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Viability of R-290 Refrigerant as Residential AC Retrofit: Effect of Charge Mass Variations

Irham Aulia [1,*], Haftirman [1] and Ega Taqwali Berman [2]

[1]Department of Mechanical Engineering, Universitas Mercu Buana, Meruya Selatan, Jakarta 11650, Indonesia
[2]Mechanical Engineering Education Program, Universitas Pendidikan Indonesia, Bandung 40154, Indonesia
*Corresponding Authors: irhamaulia1103@gmail.com (IA)

Abstract

The growing concerns over ozone depletion and global warming caused by refrigerants have led to the search for environmentally friendly alternatives. This study evaluates the impact of varying R-290 refrigerant charge masses on the performance of a wall-mounted residential air conditioner using the drop-in substitute method. A ¾ HP residential AC unit originally charged with 550 grams of R-22 refrigerant was retrofitted with R-290 and tested at charge masses of 140 grams, 165 grams, and 190 grams—approximately 25%, 30%, and 35% of the original R-22 charge, in accordance with the commonly applied "one-third rule." The results showed that retrofitting with R-290 increased the Refrigeration Effect (RE) by up to 75%, Compression Work (W_c) by 68%, and Coefficient of Performance (COP) by up to 18%. The system with a 25% refrigerant charge was unable to reach the set temperature due to a 23% reduction in cooling capacity, while the 30% charge showed a 10% reduction. The 35% refrigerant mass retrofit proved the most suitable, achieving adequate cooling capacity, an 18% increase in COP, and a 14% reduction in power consumption. Additionally, the retrofit resulted in an indirect CO_2 emission reduction of 1.15 metric tons annually, highlighting the environmental and energy-saving advantages of using R-290. These findings provide empirical validation of the one-third rule for refrigerant mass variation in R-290 retrofits and offer valuable insights into optimizing performance and efficiency in residential AC units, with significant energy and environmental benefits.

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1. Introduction

In recent years, human needs have diversified significantly, with comfort becoming a primary concern in daily indoor activities. One of the most effective ways to achieve such comfort is through the installation of indoor air conditioning systems. These systems, commonly referred to as air conditioning (AC) units, are essential for cooling indoor spaces. According to Arismunandar and Saito (1996), air conditioning is the process of cooling air to a temperature and humidity level suitable for the conditions of a specific room [1]. AC units are widely chosen due to their recognized efficiency in cooling indoor environments.

AC systems function as heat exchange mechanisms based on a closed vapor compression cycle, which consists of four primary stages: compression, condensation, expansion, and evaporation. The main components of AC systems include the compressor, condenser, expansion valve, and evaporator, with refrigerants serving as the working fluid in this cycle.

Refrigerants are fluids used in heat pumps and refrigeration cycles to absorb and release heat, thereby cooling or heating a space. They must possess favorable thermodynamic properties, be non-corrosive, and exhibit low toxicity. Initially, chlorofluorocarbons (CFCs) were introduced as refrigerants in the 1930s due to their desirable thermophysical and safety characteristics. However, in 1974, the link between CFC refrigerants and ozone depletion was discovered, leading to the development of environmental metrics such as Ozone Depletion Potential (ODP) and Global Warming Potential (GWP). ODP measures a substance's impact on ozone depletion relative to CFC-11, while GWP indicates a refrigerant's potential to contribute to global warming over 100 years, relative to CO_2 [2].

In response to environmental concerns, hydrochlorofluorocarbon (HCFC) refrigerants, such as R-22, were introduced as alternatives to CFCs. However, R-22 still has a non-zero ODP value (0.055)

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and a high GWP of 1,810. Consequently, under the Montreal Protocol (1987), refrigerants containing chlorine—which contribute to ozone depletion—were scheduled to be phased out by 2020 in industrialized countries and by 2030 in developing nations, in favor of more environmentally friendly alternatives [3].

The Kigali Amendment to the Montreal Protocol (2016) expanded the protocol's scope by addressing hydrofluorocarbons (HFCs), which, though not harmful to the ozone layer, have high Global Warming Potentials (GWPs) and thus contribute significantly to climate change. Although R-22 is classified as a hydrochlorofluorocarbon (HCFC), the Kigali Amendment's regulation of HFCs has accelerated the transition to refrigerants with lower GWP values, as both environmental and climate impacts have become central to refrigerant selection [4].

