International Journal of Heat and Technology
Vol. 42, No. 3, June, 2024, pp. 1073-1080
Journal homepage: http://iieta.org/journals/ijht

Enhancing Air Conditioner Efficiency Through Evaporative Cooling of the Compressor: Field Test Results

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https://doi.org/10.18280/ijht.420334

Received: 29 March 2024
Revised: 7 May 2024
Accepted: 22 May 2024
Available online: 27 June 2024

Keywords:
evaporative cooling, condensate water, cooling capacity, coefficient of performance

ABSTRACT

Energy demand for the air conditioning sector is increasing due to increasing population, increasing living standards, and global warming. This increase in demand must be accompanied by efforts to increase energy efficiency. Evaporative cooling is one effort that can be chosen to increase the energy efficiency of the air conditioning system. The use of evaporative cooling by utilizing condensate water from the evaporator has been experimentally investigated. This research was conducted directly on an air conditioner unit that had already been installed in a room. Specifically, experiments were carried out by flowing and dripping condensate water into the compressor body of an air conditioner and examining its effect on the performance of the air conditioner. The research results show that the use of condensate water can reduce suction temperature, discharge temperature and condensation temperature by 0.7℃, 3.2℃, and 1.2℃, respectively. As a result, cooling capacity increases by 2.8%, energy consumption decreases by 3.5%, and energy efficiency ratio increases by 7.6%. Overall, the use of condensate water for compressor cooling can improve air conditioner performance.

1. INTRODUCTION

The demand for energy for buildings increases due to the increase of human population and living standards. In addition, global warming also affects the demand for energy. Planning of energy supply in the future requires an understanding of technology uptake [1]. Combined with climate change issue, the energy demand for cooling purposes will also considerably increase [2]. The global cooling days could increase significantly due to a small increase in mean temperature. This could cause a notably increase in demand of energy for cooling [3]. To reduce the rate of increase in energy demand, various efforts have been made, including by utilizing evaporative cooling.

Evaporative cooling is a process of cooling the surrounding by employing the evaporation of water. This technique has been used by humans for centuries and extensive studies to determine its efficiency have been carried out. In this process, air is cooled and humidified due to the interaction of air and water [4]. This system can be combined with an air conditioning system or can be used separately. Because it does not require a compressor in the process, this system can reduce the use of energy and the rate of environmental damage [5].

The performance of an evaporative cooler depends on the ambient conditions, including its dry-bulb and wet-bulb temperature. It is also affected by the material used for the evaporative pads. Natural fibers are popular materials used for the pads. Palm fibers have a low efficiency, but it is widely used due to its abundant availability [6, 7]. Despite having a high pressure drop, rice husk can also be used for evaporative pads with an efficiency up to 59%. Lotfizadeh et al. [8, 9] reported that aspen fibers have a moderate cooling efficiency. A maximum cooling efficiency of 69% has been reported by Adekanye et al. [10] by use of jute fibers. The higher efficiency was obtained by the use of coconut fiber with an efficiency up to 85% [11]. Various materials, such as coconut, jute, and cotton fiber, have been utilized by Naveenprabu and Suresh [12]. Among the materials studied, cotton fiber has the highest cooling efficiency, up to 95%. In addition, it also has a small pressure drop [4]. However, it has a limitation, i.e., its cost is higher than that of other materials.

Evaporative coolers can be classified as direct and indirect evaporative cooling systems [13]. A direct evaporative cooler and indirect evaporative cooler can be operated individually. However, combination of both types could improve its efficiency, resulting in an energy saving up to 82% over the conventional cooling [14, 15]. The direct evaporative cooler can be categorized as active and passive. An active evaporative cooler is operated using an electrical device while the passive evaporative cooler is operated naturally without assistance of a fan [16, 17].

Modification of water spray could enhance the heat transfer between air and water. This could improve the cooling efficiency [18]. The improvement of cooling efficiency could also be achieved by the pad design and the honeycomb can be considered as the best that offers the higher heat transfer area for water evaporation [19].

