



The Effect of Outdoor Air Temperature on Electricity Consumption in Split Type Air Conditioner: A Field Testing

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<https://doi.org/10.18280/ijht.440430>

ABSTRACT

Received: 13 June 2026

Revised: 9 August 2026

Accepted: 17 August 2026

Available online: 31 August 2026

Keywords:

outdoor air, electricity consumption, power input, cooling capacity, coefficient of performance

Electricity consumption by an air conditioner (A/C) is significantly affected by its performance. The parameters commonly used to indicate A/C performance are power input, cooling capacity, and coefficient of performance (COP). Air conditioning is considered to have better performance when the power input is lower, the cooling capacity is greater, and the COP is higher. A/C performance is affected by outdoor air temperature; the lower the outdoor air temperature, the higher the performance. In this study, the effect of outdoor air temperature on split A/C performance will be investigated quantitatively. This research was conducted on a split A/C with a power input of 840 W and using R32 as the working fluid. The study examines the effect of outdoor air temperature (19 °C–32 °C) on split A/C performance. Results show that each 1 °C increase leads to a 2.04% drop in COP and a 0.02 kWh rise in electricity consumption.

1. INTRODUCTION

Electrical energy consumption by buildings, both residential and commercial, globally accounts for 30% and contributes to global CO₂ emissions by 15% [1]. Meanwhile, air conditioning is the largest electricity consumer in buildings [2, 3]. Therefore, several technologies were developed to reduce electricity consumption, including inverters to regulate compressor rotation [4-6] and nanoparticles mixed in compressor lubricant [7-9]. In addition to the use of these technologies, the outdoor air temperature also greatly affects the A/C's electricity consumption.

Outdoor air conditions are generally expressed by dry tube temperature and relative humidity (RH). For the case in Indonesia, when the outdoor air temperature increases, the RH will decrease. For example, in the morning and evening, the outdoor temperature is lower than at noon, but the RH in the morning and evening is much higher than at noon [10, 11]. The nameplate generally states the A/C performance, e.g., cooling capacity 9000 Btu/h, power input 840 W. However, when installed, the cooling capacity and power input may differ from the nameplate, either higher or lower. For example, an A/C with a cooling capacity of 9000 Btu/h, when installed in the Jakarta area, which has a hot outdoor air temperature, can produce 9000 Btu/h according to specifications, but when installed in Bandung, which has a lower air temperature will produce a cooling capacity of more than 9000 Btu/h.

Outdoor air temperature greatly affects the performance of air conditioners, namely power consumption, cooling capacity, and coefficient of performance (COP) [12-14]. When

the temperature is low, the AC power input decreases and the cooling capacity increases. In other words, for the same A/C capacity and the same number of operating hours, the A/C electricity cost in Jakarta will be higher than that in Bandung, because the outdoor air temperature in Jakarta is higher than in Bandung, both in the morning, afternoon, and evening. One of the main reasons for the increase in electricity consumption due to high outdoor air temperature is that it increases the condensing temperature, resulting in increased compressor work [15, 16]. In other words, one method of improving split A/C performance to reduce electricity consumption is to place the outdoor unit in a shaded location that is not exposed to direct sunlight.

Some studies that discuss changes in AC performance due to changes in outdoor air temperature are among others Yau and Pean [14]; Joudi and Al-Amir [17]; Setyawan and Badarudin [18]; and Mitrakusuma et al. [19]. Yau and Pean [14] conducted tests on split A/C and reported that every 1 °C increase in outdoor air temperature resulted in a 2% decrease in cooling capacity and COP. Another study with split A/C was conducted by Joudi and Al-Amir [17] by varying the outdoor air temperature from 35 °C to 55 °C. Based on their test using R290 instead of R22 in a split A/C, they reported that power consumption increased from 2.2 kW to 2.75 kW, and COP dropped by 20.7%. Further research was conducted by Setyawan and Badarudin [18] on a split A/C with a capacity of 2 HP and a cooling capacity of 5272 W. The research was conducted indoors where the outdoor air condition could be controlled. Tests were conducted by varying the RH of the outdoor air, but the outdoor air temperature was maintained