The next generation of refrigerants, including R-410A, R-32, and R-407C, have zero Ozone Depletion Potential (ODP) but still possess relatively high GWP values—2018, 675, and 1770, respectively. Higher GWP values indicate a greater contribution to global warming over a century. In line with the Kigali Amendment, the industry is now shifting toward natural refrigerants such as R-290 (propane), which has both a low GWP and zero ODP, making it a promising candidate for residential AC retrofits.

To address both ozone depletion and global warming concerns, the use of natural refrigerants has gained attention as an environmentally friendly alternative [5–7]. Research has demonstrated that natural refrigerants offer high energy efficiency, and a lower environmental impact compared to synthetic refrigerants. For example, Zhou et al. (2010) found that R-290 requires only 30–40% of the mass and flow rate of R-22 due to its lower density [8]. Similarly, Shrivastava and Chandrakishor (2016) noted that R-290 has significantly better thermophysical properties than R-22, with specific heat capacities up to 53% and 67% higher in liquid and vapor states, respectively [9]. Moreover, R-290's thermal conductivity in both states is also higher—by 10.5% and 40%.

Widodo (2022) reported that substituting R-32 with R-290 in an AC unit reduced energy consumption by 13.3% and increased the Coefficient of Performance (CoP) by 14% [10]. Anam (2016) found a 15% reduction in energy consumption when using R-290 as a drop-in substitute for R-410A [11]. Wei et al. (2024) stated that, in residential AC applications in California, retrofitting existing units with R-290 could yield greenhouse gas (GHG) savings of 15 to 64 million metric tons [12]. Wellid et al. (2024) also conducted experimental research on retrofitting HFC-410A with R-290 in residential AC units in Karawang, achieving a 31.91% reduction in Total Equivalent Warming Impact (TEWI) [13].

While several studies have investigated the use of R-290 as a substitute for R-22 and R-410A, limited research specifically addresses the optimal refrigerant mass for R-290 in retrofitted systems. Ding et al. (2009) stated that determining the precise refrigerant charge is critical for maximizing performance and energy efficiency, as inadequate or excessive refrigerant quantities can lead to suboptimal cooling capacity, increased energy consumption, or system inefficiencies. Insufficient refrigerant charge may raise the outlet temperature of the AC unit, while excessive charge could result in compressor damage and excessive heat discharge [14].

Current studies have largely focused on the general performance characteristics of R-290 retrofits, but there is a need for experimental data that examines how varying refrigerant masses impact CoP, energy efficiency, and cooling effectiveness. Therefore, this research addresses this gap by exploring mass variations in R-290 retrofitted AC units to identify the optimal refrigerant charge for enhanced system performance in R-22 systems.

2. Methods

This research was carried out using the drop-in substitute method, which did not involve replacing any components of the existing air conditioning unit. The unit was tested in a classroom at the HVAC-R Engineering Workshop, Department of Mechanical Engineering Education, UPI Bandung. The classroom had a floor area of 13 m^2 and a heat load of 2 kW, of which 1.5 kW was simulated using an electrical heater. The air conditioning equipment used in this experiment was a wall-mounted AC unit from LG, model number HS-C076QDA2, with a cooling capacity of 2.0 kW. Additional details can be found in Table 1.

The installation used in this study adheres to standard specifications, specifically ASTM B280 for the piping. The pipes have an outer diameter of 6.4 mm × 9.5 mm, paired with a wall thickness of 0.76 mm. The piping system spans a length of 3 meters, which is the minimum requirement for residential air conditioning units.

Table 1. Unit specification

Description	Specification
Brand	LG
No. Model	HS-C076QDA2
Capacity	2,0 kW
Power Source	1Ph/220-240V/50Hz
Power Input	590 W
Running Current	3,1 A
Rated COP	3,39
Refrigerant	R-22 (550 gr)

Table 2. Refrigerant characteristics

Refrigerant	R22	R290
Chemical Formula	CHCIF2	CH3CH2CH3
ODP	0,055	0
GWP	1.760	3
Critical Temperature (°C)	96	97
Boiling Point (°C)	-41	-42,5
Triple Point (°C)	-157,4	-187,6
Working Pressure (Psia)	117,04	106,9