In an air conditioning application, evaporative cooling can be utilized to improve the performance of an air conditioner. A study by Martínez et al. [20] showed that the use of an evaporative cooler lowered the power consumption by 11% and increased the cooling capacity by 1.8%. In a chiller, the use of evaporative cooler employing cold water could reduce the power and increase the coefficient of performance (COP) [21]. A study in a window air conditioner showed that the use of evaporative cooler could save energy up to 13% [22].

A decrease of condensing temperature by 2.2℃ and power consumption by 6.3% have been reported form an experiment of discharge cooling by using condensate water [23]. Meanwhile, an improvement of COP up to 16.4% has been reported for the use of condensate water to cool the discharge line of an air conditioner employing evaporative cooling principle [24]. A study on variation of the length of heat exchanger for discharge cooling using condensate water has also been carried out. It resulted in the improvement of cooling capacity up to 14.9% [25]. This study also reported that this method could produce a degree of subcooling up to 4.5 Kelvin.

This paper reports on the application of evaporative cooling to improve the performance of a room air conditioner. Specifically, the experiments were carried out by flowing and dripping condensate water into the compressor body of an air conditioner. Its effect on the performance of the air conditioner is the examined.

Unlike previous studies and publications, this research was conducted directly on an air conditioner unit that had already been installed in a room, not a laboratory test. Thus, this research provides more relevant and applicable results by directly observing and analyzing the performance in everyday use conditions. The evaporative cooler utilized the condensate produced by condensation of water vapor in the evaporator. The condensate dripped directly to the compressor body to cool the compressor. Its effect on the COP, power consumption, and cooling capacity of the air conditioner was analyzed. The capacity is calculated at the air side. Therefore, the COP is calculated as the ratio of the air side capacity and power consumption.

2. METHODOLOGY

The study was conducted in a staff room, located in Air Conditioning Laboratory, Department of Refrigeration and Air Conditioning Engineering, Politeknik Negeri Bandung. In this experiment, the indoor unit of the air conditioner was installed in the staff room. The outdoor unit was installed outdoors but is protected by a building balcony so that it is not exposed to direct sunlight. Due to the existence of balcony as a sunlight barrier, the outdoor environment has a small temperature fluctuation. An air conditioner with a nominal compressor capacity of 1 hp and nominal cooling capacity of 2.64 kW was used in this experiment.

The tests were carried out by operating the air conditioner and measuring temperature, pressure, electric current, voltage, power, and air velocity. The suction temperature and suction pressure were measured at suction line, indicated by point 1 (see Figure 1). The discharge temperature and discharge pressure were measured at discharge line, indicated by point 2. The condensing temperature was measured at condenser outlet (point 3) while the refrigerant entering the evaporator was measured at point 4. All these variables are used for analyzing the performance of the air conditioner from refrigerant side. Suction pressure, discharge pressure, suction temperature, discharge temperature, and condensing temperature can be used to describe the working conditions of an air conditioner.

For the air side, the parameters used are dry-bulb temperature (DBT) and wet-bulb temperature (WBT) of air entering the evaporator (point 5), DBT and WBT of air leaving the evaporator, and air velocity across the evaporator. Current, voltage, and electric power are used to analyze the power consumption of the AC unit.

To measure the air and refrigerant piping temperature, type K thermocouples with an accuracy of ±0.2% of reading and ±0.5℃ were employed. Two Pico data logger TC-08 were used for temperature data acquisition. The pressure of refrigerant in the discharge and suction line were measured using analog pressure gauge with accuracy of ±0.34 bar and ±0.07 bar for high-pressure side and low-pressure side, respectively. The volumetric flow rate of air across the evaporator was determined by measuring the air velocity at evaporator outlet using digital rotating vane anemometer with an accuracy of 3% full-scale. The electric parameters, involving current, voltage, and power were measured by using digital power meter with an accuracy of 1.7% reading for active power.

The performance of the air conditioner is expressed in cooling capacity, power consumption, and coefficient of performance (COP). The cooling capacity can be determined from Eq. (1).

$$q_e = \dot{m}\,\Delta h \tag{1}$$

Here, q_e denotes the cooling capacity or evaporator capacity, $\dot{m}$ denote the mass flow rate of air flowing across the evaporator, and Δh expresses the enthalpy difference of air entering and leaving the evaporator. The enthalpy of air was determined by using DBT and WBT data of air entering and leaving the evaporator.