constant. The results reported that changes in relative RH did not change the cooling capacity; the change that occurred was only 1.2% for changes in RH from 40% to 70%. Other research was conducted by Mitrakusuma et al. [19], who conducted their research on a split A/C using R32 as the working fluid and a cooling capacity of 2.6 kW. The study was conducted in a room where the outdoor air conditions can be controlled, namely by varying the outdoor air temperature while keeping the RH constant. The results reported that an increase in outdoor air temperature by 1 °C resulted in an increase in evaporating temperature, suction temperature, discharge temperature, and condensing temperature by 0.27 °C, 0.08 °C, 1.08 °C, and 1.04 °C, respectively. A 1 °C increase in outdoor air temperature also decreased the power input by 1.6%. Their research also reported that a 1 °C increase in outdoor air temperature decreased cooling capacity and EER by 1% and 2.1, respectively.

The purpose of this study is to quantitatively observe the change in performance of an installed split A/C due to changes in outdoor air temperature. The performance changes of A/C splits in previous studies [18, 19] were carried out in a room conditioned for testing (thermodynamic room), while in this study, observations were made on the installed A/C split. The outdoor air temperature at the unit location varies with natural conditions. In other words, this study only reports changes in split A/C performance due to temperature changes. While changes in RH in this study were not considered, research conducted by Setyawan and Badarudin [18] reported that changes in RH have no significant effect on split A/C performance when the outdoor air temperature is constant. Significant changes in AC performance are driven solely by outdoor air temperature variations [19]. Thermodynamically, when operating at high ambient temperatures, the refrigerant must be condensed at correspondingly higher pressures and temperatures, which necessitates greater compressor work and leads to higher energy absorption.

2. MATERIALS AND METHODS

2.1 Test facilities

Based on the specifications contained in the A/C nameplate, the research was conducted on a split A/C that has a cooling capacity of 9000 Btu/h with a power input of 840 W and uses R32 as the working fluid. The study was conducted on split A/Cs because this type is the most widely used in many countries [20, 21]. While R32 refrigerant is a type of refrigerant that began to be widely used in split air conditioners in Indonesia since 2015, in that year it was banned the use of R22 in new split A/C [22], because R22 still has a very high global warming potential (GWP) [23].

The tested air conditioner is shown in Figure 1. The indoor unit is installed in the room used for meetings, while the outdoor unit is placed outside the room on the west-facing side, so that in the afternoon, the outdoor unit is exposed to direct sunlight.

To get accurate data, this research utilized several pieces of equipment, namely a thermocouple, pressure gauge, clamp-on ammeter, and Voltmeter. The accuracy of each piece of equipment is shown in Table 1. From the table, it can be seen that the pressure gauge used to measure low pressure and high pressure has different accuracy and range.

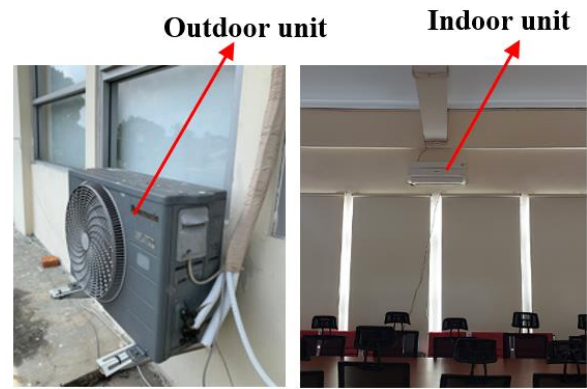


Figure 1. Outdoor and indoor split A/C unit as the object of testing

Table 1. The accuracies of measuring equipment

Equipment	Accuracy	Range
Thermocouple	± 0.1 °C	-50 to 1300 °C
High pressure gauge	± 0.5 bar	0 to 55 bar
Low pressure gauge	± 0.1 bar	-1 to 35 bar
Clamp-on-ammeter	± 0.1 A	0 to 600 V
Voltmeter	± 1 V	0 to 400 A

2.2 Test method

To obtain variations in outdoor air temperature, tests were conducted in the early morning, morning, noon, afternoon, and evening. The outdoor air temperature changes observed were 19 °C, 22 °C, 26 °C, 28 °C, and 32 °C. Based on the test, it was found that the split A/C performance changes due to changes in outdoor air temperature from the coldest to the hottest at the location where the air conditioner is installed. The A/C parameters that are observed to change due to changes in outdoor air temperature are suction and discharge temperatures and pressures, condenser outlet temperature, evaporator outlet temperature, and electric current.