This experiment involved retrofitting the previously mentioned AC unit with R-290, as specified in Table 2, using R-22 as a baseline for comparison. Testing began with data collection from the standard unit operating with R-22 refrigerant. Subsequently, the unit was retrofitted with R-290 refrigerant in varying charge masses of 25%, 30%, and 35% of the original R-22 charge, corresponding to 140 grams, 165 grams, and 190 grams, respectively. During each test, the unit underwent vacuuming, minimal compressor oil addition, and refrigerant recovery to ensure data accuracy and environmental safety. A 15-minute test run was conducted to stabilize system pressure and ensure there were no faults in the components or installation. The research steps are summarized in the flow diagram depicted in Figure 1 below.

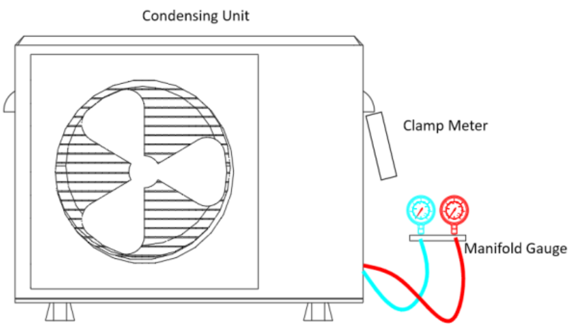

Figure 1. Schematic plan for data measurement

Data collection began once the room temperature reached the initial value of 30 °C, typically occurring around 13:00. After collecting data for both the baseline and retrofitted units, an analysis was conducted to derive the performance parameters of the test unit, as shown in Figure 2. The calculations for key parameters—including Refrigeration Effect (RE), Compression Work (W_c), Theoretical Power (HP), and Coefficient of Performance (COP)—were based on equations and methodologies outlined in the ASHRAE Handbook [15]. Enthalpy values were determined through interpolation using data from the thermodynamic properties table for each refrigerant, and these values were then plotted on the p-h diagram in Figure 3. additional parameters, such as cooling time (t) and power consumption (E), were also evaluated to provide a comprehensive assessment of system performance in this study.

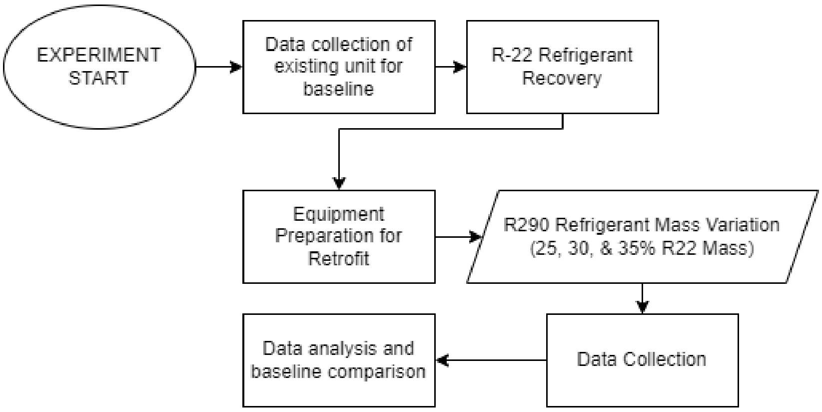

Figure 2. Research flowchart

The data logging equipment was calibrated before each session to ensure accurate measurements of temperature and pressure. The experimental setup included sensors positioned at critical points within the system to capture real-time data. Ambient temperature was also recorded concurrently to account for any environmental influences on system performance.

