

Energy savings in residential air conditioners using condensate cooling in discharge and liquid lines

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Abstract

This research investigates the use of condensate produced by the evaporator to cool the discharge and liquid lines in order to reduce electricity consumption in a residential split-type air conditioner (AC). The experimental setup used a 0.75 kW compressor with R32 refrigerant, where the discharge and liquid line heat exchangers were 20 cm and 15 cm long, respectively. Data were collected over 180 minutes at 5-minute intervals. Results show that using the liquid line cooler (LLC) alone reduced electricity consumption by 5.3% and increased cooling capacity by 2.3%. Using the discharge line cooler (DLC) alone reduced electricity consumption by 8.3% and increased cooling capacity by 7.3%. When both coolers were applied simultaneously (LDC mode), electricity consumption decreased by 10.9% and cooling capacity increased by 9.7%. The corresponding improvements in coefficient of performance (COP) were 9.1% (LLC), 18.6% (DLC), and 24.7% (LDC). These results indicate that using condensate to both the discharge and liquid lines is more effective in reducing electricity consumption and improving AC performance than cooling only one line.

Keywords:

Condensate, discharge line, liquid line, residential AC, COP improvement

1 Introduction

The most significant consumption of electrical energy in residential areas is by Air Conditioning (AC), which is about 50% [1]-[4]. The solution to reduce the percentage of AC electricity consumption is to improve its performance. One of the methods that has been implemented to improve the performance of residential AC is the inverter [5]-[7]. The function of the inverter is to adjust the compressor rotation so that the compressor rotation works optimally, following the cooling load in the conditioned room. Using inverters reduced electrical energy consumption by more than 10% [8]-[10]. A decrease in electrical energy consumption will reduce the global warming effect indirectly from the refrigeration sector [11], [12]. Based on research conducted by Cabello et al. [12], the contribution of the refrigeration sector to global warming can be direct or indirect. The contribution directly comes from refrigerant leakage, and indirectly comes from power consumption, which are 37% and 63%, respectively [11], [12]. This means that improving AC performance

reduces operating costs for AC users but also reduces the global warming effect of the AC sector.

Another method to improve the performance of residential AC that is still under investigation is to utilize the condensate produced by the evaporator. In general, there are two methods of utilizing condensate to improve performance: the first is using the Evaporative Cooling (EC) principle to cool the air that will cool the condenser [13]-[16], while the second is using condensate as a Discharge Line Cooler (DLC) [17], [18]. Sawan et al. [13] tested split AC in the hot months, namely June, August, and October, using EC in front of the outdoor unit to cool the air before passing through the condenser. Due to the principle of EC, the temperature dropped by several degrees and decreased power consumption by 5.0%, 4.5%, and 5.3% in June, August, and October, respectively. Similar research was conducted by Ibrahim et al. [14] using a split AC with a cooling capacity of 1.5 tons of refrigeration. They reported that the EC method of air before passing through the condenser surface can reduce power consumption by 6.1% and increase cooling capacity simultaneously. As a result of the decrease in power consumption and the increase in cooling capacity, the COP increased by 21.4%. Still using the principle of EC, research was conducted by Sawant et al. [15] on the AC window. They reported that the method can reduce input power by 13% and increase COP by 18%. Similar research to Ibrahim et al. [14] was conducted by Yang et al. [16]. The results reported that split AC energy consumption decreased by 8.1% - 9.5% and COP increased by 20%.

In contrast to the four studies above, Sumeru et al. [17], [18] utilize condensate as a discharge line cooler. Research using a split AC with a compressor capacity of 0.75 kW using R410A refrigerant has resulted in a 5.9% decrease in power consumption and a 16.4% increase in COP [17]. A relatively significant increase in COP due to an increase in cooling capacity due to a decrease in condenser outlet temperature (subcooling) by 2.7°C [17]. Similar research was conducted on a split AC using R32 refrigerant and varying the length of the heat exchanger installed on the discharge line, namely 18 cm, 20 cm, and 22 cm [18]. The results reported that the COP improvements for 18 cm, 20 cm, and 22 cm were 9.1%, 14.4%, and 27.3% [18], respectively.