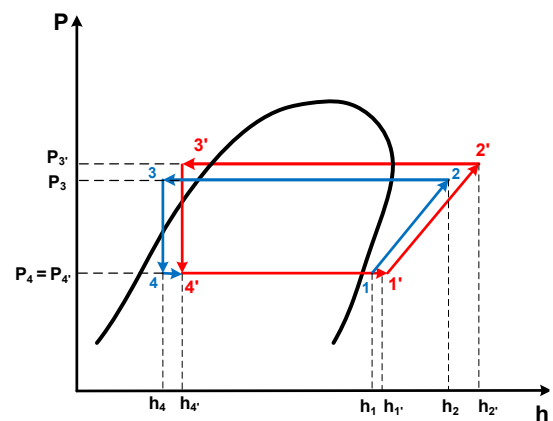


Figure 2. Refrigeration cycle of split-type A/C on the P-h diagram [24]

The measurement results for each outdoor air temperature will be depicted on a P-h diagram as shown in Figure 2. The figure shows two refrigeration cycles, which are colored blue and red. The blue line represents a lower ambient temperature, while the red line indicates a higher ambient temperature. It can be seen from the figure that the enthalpy difference (2'-1', red line) is higher than that of (2-1, blue line).

A higher enthalpy difference indicates higher power

consumption by the compressor. It can be seen in the figure that the increase in outdoor temperature results in an increase in compressor discharge pressure, from point 2 to point 2'. As a result of this increase in discharge pressure, the condensing temperature will increase. Because in this study five different outdoor air temperatures were tested, there will also be five refrigeration cycles with different values of evaporating and condensing temperatures on the P-h diagram.

Based on the P-h diagram in Figure 2, the equations to calculate compression work, power input, refrigeration effect, cooling capacity, COP, and electricity consumption are shown by the following equations:

$$W = (h_1 - h_2) \quad (1)$$

$$P = V \cdot I \quad (2)$$

$$\dot{m} = \frac{V \cdot I \cos \varphi}{(h_2 - h_1)} \quad (3)$$

$$RE = (h_1 - h_3) \quad (4)$$

$$Q = \dot{m}(h_1 - h_3) \quad (5)$$

$$COP = \frac{Q}{P} = \frac{(h_1 - h_3)}{(h_2 - h_1)} \quad (6)$$

$$EC = V \cdot I \cdot h \quad (7)$$

Meanwhile, to calculate the increase in electricity consumption and decrease in COP due to an increase in outdoor air temperature (from t_1 to t_2), Eqs. (8) and (9) are used,

$$P_{inc} = \frac{(P_{t2} - P_{t1})}{P_{t2}} \quad (8)$$

$$COP_{dec} = \frac{(COP_{t1} - COP_{t2})}{COP_{t1}} \quad (9)$$

where,

W = compression work

P = power input

RE = refrigeration effect

Q = cooling capacity

$\dot{m}$ = mass flow rate of refrigerant

$\cos \varphi$ = power factor

EC = electricity consumption

h_1 = specific enthalpy at point 1

h_2 = specific enthalpy at point 2

h_3 = specific enthalpy at point 3

P_{inc} = power input increment

COP_{dec} = COP decrement

P_{t1} = power consumption at t_1 (lower temperature)

P_{t2} = power consumption at t_2 (higher temperature)

Thermodynamically, the change in electricity consumption by air conditioners is not only measured by the change in power input to the compressor, but also by the change in cooling capacity generated by the evaporator. As an illustration, in the case of replacing refrigerant from R134a with R290 in a refrigeration machine [25], a 33.3% decrease in compressor power input was reported. However, because it was followed by a 51.0% decrease in cooling capacity, the

COP decreased by 26.3%. As the COP decreases, electricity consumption increases by the COP decrease, i.e., 26.3%. The increase in electricity consumption of the refrigerator or A/C is as much as the decrease in COP, not as much as the decrease in compressor power consumption, which is 33.3%. This explanation will be used as the basis for the results and discussion chapter.

