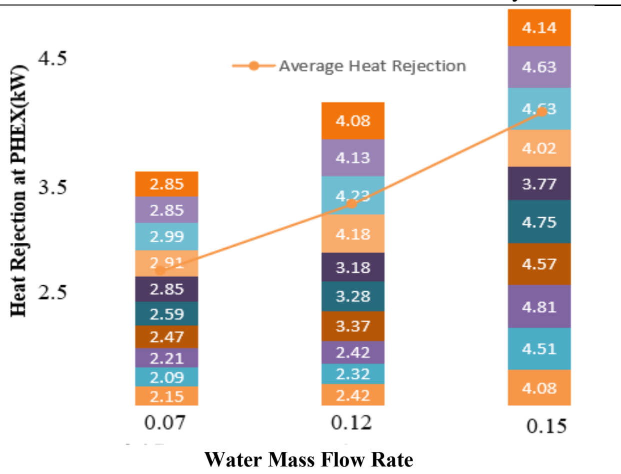


Fig.7 Effect of Water Mass Flow Rate on Heat Rejection in PHEX.

Heat rejection capacity mainly implies that the refrigeration subcooling effect is increasing. For this experiment, heat rejection capacity was 2.6 kW, 3.36 kW and 4.39 kW, respectively, for 0.07 kg/s, 0.12 kg/s and 0.15 kg/s water flow rate at PHEX. As the temperature difference and water flow rate increased, heat rejection in the plate heat exchanger (PHEX) also rose.

3.5 Comparison of COP

Figure 8 shows a comparison of the COP of the AC system for the air-cooled condenser and the water-cooled plate heat exchanger. The graph demonstrates that COP for PHEX was higher than COP for the air-cooled condenser. The average COP for 0.07 kg/s flow rate was 2.17. For 0.12 kg/s and 0.15 kg/s, flow rate COP were 2.54 and 2.78, respectively. Whereas for air-cooled condenser, the average COP was 1.99, which is almost 28% percent lower than COP for a higher flow rate at PHEX. Sumeru et al. [13] carried out an experimental study on a residential air conditioning system using water condensate for subcooling. Their findings showed that condensate water reduced the refrigerant temperature by 2.7°C at the condenser output, resulting in a 16.4% increase in COP. Reddy et al. [14] experimentally investigated an air conditioning system using a ground source heat exchanger. The study found that filling the bore with water increased the system's COP from 2.11 to 3.72.

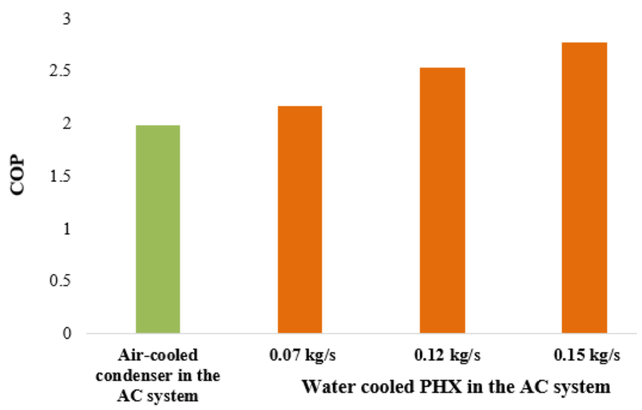


Fig.8 Comparison of COP of the AC system with air-cooled condenser and water-cooled PHEX.

4. Conclusion

In this experiment, the performance efficiency of an air conditioning system working with R-22 refrigerant was studied by replacing the conventional air-cooled condenser with a ground-coupled PHEX. The brazed PHEX performance comparison with that of the air-cooled condenser was evaluated using the same air conditioning unit. Replacing the conventional air-cooled condenser with a ground-coupled PHEX led to a significant improvement in COP, with the ground-coupled PHEX achieving a 28% higher COP than the air-cooled condenser. The performance was further optimized at higher water flow rates and lower ground water temperatures. It was found that both COP and cooling capacity increased with increased water flow rates, attributed to the enhanced heat rejection capacity of the PHEX. The effect of ground water temperature was investigated, and it was discovered that the COP was highest at low water temperatures. The highest average heat rejection was found at the highest mass flow rate of water maintained at the inlet of PHEX.

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NOMENCLATURE

$\dot{m}_c$	: mass flow rate of water, kg/s
c_{pc}	: specific heat of water, kJ/kg·K
T_{co}	: outlet temperature of water, K
T_{ci}	: inlet temperature of water, K
$\dot{m}_h$	: mass flow rate of refrigerant, kg/s
c_{ph}	: specific heat of refrigerant, kJ/kg·K
T_{ho}	: outlet temperature of refrigerant, K
T_{hi}	: inlet temperature of refrigerant, K
$\dot{m}_{air}$	: mass flow rate of air leaving evaporator outlet, kg/s
ρ	: density of air, kg/m3
A	: area of evaporator outlet, m^2
V	: air velocity, m/s
Δh_{air}	: enthalpy difference between return air and leaving air at evaporator, kJ/kg
h_1	: enthalpy of refrigerant at inlet side of compressor, kJ/kg
h_2	: enthalpy of refrigerant at exit side of compressor, kJ/kg
h_4	: enthalpy of refrigerant at entry side of evaporator, kJ/kg
m_{ref}	: mass flow rate of refrigerant R-22, kg/s