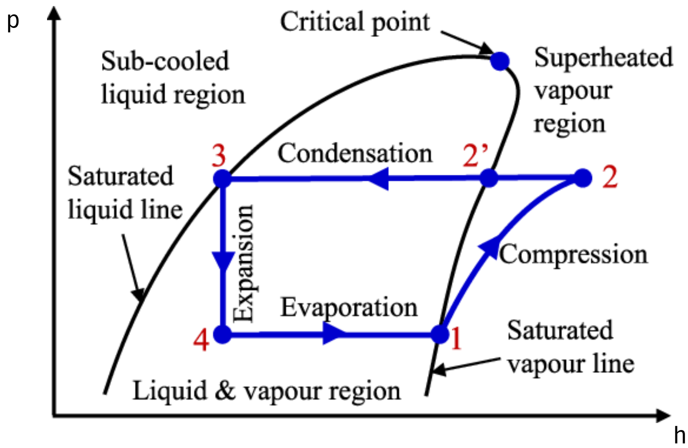

Figure 3. p-h diagram

3. Results and Discussion

3.1. Mass flow rate analysis

The mass flow rate ṁ of the refrigerant is a crucial factor in determining cooling capacity and overall system performance. It can be calculated using several methods, depending on the available data and system configuration. A common approach to estimate the mass flow rate can be done using the power input to the compressor and the enthalpy change across the compression process:

$$\dot{m} = \frac{P \times \eta}{h_2 - h_1} \tag{1}$$

In this analysis, ṁ represents the mass flow rate of the refrigerant, measured in kilograms per second (kg/s). P denotes the power input to the compressor, expressed in kilowatts (kW). The symbol η indicates the compressor efficiency, which is assumed to be 0.75 for non-inverter air conditioning units. h_2 refers to the enthalpy of the refrigerant at the compressor discharge, while h_1 represents the enthalpy at the compressor suction. Both enthalpy values are given in kilojoules per kilogram (kJ/kg).

The accuracy of mass flow rate calculations is highly dependent on precise measurement of parameters like suction and discharge pressures, refrigerant properties, and compressor power input. In a retrofit scenario, comparing mass flow rates before and after retrofitting with R-290 is essential to understand the impact of refrigerant change on the system. The average mass flow rate based on the calculation that has been done is shown in Table 3.

Table 3. Mass flow rate analysis

Unit	ṁ (kg/s)
R-22 (baseline)	0.0106
R-290 140 gr (25%)	0.0047
R-290 165 gr (30%)	0.0054
R-290 190 gr (35%)	0.0061

3.2. Refrigeration effect and cooling capacity analysis

Refrigeration Effect (RE) refers to the amount of heat absorbed by the evaporator. The RE is determined by calculating the Δh value along the Evaporation process line in p-h Diagram. The calculation is shown in the equation below:

$$RE = h_1 - h_4 \quad (2)$$

In this study, h_1 refers to the enthalpy of the refrigerant at the evaporator outlet, measured in kJ/kg. This value corresponds to the suction line just before the refrigerant enters the compressor. Meanwhile, h_4 denotes the enthalpy of the refrigerant at the evaporator inlet, also in kJ/kg, representing the state of the refrigerant immediately after it passes through the expansion valve.

Cooling capacity (Q_e) is a fundamental parameter in assessing the performance of an air conditioning system, representing the total amount of heat absorbed by the refrigerant in the evaporator during its phase change from liquid to vapor. This heat absorption process provides the desired cooling effect in a conditioned space. The equation used to calculate cooling capacity is expressed as:

$$Q_e = \dot{m} \times RE \quad (3)$$

In this context, Q_e represents the cooling capacity of the system, measured in kilowatts (kW), which indicates the total amount of heat removed from the conditioned space. ṁ denotes the mass flow rate of the refrigerant, expressed in kilograms per second (kg/s). RE refers to the refrigeration effect, measured in kilojoules per kilogram (kJ/kg), which is the amount of heat absorbed by each unit mass of refrigerant as it passes through the evaporator.

Figure 4 illustrates the Refrigeration Effect values for each unit per 1 °C decrease in both baseline and retrofit units while Figure 5 illustrates the cooling capacity values for each unit per 1 °C decrease in both baseline and retrofit units.