3. RESULTS AND DISCUSSION

3.1 Effect on compressor

The easiest parameter to measure due to changes in outdoor air temperature in split air conditioners is the electric current in the compressor. An increase in outdoor air temperature leads to an increase in current, as seen in Figure 3. It can be seen in the figure that the smallest electric current occurs at an outdoor temperature of 19 °C, which is 3.53 amperes, and the largest at an outdoor temperature of 32 °C, which is 4.37 amperes. The relationship between the increase in electric current and the increase in outdoor temperature is not exactly linear, as there is a significant increase from the outdoor temperature of 26 °C to 28 °C. If the graph in Figure 3, the linear regression line is drawn, the increase in electric current to the increase in outdoor air temperature is about 0.074 A per 1 °C increase in outdoor air temperature.

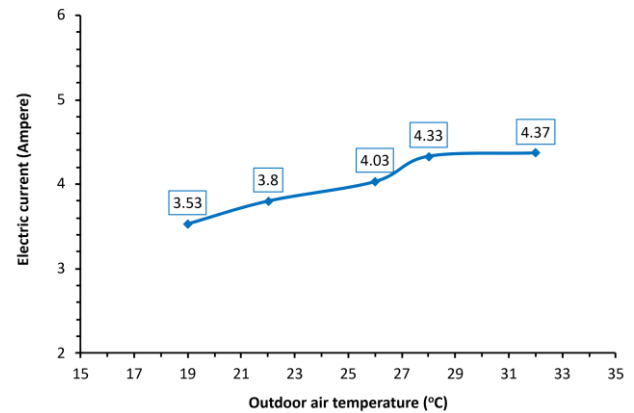


Figure 3. Electric current vs. outdoor air temperature

Based on the electric current data in Figure 3 and using Eq. (2), the power input of the compressor is shown in Figure 4. It can be seen from the figure that for outdoor temperatures of 19 °C and 22 °C, the power input of the split AC is lower than the value written on the nameplate, which is 840 W. The power input at 19 °C and 22 °C is 776.5 W and 836.0 W, respectively. The power input is above the value written on the nameplate when the outdoor air temperature is above 22 °C. If a linear regression line is drawn, each 1 °C increase in outdoor air temperature results in an increase in power input of approximately 16.3 W.

Figure 4 also shows that the increase in power input from an outdoor temperature of 19 °C to 32 °C is 184.9 W, or an increase of about 23.7% for an outdoor temperature difference of 13 °C. In other words, the increase in power input for every 1 °C increase in outdoor air temperature is about 1.8%. This increase in power input is slightly higher than that reported by Mitrakusuma et al. [19], which is 1.6%. This difference occurred because the research conducted by Mitrakusuma et al. [19] was conducted in a test room where the RH of the

outdoor air was maintained constant at 50%. Whereas in this study, the RH of the outdoor air was not regulated and followed the outdoor air temperature. In this study, the RH of the outdoor air was always higher than in the test conducted by Mitrakusuma et al. [19], because the RH of the outdoor air during the tests was always above 70%.