In contrast to the research conducted by Sumeru et al. [17], [18], where condensate is used only as a discharge line cooler, this study aims to utilize condensate as a discharge line and liquid line cooler. The method that will be developed in this study is expected to improve performance more when compared to the method done by Sumeru et al. [17], [18].

2 Materials and methods

2.1 Test facilities

This study was conducted on a split-type AC with a compressor capacity of 0.75 kW and using R32 as the refrigerant. The test was conducted on an AC that was installed in an office. The schematic diagram of the AC test is shown in Fig. 1. The evaporator is inside the indoor unit placed in the conditioned room, while the compressor, condenser, and capillary tube are in the outdoor unit. The photo of the heat exchanger placement on the liquid line and discharge line on the outdoor unit is shown in Fig. 2. In the figure, there are two holes in the two heat exchangers, namely, an inlet from the condensate discharge and an outlet to discharge the condensate into the environment. The condensate is collected in a container before being discharged into the environment.

The properties of R32 are shown in Table 1 [19]-[22]. The table shows that the GWP (global warming potential) value of R32 is still quite high, at 675. The table also shows that the discharge temperature of R32 in AC with evaporation and condensation temperatures of 5 °C and 40 °C, and superheating of 10 K, is above 80 °C [22]. The high discharge temperature can potentially be lowered when cooled by condensate, because the condensate temperature is below 15 °C [17], [18]. The measuring instruments used are a thermometer, a pressure gauge, an ammeter, and a

voltmeter. The accuracy of these measuring instruments is shown in Table 2 [18]. From the table, the accuracy of the pressure gauge for low pressure is lower than that for high pressure. Measurement of electric current and voltage aims to determine the input power into the AC.