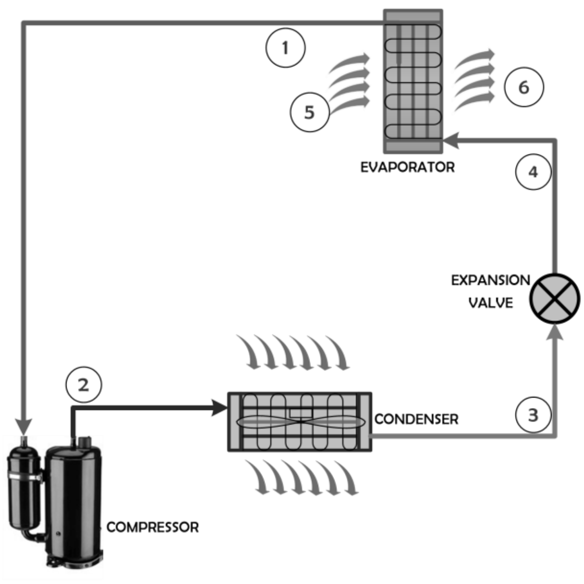

Figure 1. Schematic diagram of a split AC

The mass flow rate of air can be determined from the product of air volumetric flow rate (Q) across the evaporator outlet and air density (ρ), or:

$$\dot{m} = Q\rho \tag{2}$$

The density of air can be determined if the DBT and WBT are known. As the volumetric flow is the product of cross-sectional area and air velocity, then Eq. (2) can be expressed as:

$$\dot{m} = v\, A\, \rho \tag{3}$$

where, v is the average air velocity and A the cross-sectional area of evaporator air outlet. The air velocity can be obtained from measurement using rotating vane anemometer at the evaporator outlet.

Combining Eqs. (1) and (3) results in:

$$q_e = v\, A\, \rho\, \Delta h \tag{4}$$

or:

$$q_e = v\, A\, \rho\, (h_1 - h_2) \tag{5}$$

where, h_1 and h_2 are the air enthalpy at evaporator inlet and outlet, respectively. In Eq. (5), the air velocity and the cross-sectional area at the evaporator outlet can be directly obtained from measurement. The air density and air enthalpy can be obtained from the measurement of DBT and WBT at the evaporator inlet and outlet.

To determine the coefficient of performance (COP), the following equation can be used.

$$COP = \frac{q_e}{P} \tag{6}$$

where, P is the required power to operate the AC. Power can be obtained from direct measurement by a power meter or by measurement of electric current and voltage. Eqs. (1) to (6) have also been used for determining the performance of an air conditioner in terms of cooling capacity, power consumption, and COP in previous publications [26-31].

3. RESULTS AND DISCUSSION

3.1 Ambient temperature

The profile of the ambient air where the outdoor unit is installed is presented in Figure 2. As can be seen, the fluctuations temperature is small because the staff room is semi open, located in a shady place, and not exposed to direct sunlight.

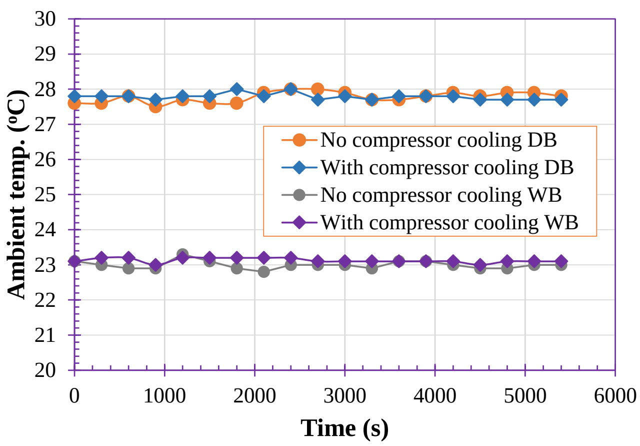

Figure 2. Profile of ambient DB and WB temperature for the AC test with compressor cooling and without compressor cooling

The first test, without compressor cooling, was carried out at ambient dry-bulb (DB) temperature range of 27.6℃ to 28.0℃ with an average of 27.8℃. The ambient wet-bulb (WB) temperature ranges from 22.9℃ to 23.3℃ with an average of 23.0℃. In the second test, with compressor cooling, the ambient DB temperature was recorded at a range of 27.7℃ to 27.9℃ with an average of 27.8℃, while the WB temperature is in the range of 23.1℃ to 23.3℃ with an average of 23.2℃. The relative humidity (RH) of the ambient air is about 65%, typical for tropical area.