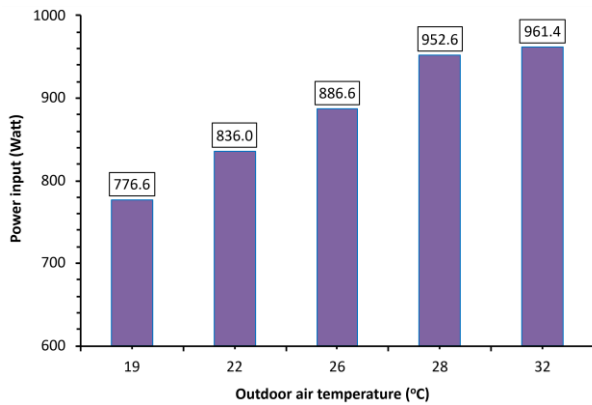


Figure 4. Power input vs. outdoor air temperature

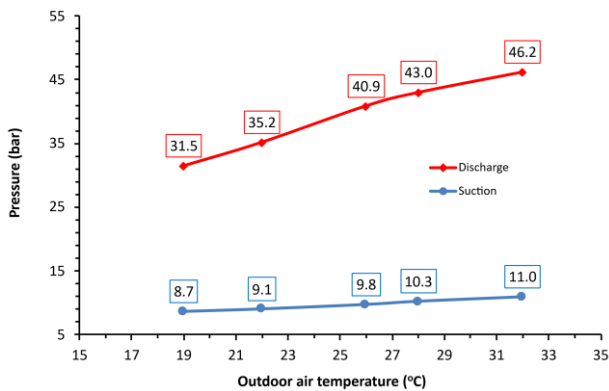


Figure 5. Discharge and suction pressures vs. outdoor air temperature

The increase in power input to the split A/C is due to an increase in discharge pressure. The discharge temperature increases when the outdoor air temperature increases. The relationship between discharge pressure and outdoor air temperature is shown in Figure 5. The figure shows that in addition to increasing the discharge pressure, an increase in outdoor air temperature will also increase the suction pressure, but the increase in suction pressure is not as high as the increase in discharge pressure. This means that the compression ratio, which is the ratio of the discharge pressure to the suction pressure of the compressor, increases as the outdoor air temperature increases. This increase in compression ratio causes the compressor power input to increase as well. At an outdoor air temperature of 19 °C, the compression ratio is 3.6 (31.5/8.7) and becomes 4.2 (46.2/11.0) at an outdoor temperature of 32 °C. This increase in compression ratio due to increased external temperature is similar to that reported by Mitrakusuma et al. [19], but the values are different. The compression ratio reported by the study of Mitrakusuma et al. [19] was 1.94 to 2.08 for outdoor temperatures from 24 °C to 30 °C, while in this study it was from 3.6 to 4.2 for outdoor temperatures from 19 °C to 32 °C.

The increase in compression ratio due to the increase in outdoor air temperature affects the compression work, as shown in Figure 6. The figure indicates that the compression

work increases with increasing outdoor air temperature. The increase in compression work is due to the increase in discharge pressure being greater than the increase in suction pressure, so that, based on Figure 2, the increase in h_2 value is greater than the increase in h_1 value for each increase in outdoor air temperature. The work of compression is calculated by Eq. (4), which is the difference between h_2 and h_1 , so that the increase in h_2 value due to the increase in outdoor air temperature results in an increase in the refrigeration effect.

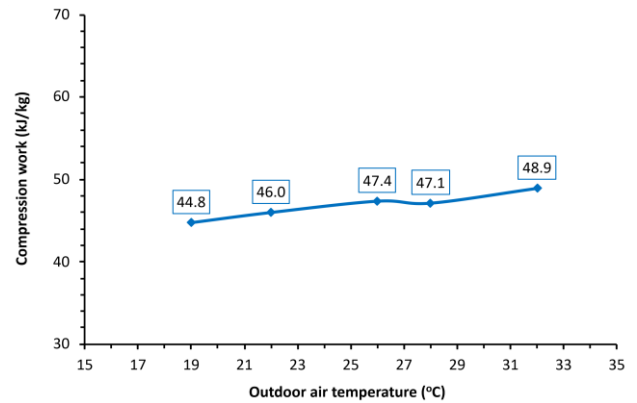


Figure 6. Compression work vs. outdoor air temperature

3.2 Effect on condensing and evaporating temperatures

Due to changes in compressor suction and discharge pressures, there will be changes in condensing and evaporating temperatures, as shown in Figure 7. Due to the increase in outdoor air temperature, in addition to causing an increase in condensing temperature, it also causes an increase in evaporating temperature. However, the increase in evaporating temperature is not as high as the increase in condensing temperature. The condensing temperature increases from 50.1 °C (at 19 °C outdoor temperature) to 67.5 °C (at 32 °C outdoor temperature), while the evaporating temperature increases from 2.1 °C to 9.8 °C when the temperature is increased from 19 °C to 32 °C. This means that the condensing temperature increases by 17.4 °C and the evaporating temperature increases by 7.7 °C for an increase in outdoor air temperature from 19 °C to 33 °C.