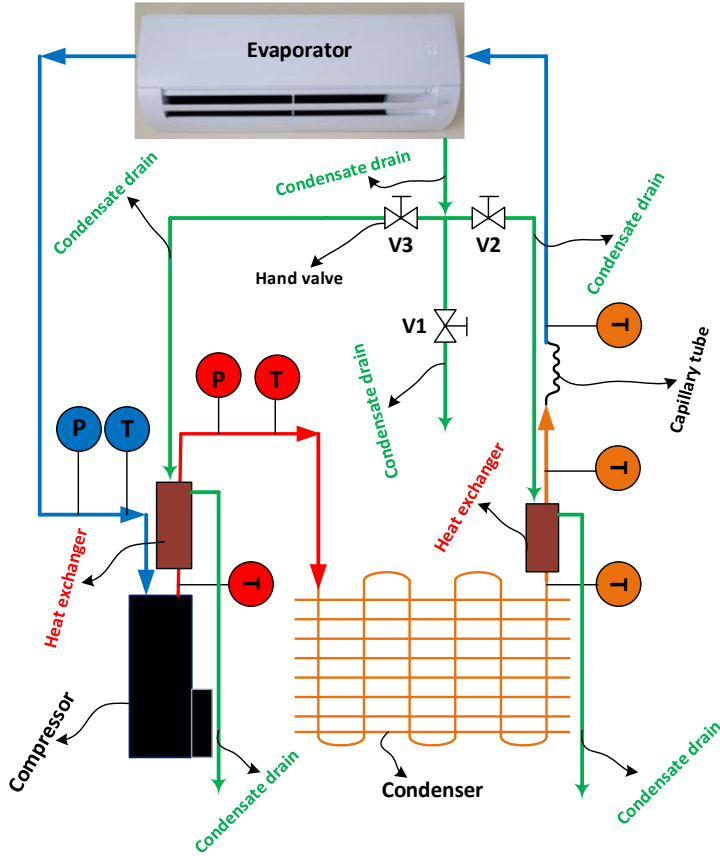


Fig. 1. Schematic of experimental setup

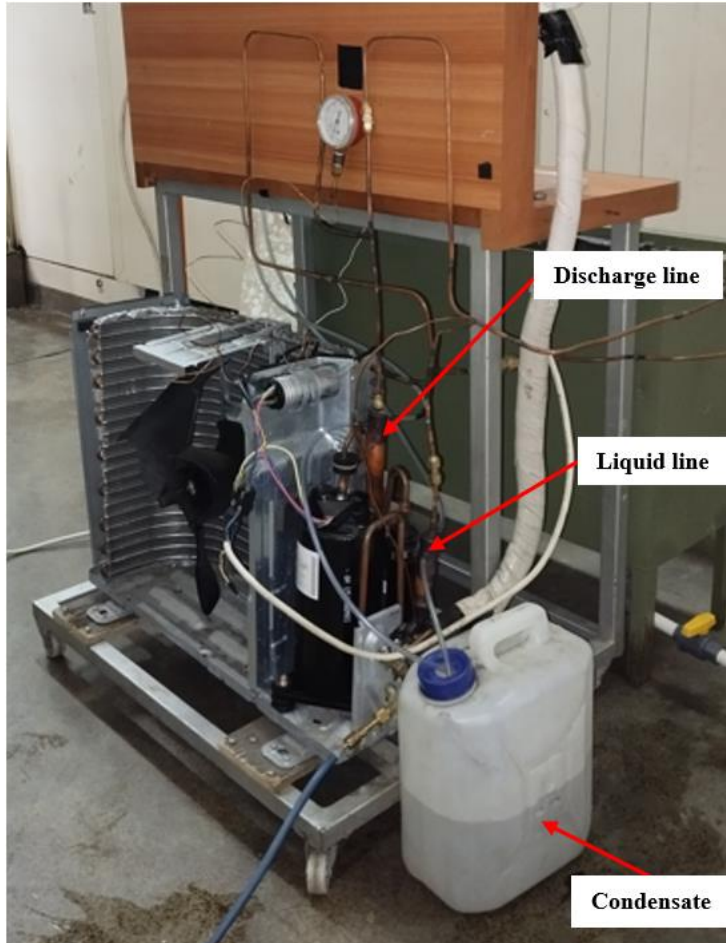


Fig. 2. Photo of the experimental rig of the liquid line and discharge line cooler

Table 1. The properties of R32 [19]-[22]

Parameters	Value	Unit
NBP	-57.7	°C
GWP	675	-
T _{critical}	78.1	°C
P _{critical}	5.78	Mpa
T _{discharge}	> 80°C	°C

Table 2. The accuracy of measuring equipment

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

2.2 Test method

There are 4 modes in testing in this study, namely Standard (STD), Liquid Line Cooler (LLC), DLC, and Liquid & Discharge Line (LDC), as shown in Fig. 1. Each mode conducted data collection for 180 minutes from 11:00 to 14:00 local time. Tests for each mode were carried out on different days, where the cooling load in the room was constant, namely 24 °C, and the outside air temperature was also the same as in the previous mode test, 30 °C.

The first test is STD mode, where hand valves V2 and V3 are closed, while V1 is opened. In this mode, the condensate is directly discharged through the condensate drain to the environment. The second test, hand valve V2 is opened, V1 and V3 are closed, so that the condensate flows into the heat exchanger located in the liquid line. In the third test, the hand valve V3 is opened, and V1 and V2 are closed so that the condensate flows to the heat exchanger located in the discharge line. In the fourth test, V2 and V3 are opened, and V3 is closed so that the condensate flows into the heat exchanger located in the liquid and discharge lines. Furthermore, each test will be drawn on a P-H diagram to calculate the refrigerant mass flow rate, cooling capacity, and COP of the AC. Theoretically, the AC refrigeration cycle in the P-H diagram for the four test modes is shown in Fig. 3. The order of high pressure (working pressure) from highest to lowest is STD, LLC, DLC, and LDC, respectively. This working pressure is directly related to AC power consumption. The higher the working pressure, the higher the power consumption, and vice versa. The Eqs. (1) to (7) [17,18] to calculate the mass flow rate, cooling capacity, and COP of AC for various modes are:

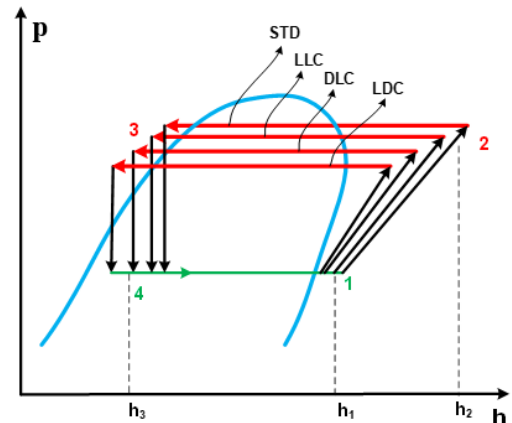


Fig. 3. Refrigeration cycle of residential AC on the P-h diagram

$$P = V \cdot I \quad (1)$$

$$\dot{m} = \frac{V \cdot I \cos \theta}{(h_2 - h_1)} \quad (2)$$

$$Q = \dot{m} (h_1 - h_3) \quad (3)$$

$$COP = \frac{Q}{P} = \frac{(h_1 - h_3)}{(h_2 - h_1)} \quad (4)$$

$$P_{red} = \frac{(P_{STD} - P_{Con})}{P_{STD}} \quad (5)$$

$$Q_{imp} = \frac{(Q_{Con} - Q_{STD})}{Q_{STD}} \quad (6)$$

$$COP_{imp} = \frac{(COP_{Con} - COP_{STD})}{COP_{STD}} \quad (7)$$

where P is power consumption, Q is cooling capacity, \dot{m} is the mass flow rate of refrigerant, $\cos \varphi$ is the power factor, h_1 is the specific enthalpy at point 1, h_2 is the specific enthalpy at point 2, h_3 is the specific enthalpy at point 3, P_{STD} is power consumption during the STD mode, P_{Con} is power consumption during condensate as a cooler mode, Q_{STD} is the cooling capacity during the STD mode, Q_{Con} is cooling capacity during condensate as a cooler mode, P_{red} is power consumption reduction, Q_{imp} is a cooling capacity improvement, and COP_{imp} is COP improvement.

3 Results and discussion

3.1 Power consumption

The effect that is directly felt by split air conditioners due to the use of condensate as a discharge line and liquid line coolant is a decrease in temperature. A decrease in temperature in the discharge line causes a decrease in discharge pressure. While the decrease in temperature in the liquid line results in a decrease in refrigerant temperature at the outlet of the condenser also impacts the decrease in discharge pressure. Fig. 4 shows the change in discharge pressure due to the utilization of condensate for cooling the liquid line only, the discharge line only, and both. The average discharge pressure for 180 minutes for STD, LLC, DLC, and LDC is 31.4, 29.2, 28.3, and 27.3 bar, respectively. From these results, the DLC method reduces the discharge pressure more than the LLC method. Of course, the most significant pressure drop occurs in the LDC method because it uses condensate as a coolant in both lines, namely in the discharge and liquid lines.