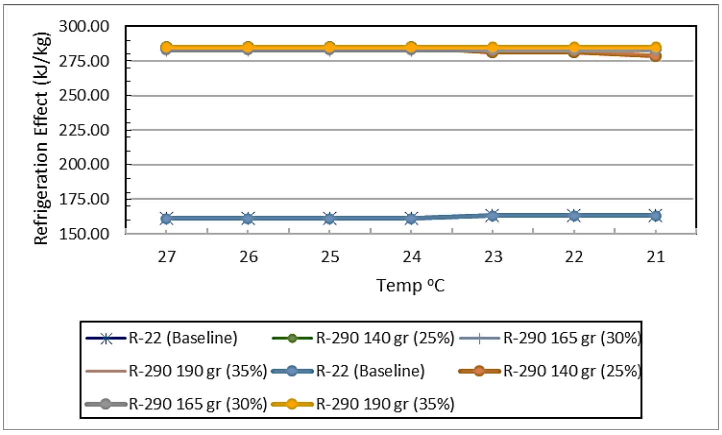

Figure 4. Refrigeration effect analysis

Based on the test results, the average RE value obtained for R-22 units is 162.00 kj/kg. For units using R-290 refrigerant, the values obtained for each refrigerant mass variation of 140 grams, 165 grams, and 190 grams are 282.99 kJ/kg, 283.10 kJ/kg, and 285.10 kJ/kg respectively. Overall, the average increase in Refrigeration Effect values for R-290 units compared to the baseline R-22 system was approximately 76%.

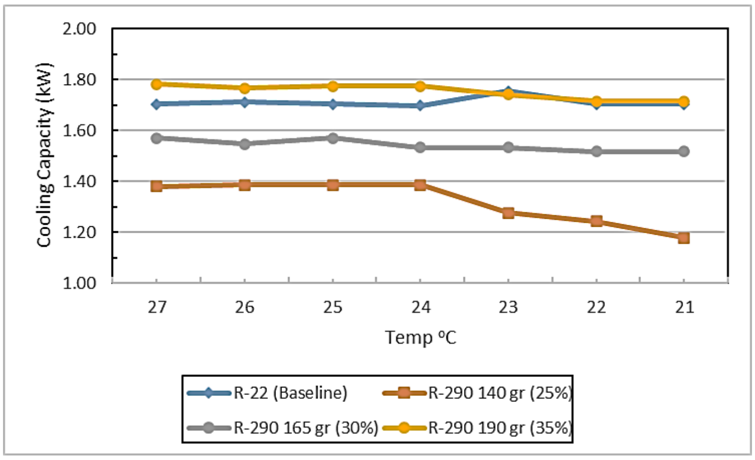

Figure 5. Cooling capacity analysis

The higher Refrigeration Effect of R-290 compared to R-22 is due to its better thermodynamic properties. R-290, a hydrocarbon refrigerant, has a higher latent heat of vaporization, meaning it can absorb and release more heat, improving overall performance and cooling efficiency.

In terms of cooling capacity, the baseline R-22 unit achieved a final cooling capacity of 1.70 kW, which is lower due to the compressor's reduced performance from prolonged use. For the retrofit units using R-290, the cooling capacities were 1,32 kW, 1.54 kW, and 1.75 kW respectively. Notably the R-290 unit with 140 grams of refrigerant could not achieve the target room temperature due to its insufficient cooling capacity, as the lower refrigerant mass was not able to absorb enough heat to maintain the desired temperature.

3.3. Compression work analysis

The value of compression work (W_c) is determined by the difference between two enthalpy values: one at the compression point (superheat) and one at the saturated vapor point (suction).

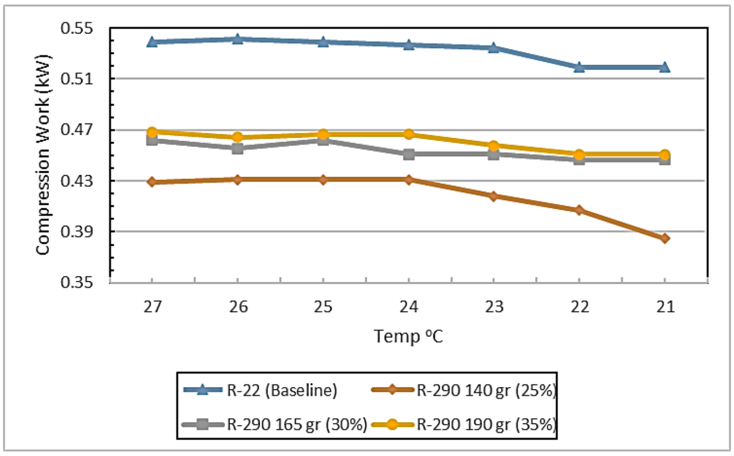

Figure 6. Cooling capacity analysis

This value represents the heat generated by the refrigerant during compression, as shown in equation (4):

$$W_c = h_2 - h_1 \quad (4)$$

In this context, h_2 refers to the enthalpy of the refrigerant at the compressor outlet, representing the state of the refrigerant after compression, and is measured in kilojoules per kilogram (kJ/kg). h_1 denotes the enthalpy at the compressor inlet, corresponding to the state of the refrigerant before compression, also expressed in kJ/kg.