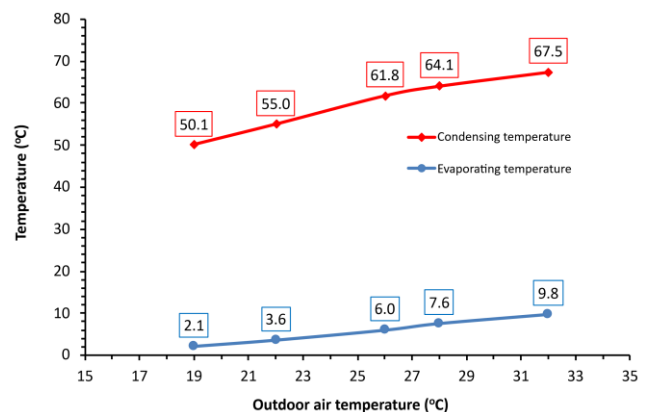


Figure 7. Condensing and evaporating temperatures vs. outdoor air temperature

The next impact due to the increase in condensing and evaporating temperatures is on the condenser outlet

temperature, as seen in Figure 8. The figure shows that the outlet temperature of the condenser increases as the outdoor air temperature increases, from 31.3 °C to 36.7 °C. Due to the increase in outdoor air temperature from 19 °C to 32 °C, the outlet temperature of the condenser increases from 31.3 °C to 36.7 °C, or a temperature increase of 5.4 °C for a 13 °C increase in outdoor air temperature. In other words, the condenser outlet temperature increases by 0.42 °C for every 1 °C increase in outdoor air temperature.

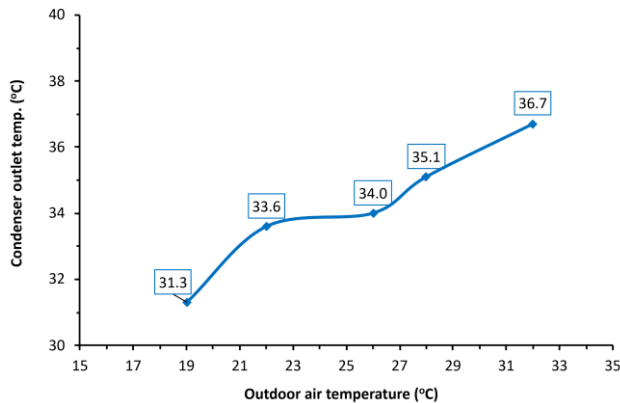


Figure 8. Condenser outlet temperature vs. outdoor air temperature

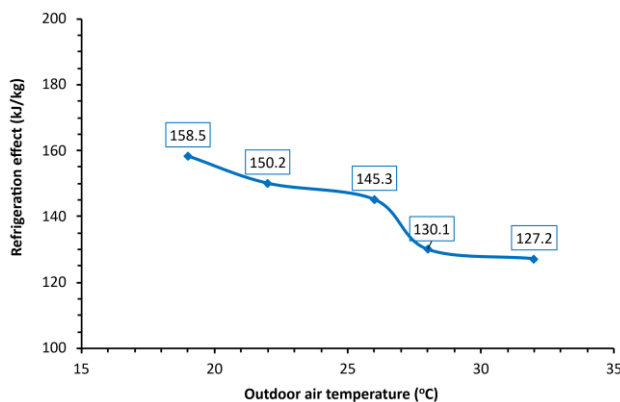


Figure 9. Refrigeration effect vs. outdoor air temperature

Increasing the condenser outlet temperature results in a decrease in the refrigeration effect because, based on Figure 2, the enthalpy value at the condenser outlet is at point 3. Since the refrigeration is calculated by Eq. (4), the refrigeration effect will decrease as the condenser outlet temperature increases, as shown in Figure 9. The figure shows that the refrigeration effect decreases from 158.5 kJ/kg to 127.2 kJ/kg when the outdoor air temperature increases from 19 °C to 32 °C. This means that for an increase in outdoor air temperature of 13 °C, the refrigeration effect drops by 31.3 kJ/kg, or a decrease of 2.41 kJ/kg for every 1 °C increase in outdoor temperature.