What is emphasized from the result is that both tests are carried out under similar environmental conditions. Both outdoor dry-bulb temperature and wet-bulb temperature during the test are almost constant. Therefore, the results obtained during the tests are comparable.

3.2 Suction temperature and suction pressure

The test results show that compressor cooling using condensate water can reduce the suction temperature. Without compressor cooling, the suction temperature ranges from 6.2℃ to 7.1℃ with an average of 6.7℃. After cooling the compressor by condensate water, the suction temperature dropped to the range of 5.6℃ to 6.4℃ with an average of 6.0℃. The profile of suction temperature measurements with and without compressor cooling are given in Figure 3. A decrease in suction temperature can be caused by a decrease in discharge temperature and pressure which will be discussed in the next paragraph. The decrease of suction temperature could also be caused by the decrease of the temperature of the compressor body that causes a decrease in the temperature of the suction pipe. The decrease in suction temperature due to compressor cooling also causes a decrease in suction pressure. Figure 4 shows the profile of suction pressure resulted from the experiment.

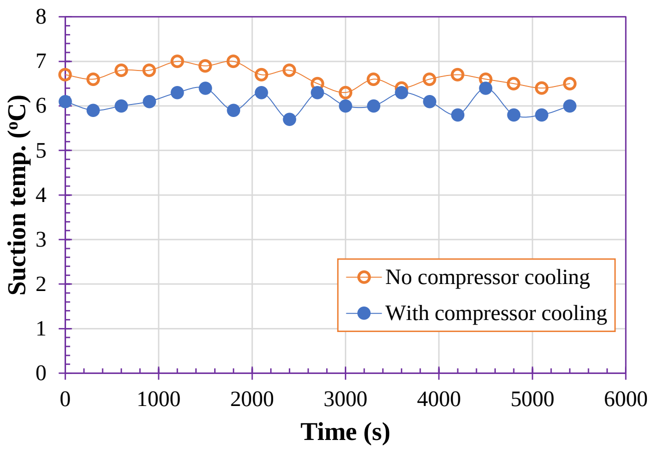

Figure 3. Suction temperature with compressor cooling and without compressor cooling

Without compressor cooling the suction pressure has a range of 7.0 bar to 7.3 bar with an average of 7.2 bar. After applying compressor cooling using condensate water from evaporator, the suction pressure decreases to the range of 6.9 bar to 7.2 bar with an average of 7.0 bar. A slight decrease in suction pressure was also resulted from an experiment using condensate water to cool the condenser air [32, 33]. The decrease in suction pressure in this experiment is mainly caused by the temperature drop due to compressor cooling because a decrease in temperature is usually accompanied by a decrease in pressure.

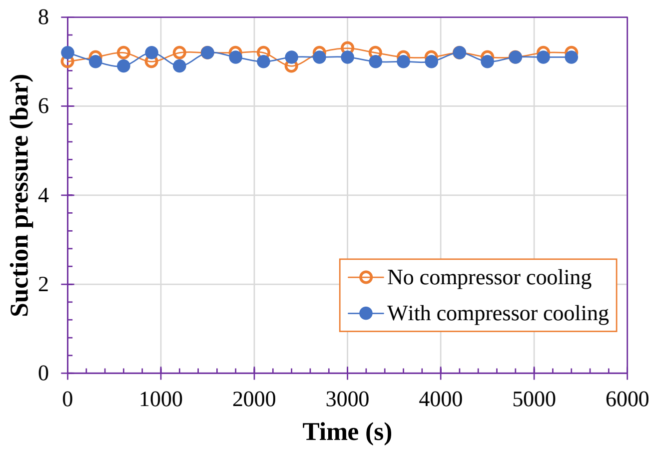

Figure 4. Suction pressure with compressor cooling and without compressor cooling

