Jurnal Polimesin
Department of Mechanical Engineering
State Polytechnic of Lhokseumawe
http://e-jurnal.pnl.ac.id/polimesin
e-ISSN : 2549-1999 No. : 2 Month : April
p-ISSN : 1693-5462 Volume : 23 Year : 2025

Processing dates: received on 2024-12-30, reviewed on 2025-03-07, accepted on 2025-03-19 and online availability on 2025-04-30

Energy and exergy performance of R290 as a substitute for R404A in freezers: experimental investigation

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Abstract

The refrigeration sector significantly contributes to global warming due to the high Global Warming Potential (GWP) of commonly used refrigerants. This study experimentally investigates the feasibility of using R290 as a low-GWP substitute for R404A in freezer applications. Although R290 and R404A have similar normal boiling points, their GWP values differ significantly (3 for R290 vs. 3922 for R404A), making R290 a more environmentally friendly alternative. Experiments were conducted on a freezer originally designed for R404A with a 1/3 HP compressor and a refrigerant charge of 170 g. After baseline testing with R404A, the system was retrofitted with R290, using an optimized charge of 62.9 g. The system's performance was analyzed over 120 minutes, with energy and exergy evaluations conducted at 60 minutes, when the cabin temperature stabilized. Results from energy analysis indicate that replacing R404A with R290 led to a 6.1% increase in cooling capacity, a 6.0% reduction in power consumption, and a 12.4% improvement in COP. Exergy analysis showed that total irreversibility decreased from 318.1 W (R404A) to 289.8 W (R290), with compressor irreversibility being the dominant factor (50.8% for R404A vs. 51.3% for R290). The findings confirm that R290 enhances system performance by reducing irreversibility and energy consumption. These results highlight R290 as an energy-efficient and environmentally friendly alternative to R404A, providing both operational cost savings and reduced environmental impact. However, to achieve optimal performance, compressor lubricant replacement is recommended when transitioning to R290.

Keywords:
Freezer, GWP, exergy analysis, R404A, R290.

1 Introduction

The increasing concern over environmental sustainability and the influence of refrigerants on global warming has led to a shift in the refrigeration industry towards more eco-friendly alternatives. Hydrofluorocarbons (HFCs), such as R404A, have come under scrutiny due to their high Global Warming Potential (GWP) and harmful environmental effects. The quest for sustainable and efficient refrigerants has increased. One such promising alternative is R290, a naturally occurring hydrocarbon.

One of the considerations for replacing refrigerant in a freezer is the cabin temperature due to the refrigerants' different Normal Boiling Point (NBP) temperatures. Thus, refrigerant replacements should be done with care. For instance, replacing R404A with R600a increases cabin temperatures from -40 ˚C to -10 ˚C. This is due to the significant difference in the NBP temperatures, which are -46.5 ˚C and -11.8 ˚C for R404A and R600a [1-3], respectively. Research conducted by Sumeru et al. shows that replacing R404A refrigerant with R290 does not significantly change the temperature of the freezer cabin because the NBP temperatures of both are almost the same, namely -46.5 ˚C and -42.1 ˚C, respectively. [4], drop-in R404A with R290 in the freezer resulted in cabin temperatures of -40.1ºC and -38ºC, respectively.

In terms of the environment, replacing R404A with R290 results in a significant reduction in the contribution to global warming because there is a wide gap in their GWP, namely 3922 and 3 for R404A and R290, respectively [5-7], as seen in Table 1. This means that replacing R404A refrigerant with R290 needs urgent attention, considering the current rate of global warming, which will be 1.4 ˚C to 5.8 ˚C by the end of the 21st century [8]. Some are even more pessimistic than pessimistic scientists that the increase in Earth's surface temperature can reach 0.02 ˚C per year [9]. If efforts to reduce emissions of gases that cause global warming are not immediately carried out, then the estimates of these experts can even be exceeded [10-12].

The refrigeration sector's contribution to global warming comes not only from refrigerant leakage but also from power consumption by refrigeration machines. The contribution of the refrigeration sector to global warming is 7.8% [13], both directly and indirectly. The direct contribution comes from leakage of 37%, while the indirect contribution comes from the energy consumption of refrigeration machines of 63% [14-16].