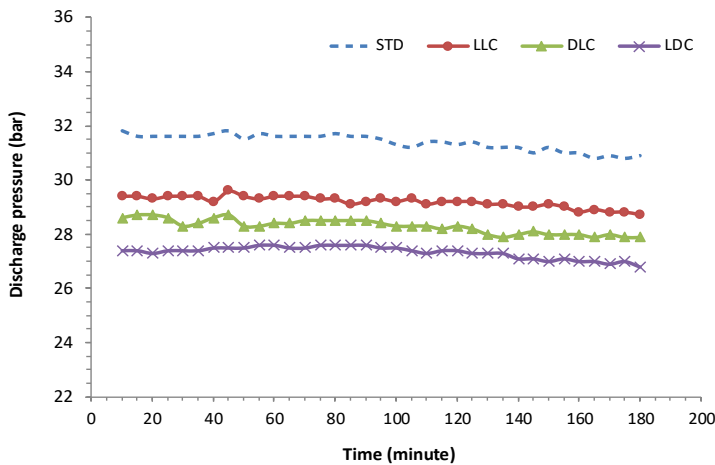


Fig. 4. Discharge pressure for the four test modes

The average discharge pressure in STD and DLC modes is 31.4 and 28.3 bar, respectively, which means a pressure drop of 3.1 bar. This decrease in discharge pressure from STD to DLC mode is greater than the research conducted by Sumeru et al. [18], who also used DLC mode with a heat exchanger length of 20 cm. The decrease in discharge pressure in the research using DLC mode by Sumeru et al. [18] is only 1 bar. The difference in discharge pressure drop may be due to the different diameters of the heat exchangers used. In this study, the copper pipe used is 1 inch in diameter, while the research by Sumeru et al. [18] used copper pipes with a diameter of $\frac{3}{4}$ inch. A larger diameter will result in a higher discharge pressure drop due to more condensate cooling the discharge line. The decrease in discharge pressure due to the utilization of condensate with the EC method as an air cooler that will cross the condenser was also reported by Ibrahim et al. [14] and Sawant et al. [15]. In their

research, Ibrahim et al. [14] presented the difference in discharge pressure before and after using the EC method in the figure, not specifying the quantitative difference. They only mentioned a significant difference in discharge pressure before and after using the EC method with condensate. The results of research by Sawant et al. [15] reported that the EC method using condensate has reduced the discharge pressure on the window AC by about 0.5 bar.

The impact of a decrease in discharge pressure results in a decrease in power consumption. This power consumption represents the electricity consumption by the AC. The power consumption of the AC was calculated using Eq. (1) by measuring the electric current and voltage of the AC. The decrease in power consumption due to using condensate as the discharge line and LLC compared to the STD mode is shown in Fig. 5. Based on Fig. 5, the average power consumption for 180 minutes for STD, LLC, DLC, and LDC modes are 824.1, 780.1, 755.5, and 734.2 W, respectively. Using Eq. (5), the decrease in power consumption against the STD mode is 5.3, 8.3, and 10.9% for LLC, DLC, and LDC, respectively. When it is assumed that the AC operates for 16 hours per day with an electricity price of Rp. 1,440.7/kWh, the monthly electricity costs for STD, LLC, DLC, and LDC are Rp. 568,895, Rp. 539,467, Rp. 522,456, and Rp. 507,726, respectively. This means that when using the LDC mode, in one month it saves Rp. 62,168 and in one year it saves Rp. 746,016.

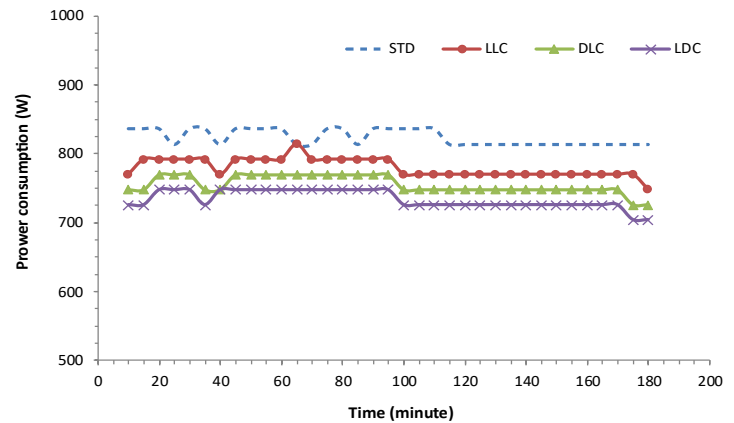


Fig. 5. Power consumption for the four test modes

The result of reducing power consumption for DLC in this study is slightly above the research conducted by Sumeru et al. [17], which is 5.9%. While other research, also conducted by Sumeru et al. [18], which used the DLC method with a heat exchanger length of 20 cm, decreased power consumption by 4.8%. The decrease in power consumption in the study by Sumeru et al. [18] is also lower than the results in this study. One of the reasons is that this study uses a larger heat exchanger diameter than the research by Sumeru et al. [18], which is $\frac{3}{4}$ inch compared to 1 inch.