Figure 6 shows the change in W_c in kJ/kg per 1 °C decrease in room temperature for both baseline R-22 unit and the R-290 retrofit units. The average compressor work values for the R-22 baseline unit are 37.81 kJ/kg. For the R-290 units, the average values are 76.46 kJ/kg for 140 grams, 70.80 kJ/kg for 165 grams, and 63.70 kJ/kg for 190 grams.

While the R-290 retrofit units show an increase in W_c, this increase corresponds to a significant rise in RE. The average increase in compression work for the R-290 units up to 202%. The higher W_c value for R-290 is due to its thermodynamic properties. R-290 has a higher latent heat of vaporization than R-22, meaning it can absorb more heat, requiring the compressor to work harder, thus increasing W_c.

To calculate the W_c value in kW, the W_c values in kJ/kg are multiplied by the mass flow rate and divided by the compressor efficiency. This conversion provides a practical measure of the compressor's power consumption, which is more relevant for evaluating system performance in real-world applications. The formula for calculating W_c is shown in equation (5).

$$W_c = \frac{m \times (h_2 - h_1)}{\eta} \quad (5)$$

In this analysis, $\dot{m}$ represents the mass flow rate of the refrigerant, measured in kilograms per second (kg/s). The symbol η denotes the compressor efficiency, which is assumed to be 0.75 for non-inverter AC units. h_2 refers to the enthalpy of the refrigerant at the compressor outlet, while h_1 indicates the enthalpy at the compressor inlet. Both enthalpy values are expressed in kilojoules per kilogram (kJ/kg).

Figure 7 illustrates the compressor work in terms of power consumption for both the R-22 baseline unit and the R-290 retrofit units. This figure provides a clearer understanding of the energy usage of the compressor as the refrigerant mass and room temperature change.

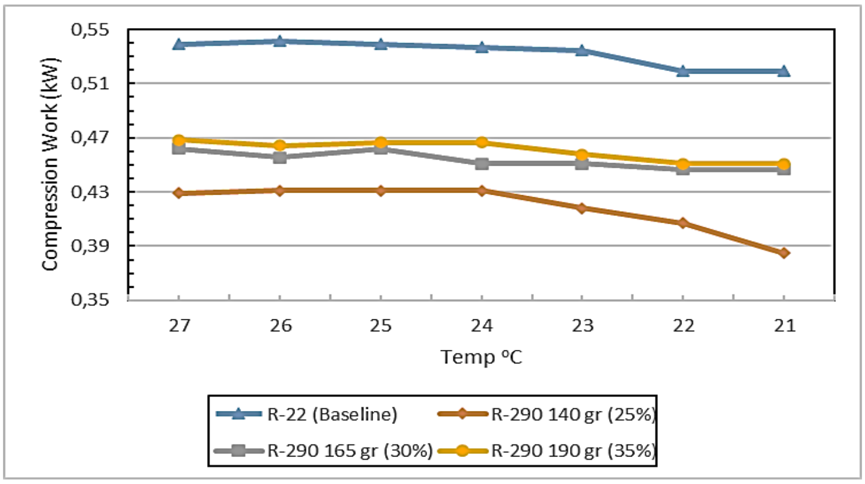

Figure 7. Compression work analysis in kW

3.4. Coefficient of Performance analysis

The Coefficient of Performance (COP) is a key indicator of an air conditioning system's efficiency. The ideal COP is calculated using the ratio of RE to compression work (W_c). Representing the theoretical maximum efficiency, assuming no energy losses or operational inefficiencies.

However, in real-world applications, the efficiency of a system is often lower due to factors like compressor inefficiencies, heat losses, and other operational limitations. For this reason, the realistic COP is typically calculated as the ratio of the cooling output (Q_e) to the power input as shown in equation (6). This version of COP reflects actual performance under operating conditions, considering both energy consumption and cooling capacity.