Using the data in Figure 9 and using Eq. (5), the cooling capacity is calculated and shown in Figure 10. In the figure, the cooling capacity decreases as the outdoor air temperature increases, i.e., from 2,750 kW to 2,500 kW for the outdoor temperature from 19 °C to 32 °C. This means that for an increase in outdoor air temperature of 13 °C, there is a decrease in cooling capacity of 250 W, or a decrease of 9.09%. Therefore, the average decrease in cooling capacity per 1 °C increase in outdoor air temperature is 0.70%. This decrease in

cooling capacity in this study is lower than the research conducted by Yau and Pean [14], which is 2% for every 1 °C increase in outdoor air temperature. Yau and Pean [14] conducted their research with modelling and did not consider RH variations due to changes in outdoor air temperature.

The decrease in cooling capacity due to an increase in outdoor air temperature in this study is also slightly lower when compared to the research conducted by Mitrakusuma et al. [19], which is 1% for every 1 °C increase in outdoor temperature. This means that the results of this study are also lower than those of the research conducted by Mitrakusuma et al. [19]. This difference may be due to differences in RH when collecting data. In the research conducted by Mitrakusuma et al. [19], the increase in outdoor temperature was not followed by an increase in RH because the RH of the outdoor air was maintained constant at 50%. Whereas in this study, the RH of the outdoor air followed the outdoor air temperature. In this study, when the outdoor air temperature is low, the RH of the air is very high, which is above 90%. The differences between the results of this study and other studies require further study.

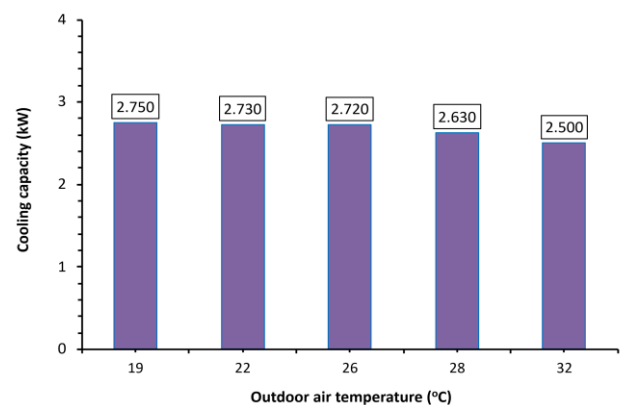


Figure 10. Cooling capacity vs. outdoor air temperature

3.3 Effect on coefficient of performance and electricity consumption

In the previous section, it was explained that an increase in outdoor air temperature will result in an increase in power input and a decrease in the cooling capacity of the split A/C. Based on Eq. (6), a decrease in cooling capacity and an increase in cooling capacity leads to a decrease in COP. The decline in COP due to the increase in outdoor air temperature is illustrated in Figure 11. The figure shows that the highest COP value occurs at an outdoor air temperature of 19 °C, which is 3.54, while the lowest COP value is observed at 32 °C, which is 2.60. This means that with an increase in temperature of 13 °C, i.e., from 19 °C to 32 °C, the split A/C experienced a decrease in COP of 26.55%, or an average of 2.04% for every 1 °C increase in outdoor air temperature. In this study, the decrease in COP due to an increase in outdoor air temperature is more dominantly due to an increase in power input, which is 1.48%, rather than a decrease in cooling capacity, which is only 0.70% for every 1 °C increase in outdoor air temperature. Based on the p-h diagram, an increase in outdoor temperature raises the enthalpy difference during the compression process more significantly compared to the reduction in the enthalpy difference of the evaporation process.

The average decrease in COP of 2.04% for every 1 °C increase in outdoor air temperature is the same as the results

conducted by Yau and Pean [14], which is 2%. The results of the decrease in COP in this study are also almost the same as the results reported by the research of Mitrakusuma et al. [19], which is 2.1%; the difference is only 0.1%. In other words, the decrease in COP due to an increase in outdoor air temperature every 1 °C both in theory [14] and experiment [19] and this study yielded the same result, which is approximately 2%.