The comparison of the decrease in power (P_{red}) consumption of the DLC and LDC methods with other studies is shown in Table 3. In the table, the most significant decrease in power consumption was reported by Sawant et al. [15], which is 13%. They performed research on AC windows using R22. This 13% reduction in power consumption is slightly higher than that of the LDC method, which was 10.9%. Although the LDC method results in a lower reduction in power consumption, compared to the study by Sawant et al. [15], both the DLC and LDC methods still result in a slightly higher reduction in power consumption than the results of Sawan et al. [13], Ibrahim et al. [14] and Yang et al. [16].

Table 3. Research results using condensate to reduce the power consumption of AC

Authors	Methods	AC types	Refrigerants	P_{red}
[13]	EC	Split	R22	4.5%-5.3%
[14]	EC	Split	R22	6.1%
[15]	EC	Window	R22	13%
[16]	EC	Split	R22	8.1%-9.5%
[17]	DLC	Split	R410A	5.9%
[18]	DLC	Split	R32	2.4%, 4.8%, 9.8%

3.2 Cooling capacity

In addition to the decrease in input power, the next effect expected from condensate utilization is a decrease in condenser outlet refrigerant temperature. This temperature decrease is due to some of the heat that the condenser should have dissipated should have been partially absorbed by the condensate. The decrease in condenser outlet temperature will cause subcooling, and this subcooling results in an increase in cooling capacity. The condenser outlet temperature during the 180-minute test for STD, LLC, DLC, and LDC modes is shown in Fig. 6. The condenser outlet temperature in STD mode is the highest. This means that the utilization of condensate as a liquid line and DLC will reduce the outlet temperature of the condenser. The average temperature reduction against STD for LLC, DLC, and LDC modes are 4.3 °C, 7.3 °C, and 9.1 °C. The decrease in condenser outlet temperature is slightly higher than the research conducted by Sumeru et al. [17]. Similar to the previous reason, the high decrease in the DLC method in this study compared to the study conducted by Sumeru et al. [17] is because this study uses a larger heat exchanger diameter than the research by Sumeru et al. [17].

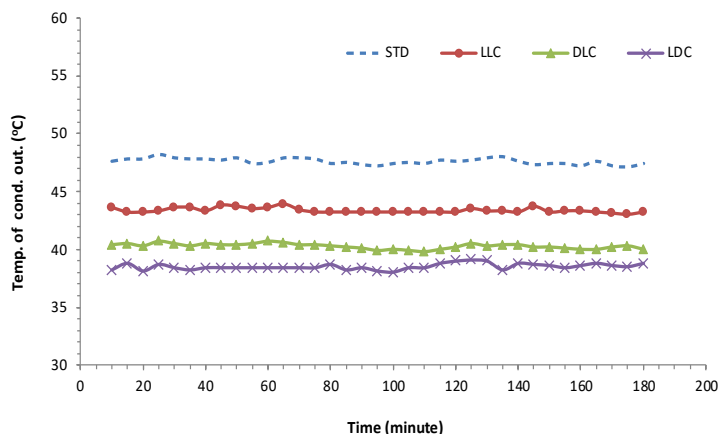


Fig. 6. Temperature of the condenser outlet for the four test modes

Referring to Fig. 3, the enthalpy value at point 3 will shift to the left when the condenser outlet temperature decreases, so the refrigeration effect value (h_1-h_3) will be greater. Since the mass flow rate of refrigerant in the AC is constant, based on Eq. (3), the greater the refrigeration effect, the more the cooling capacity increases. Based on Eq. (3), the cooling capacity for the four test modes for 180 minutes is shown in Fig. 7. It can be seen in the figure that the trend of the cooling capacity of the AC is opposite to the power consumption in Fig. 5. For power consumption, the order from lowest to highest value is LDC, DLC, LLC, and STD, while the cooling capacity order from lowest to highest is STD, LLC, DLC, and LDC. The average cooling capacity of the AC data for 180 minutes for STD, LLC, DLC, and LDC was 2547 W, 2630 W, 2769 W, and 2830 W, respectively. The percentage improvement of cooling capacity of LLC, DLC, and LDC over STD is 2.3%, 8.7%, and 9.7%, respectively.