3.3 Discharge temperature and discharge pressure

On the discharge side, there is a significant temperature difference when the condensate water from the evaporator is used to cool the compressor. Without compressor cooling, the discharge temperature ranges from 69.9°C to 70.9°C with an average of 70.3°C. The range of discharge temperature is normal for an air conditioner using R410A. By applying the compressor cooling using condensate water, the discharge temperature range becomes 67.5 to 68.3°C with an average of 68.0. Therefore, the use of evaporator condensate to cool the compressor can reduce the discharge temperature by up to 2.3°C. The profile of discharge temperature from this experiment is provided in Figure 5.

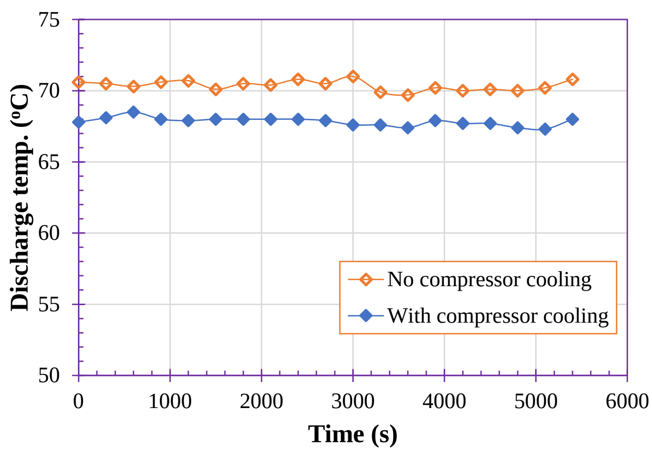

Figure 5. Discharge temperature with and without compressor cooling

As in discharge temperature, the pressure on the discharge side also slightly drops, as shown in Figure 6. Without cooling the compressor, the discharge pressure ranges from 23.4 bar to 23.8 bar with an average of 23.5 bar. After cooling the compressor, the discharge temperature drops to the range of 23.3 bar to 23.6 bar with an average of 23.4 bar. It indicates that the use of compressor cooling using condensate water could reduce the discharge pressure by 0.1 bar. A decrease of discharge pressure was also reported from an experiment of discharge line cooling by using condensate water [25].

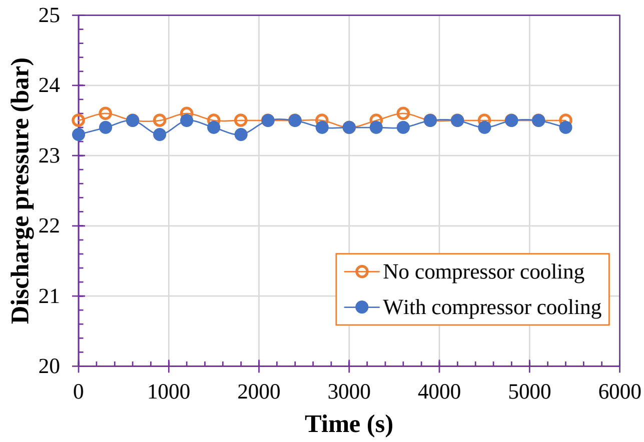

Figure 6. Discharge pressure with and without compressor cooling

3.4 Condensation temperature

The decrease in discharge temperature and pressure causes a decrease in condensation temperature. Without compressor cooling, the condensation temperature ranged from 37.9°C to 39.0°C with an average of 38.4°C. After cooling the compressor, the condensation temperature ranged from 36.5 to 38.4°C with an average of 37.2°C. Therefore, there is a decrease in condensation temperature by about 1.2°C. When compared with ambient temperature, the condensation temperature was 10.6°C higher during testing without compressor cooling. With compressor cooling, the condensation temperature was 9.4°C higher than that of ambient temperature. As a comparison, Aziz et al. [33] reported that condensing temperature decrease from about 38.5°C to 37°C by using evaporative media pad for lowering condenser air temperature. The condensation temperature profile with and without compressor cooling is presented in Figure 7.