The Coefficient of Performance (COP) is a key performance indicator for any refrigeration system, representing the efficiency of the system. It's calculated as the ratio of Refrigeration Effect (RE) and Compression Work (W_c) which are shown in equation (6).

$$COP = \frac{Q_e}{P} \quad (6)$$

In this context, Q_e represents the cooling capacity of the system, measured in kilowatts (kW), indicating the amount of heat removed from the conditioned space. P refers to the power input to the system, which is the electrical energy consumed during operation.

The average COP of the baseline R-22 unit is 3.21, which serves as a reference point for comparison. In the case of the retrofit units, the R-290 with 140 grams refrigerant shows a slight decrease of 2%, with a COP of 3.15. Meanwhile, the R-290 with 165 grams refrigerant demonstrates a 6% increase, reaching COP of 3.40. The R-290 with 190 grams refrigerant exhibits the most significant improvement, with a COP of 3.80, representing an 18% increase compared to the baseline. As comparative with other studies, these results align with previous research on the use of R-290 in retrofitting systems [10 – 11]. Figure 8 illustrates the COP for each unit per 1oC decrease in room temperature for both baseline and retrofit systems, providing a clear comparison efficiency across the different configurations.

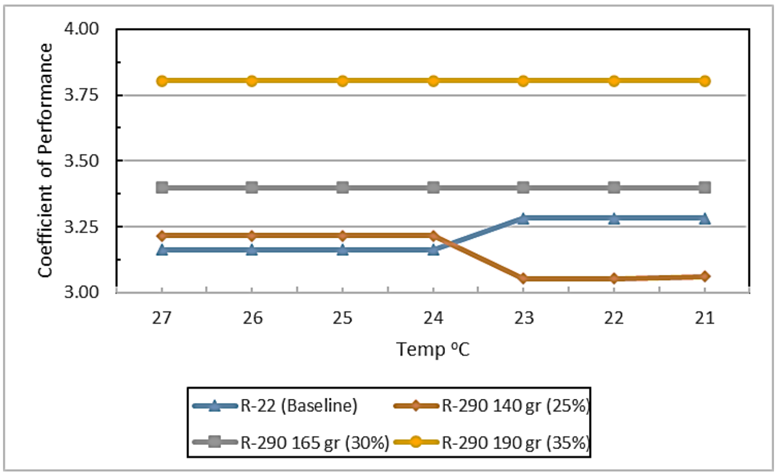

Figure 8. Coefficient of Performance analysis

3.5. Power consumption analysis

Power consumption is a critical factor in evaluating the energy efficiency of air conditioning units, particularly in residential applications where energy use directly impacts electricity costs. This study analyzed the power consumption of the baseline R-22 unit and retrofit R-290 systems to assess real-world performance as shown in Table 4.

Table 4. Power consumption analysis

Power Input (kW)	R-22 (Baseline)	R-290 140 gr (25%)	R-290 165 gr (30%)	R-290 190 gr (35%)
kWh	0.53	0.42	0.45	0.46
Opt. time	8	8	8	8
kWh/day	4.26	3.35	3.63	3.69
kWh/month	34.09	26.81	29.02	29.49
Dev.	100%	79%	85%	86%

The results indicate a noticeable reduction in power consumption with the retrofit R-290 systems compared to the baseline R-22 unit. With R-290 190 gr, the electrical consumption reduce could reach to -14% than the baseline, while maintaining higher cooling capacity and higher COP. Even the difference between R-290 165 is only around 0,06 kWh per day. R-290 140 gr mass variation may have lower power consumption, but it struggles to maintain room temperature below 24 °C due to lower cooling capacity. Even lower than the baseline around 23%.

3.5. CO_2 savings analysis

The retrofitting process with R-290 results in CO_2 emission reductions through both direct and indirect savings. Direct CO_2 savings arise from the lower Global Warming Potential (GWP) of R-290 compared to R32. With a GWP of only 3, R-290 significantly reduces the environmental impact in case of refrigerant leaks, as opposed to R-22 which has a GWP of 1,760. By replacing R-22 with R-290, the total potential CO_2 equivalent emissions from refrigerant leakage are significantly reduced up to 967.50 kg CO_2-(100 years).