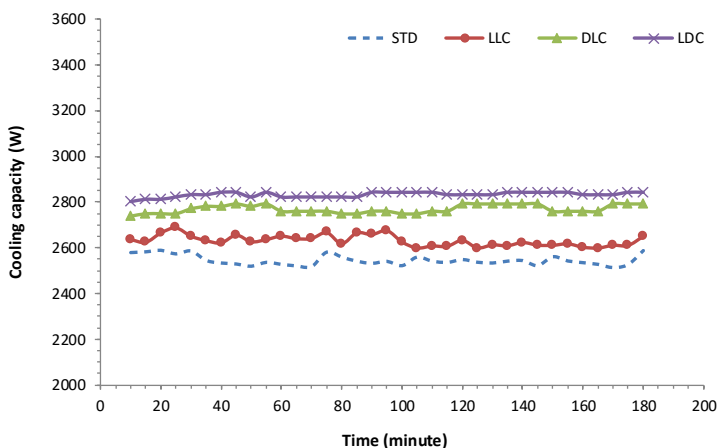


Fig. 7. Cooling capacity for the four test modes

Compared to the results of other studies, the percentage increase in cooling capacity in this study is shown in Table 4. The table shows that the percentage increase in cooling capacity of the DLC method and the LDC method is higher than that of the EC method conducted by Sawan et al. [13], Sawant et al. [15], Yang et al. [16]. Compared to the research conducted by Sumeru et al. [18], which also used the DLC method with a heat exchanger length of 20 cm, the results are almost the same, namely 8.7% compared to 8.9%, or only 0.2% different. Nevertheless, the percentage of capacity increase in this study is slightly below the study by Sumeru et al. [17], which reached 11.2%. This may be due to the difference in refrigerant used, so the refrigerant mass flow rate in the evaporator is also different. The charging mass of R410A refrigerant is 490 g [17], while the charging mass of R32 in this study is 410 g. With the same compressor capacity, the mass flow of R410A will be greater than R32, resulting in a greater increase in cooling capacity in the evaporator. This condition is probably the cause of the percentage increase in cooling capacity in this study, which is slightly lower than the results of research by Sumeru et al. [17].

Table 4. Research results using condensate to increase the cooling capacity of AC

Authors	Methods	AC types	Refrigerants	P_{red}
[13]	EC	Split	R22	NA
[14]	EC	Split	R22	30%
[15]	EC	Window	R22	3.34%
[16]	EC	Split	R22	6.2%
[17]	DLC	Split	R410A	11.2%
[18]	DLC	Split	R32	5.9%, 8.9%, 14.9%

3.3 Coefficient of Performance (COP)

The COP value is calculated by Eq. (4), which is the ratio of cooling capacity to power consumption. Since the LLC, DLC, and LDC methods increase the cooling capacity and decrease the power consumption, the COP value of these three methods will also increase the COP. The increase in COP will be higher than the increase in cooling capacity, because a decrease also follows the use of these three methods in power consumption. Fig. 8 displays the COP for the four methods, namely STD, LLC, DLC, and LDC, for 180 minutes of testing. It can be seen in the Fig. 8 that the trend of increasing COP is similar to the trend of increasing cooling capacity in Fig. 7. The COP values from the lowest to the highest are STD, LLC, DLC, and LDC, whose averages over 180 minutes of measurement are 3.1, 3.4, 3.7, and 3.9, respectively.