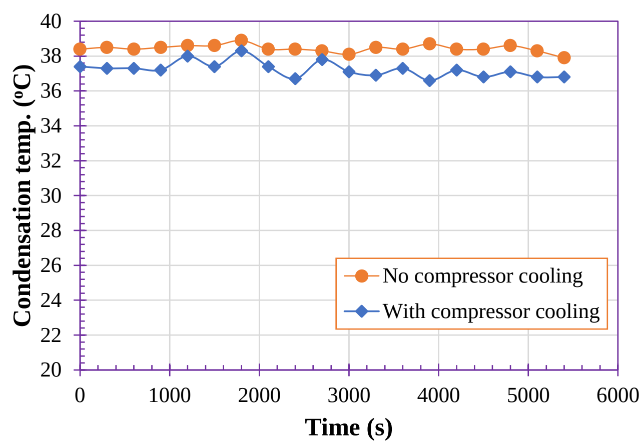

Figure 7. Condensation temperature with and without compressor cooling

3.5 Supply air temperature

The decrease in condensation temperature and suction temperature causes the supply air temperature that leaves the evaporator also decrease. This quantity was measured at the outlet of evaporator. Before compressor cooling, the supply temperature of the compressor ranges from 17.5°C to 17.8°C with an average of 17.7°C. After cooling the compressor, the supply temperature drops to an average of 17.35°C with a range of 17.2°C to 17.5°C. The supply air temperature profile is given in Figure 8.

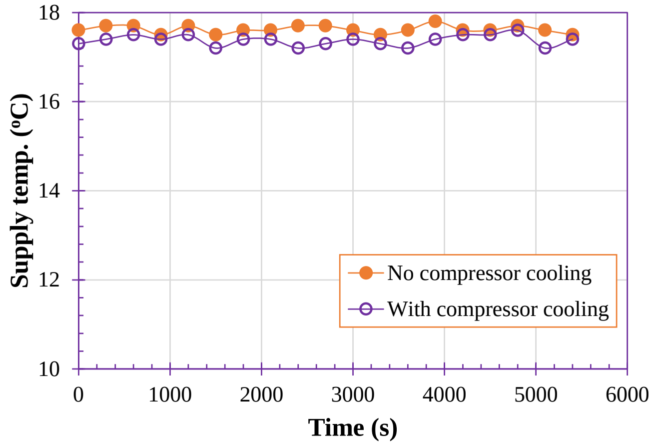

Figure 8. Supply air temperature with and without compressor cooling

3.6 Cooling capacity

The decrease in supply air temperature due to compressor cooling indicates that the AC is able to cool the air better. This can be seen from the cooling capacity profile presented in Figure 9. Cooling capacity expresses the ability of the air conditioner to remove heat in the air entering the evaporator. Simply, it is proportional to the mass flow rate and enthalpy difference between air entering and leaving the evaporator, as mentioned in Eq. (1). The lower the air temperature leaving the evaporator, the higher the cooling capacity.

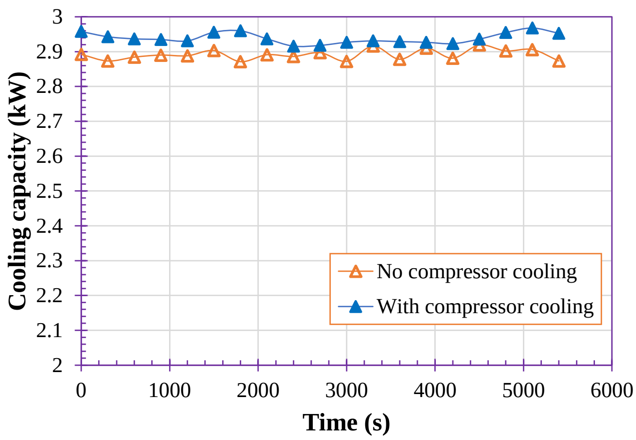

Figure 9. Cooling capacity of AC system with and without compressor cooling

Without compressor cooling, the cooling capacity of the AC ranges from 2.86 kW to 2.91 kW with an average of 2.89 kW. After compressor cooling, the cooling capacity increased to an average of 2.94 kW with a range of 2.91 kW to 2.97 kW. This means an average increase in cooling capacity of around 2.8%. Because the test was carried out at a relatively low ambient temperature of 27.6°C, the actual capacity produced is higher than that of nominal capacity.