The indirect impact of retrofitting to R-290 is observed through the reduction in electricity consumption due to improved system efficiency. As the cooling capacity increases and power input decreases, the system achieves higher energy efficiency, resulting in lower carbon emissions from electricity generation. The energy savings can be calculated by comparing power consumption before and after the retrofit, as shown in Equation (7) and (8).

$$\Delta E = E_{before} - E_{after} \tag{7}$$

$$E_{before} = \frac{Q_{e\,before}}{COP_{after}} \tag{8}$$

In this context, Q_e denotes the cooling capacity of the system, measured in kilowatts (kW), representing the amount of heat extracted from the conditioned space. COP, or Coefficient of Performance, is a dimensionless value that expresses the ratio of the cooling capacity (Q_e) to the power input, serving as an indicator of the system's energy efficiency.

The energy saving analysis by retrofit process is shown in Table 5. Based on the result, the amount of energy saving due to retrofit process could reach around 13 – 15% from the baseline.

Table 5. Energy saving analysis

Refrigerant variation	Q_e (kW)	COP	Energy (kWh)	Energy Cons.
R-22 (Baseline)	1.71	3.21	0.53	100%
R-290 140 gr (25%)	1.32	3.15	0.42	79%
R-290 165 gr (30%)	1.54	3.40	0.45	85%
R-290 190 gr (35%)	1.75	3.80	0.46	87%

Table 6. CO_2 saving analysis

Refrigerant variation	Energy Cons. (kWh/year)	Emission Factor	CO_2 Emission (kg CO_2/kWh)
R-290 140 gr (25%)	1,224.29	0.85	1,040.65
R-290 165 gr (30%)	1,324.26	0.85	1,125.62
R-290 190 gr (35%)	1,345.37	0.85	1,143.56

The reduction in electricity consumption due to the retrofit directly contributes to lower CO_2 emissions from power generation. The CO_2 savings can be estimated by converting the energy savings into equivalent CO_2 emissions using Equation (9):

$$Indirect\ CO_2\ Savings = \Delta E \times 0.85 \tag{9}$$

Where ΔE is the energy savings calculated from the difference in power consumption before and after the retrofit, and the emission factor represents the amount of CO_2 emitted per unit of electricity consumed. In this study, the energy savings are calculated based on the unit running for 2,920 hours annually (8 hours daily over the course of a year). The emission factor is based on the Indonesian electricity grid. The results of the CO_2 savings calculation are summarized in Table 6, highlighting the environmental benefits achieved through the retrofitting process.

4. Conclusions

This study investigated the performance of a wall-mounted AC unit retrofitted with R-290 refrigerant as a substitute for the commonly used R-22. The results showed that although R-290 retrofit increased compression work; however, this was offset by a substantial rise in refrigeration effect (RE), ultimately resulting in up to 18% COP compared to the baseline R-22 system. The analysis revealed that a refrigerant mass of 140 grams (equivalent to 25% of the original R-22 charge) was insufficient to achieve the desired cooling condition due to reduced cooling capacity. The inadequate heat exchange caused by reduced refrigerant flow in the system. However, increasing the R-290 mass to 190 grams (equivalent to 35% of the original R-22 charge) significantly enhanced system performance, increasing the COP of the system to 3.80 —18% higher than the baseline— and reducing the electrical consumption up to 14% hourly. Furthermore, the retrofit showed a substantial environmental benefit, with an estimated reduction of 1,143.56 kg CO_2/kWh annually due to improved energy efficiency and lower electricity consumption. Additional cost savings could be achieved in scenarios with lower cooling loads, as the unit's thermostat automatically deactivates the compressor upon reaching the set temperature, further conserving energy. Based on these findings, it is recommended that retrofitting wall-mounted, non-inverter AC units with a 2.00 kW cooling capacity should ideally use 190 grams of R-290 refrigerant (equivalent to 35% of the original R-22 mass) to achieve optimal performance. This approach not only improves cooling efficiency but also reduces energy consumption, making it a viable and environmentally friendly alternative for residential air conditioning retrofits. Given the promising results of the retrofit, it is important to explore further research into the long-term performance of compressors when using R-290 as a refrigerant. Specifically, additional studies should focus on evaluating the durability, reliability, and suitability of compressors for R-290 systems, taking into account potential wear and tear, operating pressures, and other factors that could influence their lifespan and efficiency. This research would help ensure the sustainability of R-290 retrofits and optimize the design and operation of systems using this refrigerant for both residential and commercial operations.

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