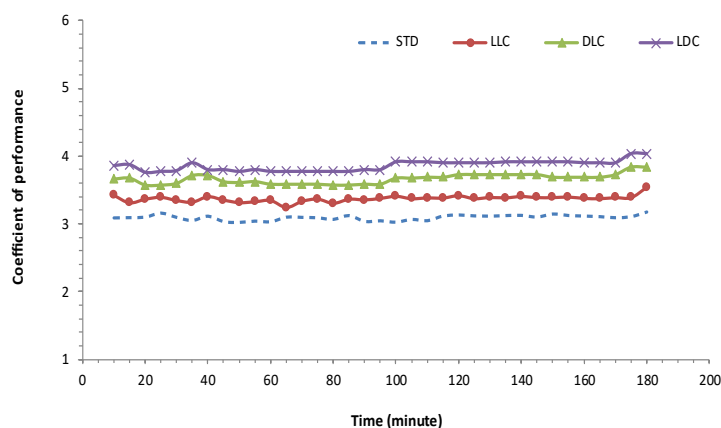


Fig. 8. Coefficient of performance for the four test modes

The percentage increase of COP of LLC, DLC, and LDC modes against STD was calculated using Eq. (7). The results are shown in Fig. 8. It can be seen that the COP values during the 180-minute tests are relatively constant. However, it can be seen that the improvement of COP from the smallest to the largest is the LLC, DLC, and LDC methods, with average values of 9.1, 18.6, and 24.7%, respectively. To determine how effective the method in this study is, it needs to be compared with other methods. The results of comparing COP improvement (Fig. 9) in this study with other studies are shown in Table 5.

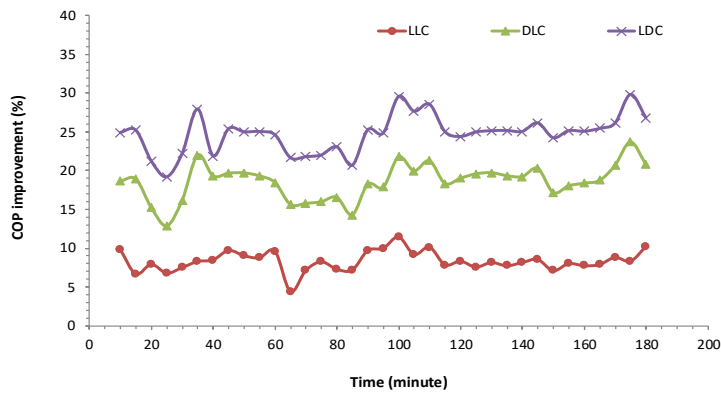


Fig. 9. COP improvement for LLC, DLC, and LDC towards STD

Table 5. Research results using condensate to increase the COP of residential AC

Authors	Methods	AC types	Refrigerants	P _{red}
[13]	EC	Split	R22	5.2%- 8.5%
[14]	EC	Split	R22	21.4%
[15]	EC	Window	R22	18%
[16]	EC	Split	R22	20%
[17]	DLC	Split	R410A	16.4%
[18]	DLC	Split	R32	9.1%, 14.4%, 27.2%

The table shows that the DLC method in this study increased COP, which is not much different from the results of other studies [13-18]. The highest COP improvement result was achieved by the LDC method, which was 27.2%. Another advantage of using the DLC or LDC method compared to the EC method on the air that will enter the condenser [13-16] is the initial and maintenance costs. The initial cost of the DLC and LDC methods is relatively cheap because it only requires the cost of copper pipes with a diameter of ¼ inch to 1 inch along 20-22 cm. In addition, the DLC and LDC methods also do not require maintenance because the copper pipes are relatively corrosion-resistant for an extended period. Meanwhile, the initial cost of the EC method [13-16] is relatively more expensive than the DLC and LDC methods. In terms of maintenance, the EC method [13-16] requires regular maintenance due to the formation of a layer of mud on the surface of the condenser, due to the interaction of dust in the air with water vapor from the evaporative cooler.

4 Conclusions

Condensate produced by residential AC units, which is normally discarded, can be utilized to reduce electricity consumption when applied as a cooling medium for the liquid line cooler (LLC), discharge line cooler (DLC), or a combination of both in the liquid-discharge line cooler (LDC) configuration. The experimental results show the impact of these on the following:

- Power consumption decreased by 5.3%, 8.3%, and 10.9% for LLC, DLC, and LDC modes, respectively, compared to the standard (STD) mode.
- Cooling capacity decreased by 2.3%, 7.3%, and 9.7% for LLC, DLC, and LDC modes, respectively.
- COP improved by 9.1%, 18.6%, and 24.7% for LLC, DLC, and LDC modes, respectively.
- In terms of saving, LDC mode operation provides electricity savings of approximately Rp. 62,168 per month and Rp. 746,016 per year.
- The COP improvement achieved in LDC mode was higher than that reported for DLC mode in previous studies.

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