As a comparison, an improvement of cooling capacity by 2.4% was reported from an experiment employing condensate water and heat exchanger with a length of 18 cm [25]. The improvement of cooling capacity increases to 4.8% when a heat exchanger with a length of 20 cm was used.

3.7 Power consumption

In addition to increasing cooling capacity, compressor cooling also reduces air conditioner energy consumption. Cooling the compressor results in more efficient compressor operation. With compressor cooling, the lubrication system will work better so as to reduce component friction. Before cooling the compressor, the air conditioner requires power between 0.742 kW and 0.753 kW with an average of 0.749 kW. After cooling the compressor, power consumption drops to a range of 0.711 kW to 0.717 kW with an average of 0.714 kW. In general, there is a decrease in power consumption of 3.5%. This improvement is lower than that achieved by Chen et al. [34] because the condensate water was only dripped directly into the compressor. In addition, some amount of water falls before evaporating and cooling the compressor. The profile of electrical power used by the air conditioner is presented in Figure 10.

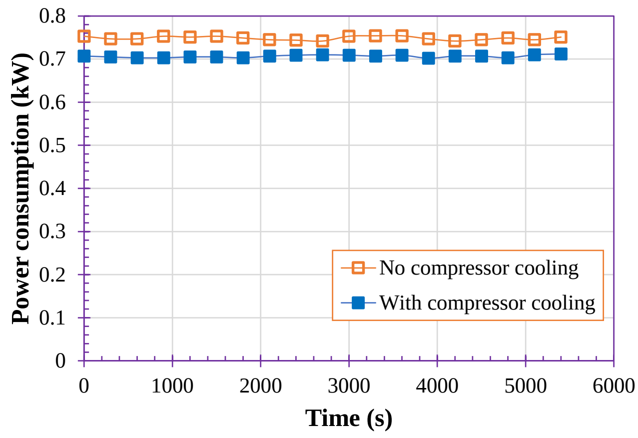

Figure 10. Power consumption with and without compressor cooling

3.8 Coefficient of performance (COP)

As the cooling capacity increases and the power consumption decreases, the coefficient of performance (COP) of the air conditioner increases. This can be seen in Figure 11. Without compressor cooling, the AC COP ranges from 3.82 to 3.91 with an average of 3.86. With compressor cooling, COP increases to a range of 4.06 to 4.16 with an average of 4.12. Overall, compressor cooling using condensate water from the evaporator increases COP by 7.6%. A similar range of COP from 3.90 to 4.35 was reported by Ketwong et al. [35] from an experiment using direct evaporative cooling. This result is also comparable to that of Chen et al. [34].

Even though the improvement of COP is quite significant, the use of condensate water for compressor cooling can be more effective if all the water evaporates in the compressor and can be directly used to cool the refrigerant. In fact, some of the water evaporates before it reaches the compressor. Therefore, not all water can be used to cool the refrigerant. Nevertheless, this performance increase is still quite good. It is because the condensate water used to cool the compressor can be obtained freely from the condensation of water vapor in the evaporator.