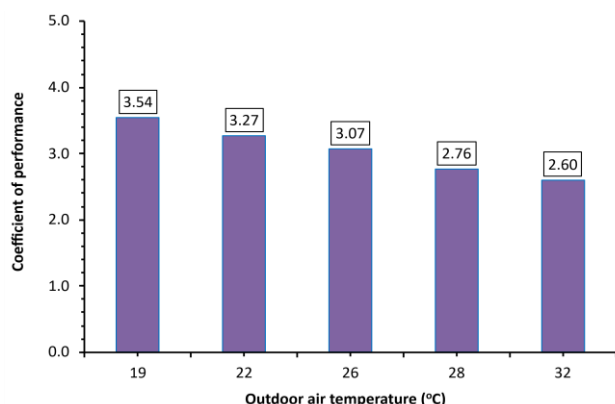


Figure 11. Coefficient of performance (COP) vs. outdoor air temperature

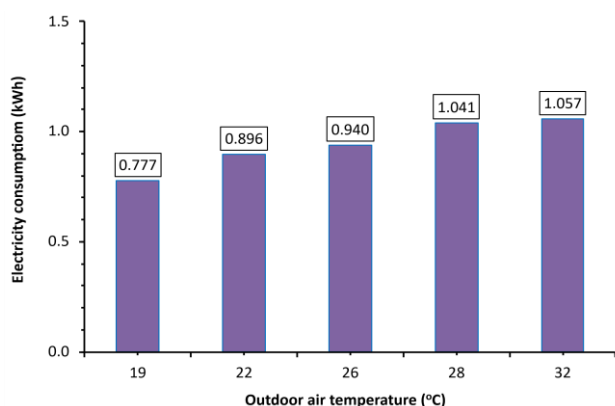


Figure 12. Electricity consumption vs. outdoor air temperature

As previously explained, a decrease in COP results in an increase in electricity consumption, where the magnitude of the increase in electricity consumption is equal to the reduction in COP. Figure 12 shows the split A/C electricity consumption from 19 °C to 32 °C outdoor air temperature, where it is assumed that the air conditioner operates for one hour for each outdoor air temperature. At an outdoor air temperature of 19 °C, the electricity consumption is 0.777 kWh, while at an outdoor air temperature of 32 °C, the electricity consumption is 1.057 kWh, or a difference of 0.28 kWh. As a result, the average increase in electricity consumption per 1 °C increase in outdoor air temperature is 0.02 kWh. This 0.02 kWh increase in electrical energy consumption per 1 °C increase in outdoor air temperature is equivalent to a 2.04% increase in electrical energy consumption for every 1 °C increase in outdoor air temperature.

Overall, this study demonstrates the significant impact of rising outdoor air temperature on the electrical power consumption of split-type air conditioners. Consequently, the placement of the outdoor unit (condenser) should avoid direct exposure to sunlight.

4. CONCLUSIONS

This study presents quantitative data on the changes in split A/C performance due to changes in outdoor air temperature. The main performance changes of the split A/C, namely power input, cooling capacity, and COP, were discussed. The data showed that the higher outdoor air temperature led to an increase in power input and a decrease in cooling capacity and COP. The average increase in power input and decrease in cooling capacity for each 1 °C increase in outdoor air temperature were 1.48% and 0.70%, respectively. The increase in power input and decrease in capacity resulted in a decrease in COP. With the decrease in COP, the split AC electricity consumption also increased. The average COP decrease per 1 °C increase in outdoor temperature was 2.04%. The increase in electricity consumption from 19 °C to 32 °C outdoor temperature was 0.28 kWh, or an average of 0.02 kWh for each 1 °C increase in outdoor air temperature.

ACKNOWLEDGMENT

The authors would like to thank the Department of Electrical Engineering and Refrigeration and Air Conditioning Engineering of Politeknik Negeri Bandung for allowing the use of their facilities for this research.

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NOMENCLATURE

W	compression work, W
P	power input, W
RE	refrigeration effect, kJ·kg ⁻¹
Q	cooling capacity, W
$\dot{m}$	mass flow rate of refrigerant, kg·s ⁻¹
$\cos \varphi$	power factor
EC	electricity consumption, W.h
h_1	specific enthalpy at point 1, kJ·kg ⁻¹
h_2	specific enthalpy at point 2, kJ·kg ⁻¹
h_3	specific enthalpy at point 3, kJ·kg ⁻¹
P_{inc}	power input increment
COP_{dec}	COP decrement
P_{t1}	power consumption at t_1 (lower temperature)
P_{t2}	power consumption at t_2 (higher temperature)