Refrigerants R404A, R410A, R407C and R134a are a family of HFCs that have been in use for about the last 30 years [17]. Initially, in the 90s, HFCs were used to replace Chlorofluorocarbons (CFCs) refrigerants, such as R11, R12 and R502 and Hydro-chlorofluorocarbons (HCFCs), such as R22, which have ozone-depleting properties [18, 19]. However, HFCs family refrigerants do not have ozone-depleting properties but have a very high global warming value. Therefore, the use of HFCs refrigerants must be discontinued immediately. The schedule for reducing the use of HFCs has started in Europe since 2014 [20]. However, in reality, HFCs are still widely used as a working fluid in refrigeration and Air Conditioning (A/C) engines in Southeast Asian countries. In Indonesia, the replacement of HFCs with Hydrocarbons (HCs) refrigerants, namely R600a and R290, in refrigeration machines is still not widely implemented.

An energy analysis of replacing R404A with R290 in freezers was done by Sumeru et al. [4]. The results of his research reported that the refrigerant replacement increased the COP by 8.05%. Based on the search for references, the exergy analysis of replacing R404A (HFCs) refrigerant with R290 (HCs) in the freezer has never been conducted. For this reason, this study aims to conduct an exergy analysis on replacing R404A refrigerant with R290 in a freezer. From this exergy analysis, the quantity of irreversibility that occurs in the main components of the freezer will be obtained [21-23]. By knowing the irreversibility of each main component of the freezer, it will be possible to optimize the dimensions of each component. Several experts have carried out an analysis on refrigerant replacement in refrigeration machines, including Joybari et al. [24] and Arman et al. [25]. Joybari et al. [24] conducted an exergy analysis on a refrigerator with a refrigerant charging mass of 145 g of R134a replaced with 60 g of R600a. The results reported that the total exergy destruction (irreversibility) for R134a and R600a is 0.05549 kW and 0.04854 kW, respectively, while the largest exergy destruction occurs in the compressor. The replacement of R134a with R600a in car air conditioners was carried out by Arman et al. [25]. The results reported that the irreversibility of R134a was higher than that of R600a. They also reported that the highest irreversibility occurs in the compressor. This means that replacing R134a

refrigerant (HFCs) with R600a (HCs) thermodynamically and resulting in improved refrigeration machine performance will also reduce the effects of global warming. Similar to the research conducted by Arman et al. [26], this research aims to investigate thermodynamically the replacement of R404A with R290. From the results of this research, it will be seen whether this replacement, in addition to reducing global warming, also has a positive impact on freezer performance. Apart from the environmental aspects, the reason for replacing R404A with R290 is that the NPB values are quite close, as shown in Table 1.

Table 1. Characteristics of various refrigerants [5-7]

Refrigerant	NBP (°C)	GWP
R134a (HFC)	-26.1	1300
R404A (HFC)	-46.5	3922
R410A (HFC)	-50.5	2088
R407C (HFC)	-43.6	1530
R600a (HC)	-11.8	3
R290 (HC)	-42.1	3

2 Materials and methods

This study was conducted on a freezer using a compressor with a capacity of 1/3 Horsepower (HP), originally using R404A as its working fluid, with a filling mass of 170 g. The freezer used for the test is shown in Fig. 1. The figure shows R290 being filled into the freezer after completion of the test using R404A.

Fig. 1. Photo of the freezer during R290 refrigerant charging

Data collection was carried out for 120 minutes, and the data was analyzed at the 60th minute. The measuring instruments used in this study are shown in Table 2. The accuracies of these measuring instruments are also shown in Table 2. Thermocouples measure temperature at 5 points, namely suction, discharge, condenser output, inlet and outlet evaporators. In comparison, the pressure gauge is installed at the compressor suction and discharge. Ampere and volt meters measure the electric current and voltage entering the compressor.

Table 2. The accuracies of measuring instruments

No.	Instrument	Accuracy
1	Thermocouple K-type	± 0,1oC
2	High-pressure gauge	± 0,5 bar
3	Low-pressure gauge	± 0,1 bar
4	Ammeter	± 0,1 A
5	Voltmeter	± 1 V

After data collection with R404A is complete, the freezer is replaced with R290, where the mass of refrigerant charging is 62.9 g. The quantities measured on the freezer are the same as when using R404A.