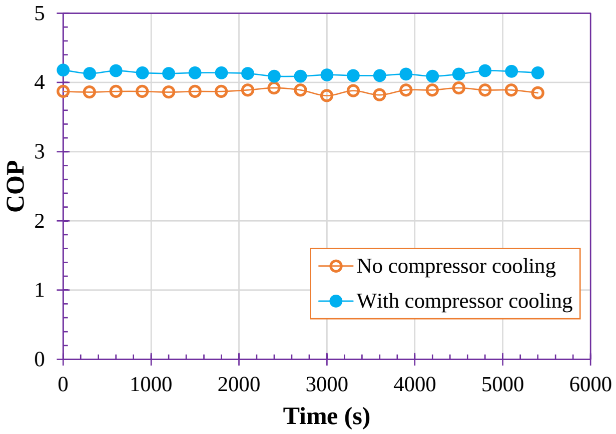

Figure 11. COP of AC system with and without compressor cooling

Table 1. Uncertainty from measurements

Parameter	Unit	AVG	SD	Instr. Unc.	Tot. Unc.
T. Ambient DB N	°C	27.8	0.15	0.07	±0.17
T. Ambient WB N	°C	23.0	0.11	0.07	±0.13
T. Ambient DB W	°C	27.8	0.09	0.07	±0.12
T. Ambient WB W	°C	23.1	0.07	0.07	±0.09
T. Suction N	°C	6.7	0.20	0.05	±0.20
T. Suction W	°C	6.0	0.22	0.05	±0.23
T. Discharge N	°C	70.3	0.35	0.15	±0.38
T. Discharge W	°C	68.0	0.29	0.14	±0.32
T. Condensation N	°C	38.4	0.21	0.09	±0.23
T. Condensation W	°C	37.2	0.44	0.09	±0.45
T. Supply N	°C	17.7	0.09	0.06	±0.11
T. Supply W	°C	17.3	0.12	0.06	±0.13
P. Suction N	bar	7.2	0.10	0.09	±0.13
P. Suction W	bar	7.0	0.09	0.09	±0.13
P. Discharge N	bar	23.5	0.07	0.35	±0.36
P. Discharge W	bar	23.4	0.07	0.35	±0.36

Notes: T - Temperature; P - Pressure; AVG - Average; SD - Standard Deviation; N - No Compressor Cooling; W - With Compressor Cooling; DB - Dry-bulb; WB - Wet-bulb; Instr. Unc - Instrument Uncertainty; Tot. Unc. - Total Uncertainty

3.9 Uncertainty analysis

Uncertainty analysis is carried out for validating results and enhancing scientific integrity. Statistical calculation and analysis combined with instrument precision and accuracy are used to determine the overall uncertainty. From the measurement of parameters used in this experiment, the mean of the measured parameter can be expressed by:

$$\bar{x} = \frac{\sum_{i=1}^{N} x_i}{N} \tag{7}$$

where, $\bar{x}$ is the arithmetic mean of the measurement, x_i is the result of the i-th measurement, and N is the number of samples. The standard deviation (σ) from the measurement can be calculated using:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N} (x_i - \bar{x})^2}{N}}. \tag{8}$$

By employing standard deviation and the accuracy and precision of the instruments, the overall uncertainty (U) can be determined using:

$$U = \sqrt{\sigma^2 + u_i^2}. \tag{9}$$

where, u_i is the uncertainty of the instrument, comprising uncertainty due its accuracy and precision.

The results of the measurements in this experiment and their uncertainties can be summarized in Table 1.

4. CONCLUSION

Experimental study on the use of condensate water to cool a compressor of a room air conditioner with a cooling capacity of 2.64 kW has been carried out. From the experiment, it is obvious that the use of condensate water could decrease the suction temperature 0.7°C and decrease the discharge temperature 2.3°C on average. In addition, the condensing temperature and supply air temperature could be reduced by 1.2°C and 0.4°C, respectively.

The decrease of supply air temperature causes the increase of cooling capacity from 2.89 kW to 2.94 kW or increase by 2.8%. The use of condensate water could also reduce the power consumption from 749 W to 714 Watt, or about 3.5%. The increase of cooling capacity and the decrease of power consumption results in the increase of coefficient of performance from 3.86 to 4.12 or increase by 7.6%. The important finding from this research is that the use of free condensate water for compressor cooling can improve the performance of an air conditioner.

ACKNOWLEDGMENT

The research and article preparation were supported by the Ministry of Education, Culture, Research, and Technology. The authors also thank Politeknik Negeri Bandung for its kind support during the implementation of the research.

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NOMENCLATURE

A	cross sectional area, m^2
COP	coefficient of performance
h	enthalpy, kJ kg^{-1}
$\dot{m}$	mass flow rate, kg s^{-1}
N	number of samples
P	input power, kW
q	cooling capacity, kW
Q	volumetric flow rate, m^3 s^{-1}
t	temperature, ℃
U	uncertainty
v	air velocity, m s^{-1}
x	value of measurement result
$\bar{x}$	arithmetic mean

Greek symbols

ρ	density (kg. m^{-3})
σ	standard deviation

Subscripts

e	evaporator

Abbreviations

DBT	dry-bulb temperature
WBT	wet-bulb temperature