Freezers have four main components: compressors, condensers, capillary tubes, and evaporators [25]. The freezer refrigerant cycle using R404A and R290 in the Ph (pressure vs. entropy) diagram is shown in Fig. 2. Points 1, 2, 3, and 4 represent temperature, pressure, enthalpy, and entropy at suction, discharge, condenser outlet, and evaporator inlet, respectively.

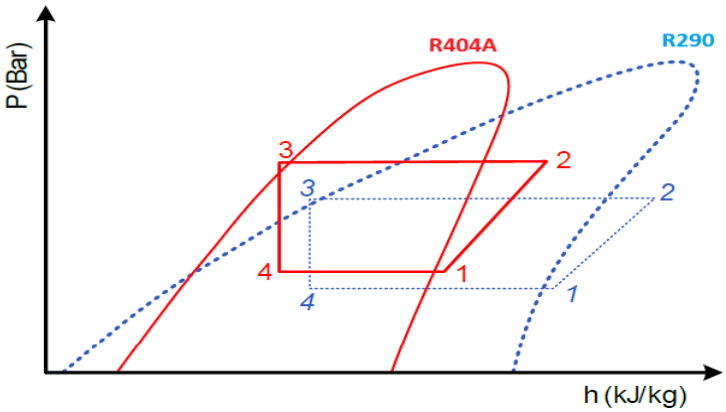

Fig. 2. The refrigerant cycle of the freezer on the Ph diagram for R404A and R290 [3, 25]

Energy and exergy analysis was performed based on the data at these points. The equations for performing energy and exergy analysis are shown in Eqs. (1) to (10) [25, 26].

$$Q = \dot{m} \cdot (h_1 - h_3) \tag{1}$$

$$P = \dot{m} \cdot (h_2 - h_1) = V.I \tag{2}$$

$$COP = \frac{Q}{P} \tag{3}$$

$$COP_{imp} = \frac{COP_{R290} - COP_{R404A}}{COP_{R404A}} \cdot 100\% \tag{4}$$

Irreversibility in the compressor:

$$I_{comp} = \dot{m} \cdot (h_1 - T_o \cdot s_1) + \dot{m} \cdot (h_2 - T_o \cdot s_2) \tag{5}$$

Irreversibility in the condenser:

$$I_{cond} = \dot{m} \cdot (h_2 - T_o \cdot s_2) + \dot{m} \cdot (h_3 - T_o \cdot s_3) - Q_{cond} \cdot \left(1 - \frac{To}{T_{cond}}\right) \tag{6}$$

Irreversibility in the expansion:

$$I_{exp} = \dot{m} \cdot T_o \cdot (s_4 - s_3) \tag{7}$$

Irreversibility in the evaporator:

$$I_{evap} = \dot{m} \cdot (h_3 - T_o \cdot s_3) + Q_{evap} \cdot \left(1 - \frac{To}{T_{cabin}}\right) - \dot{m} \cdot (h_1 - T_o \cdot s_1) \tag{8}$$

The total irreversibility:

$$I_{Total} = I_{comp} + I_{cond} + I_{exp} + I_{evap} \tag{9}$$

The Second Law of efficiency:

$$\eta_{Sec.} = (1 - \frac{I_{Total}}{W_{comp}}) \tag{10}$$

Where Q is cooling capacity (W), $\dot{m}$ is mass flow rate of refrigerant (kg/s), h_1 is enthalpy at point 1 (kJ/kg), h_2 is enthalpy at point 2 (kJ/kg), h_3 is enthalpy at point 3 (kJ/kg), P is power consumption of compressor (W), I is electrical current (Ampere), V is voltage (Volt), COP_{imp} is COP improvement (%), T_o is ambient temperature, T_{cond} is condensing temperature, T_{cabin} is cabin temperature, s_1 is specific

entropy at point 1, s_2 is specific entropy at point 2, s_3 is specific entropy at point 3, s_4 is specific entropy at point 4, and Q_{cond} is condenser capacity.

3 Results and discussion

3.1 Freezer performance test

After 60 minutes of operation, the suction and discharge pressures are shown in Fig. 3. The figure displays the suction and discharge pressure of the freezer when using R404A and R290 refrigerants. From the Figure, the suction pressure of R290 is slightly lower than R404A, which is 1.1 bar compared to 1.2 bar. At a suction pressure of 1.1 bar, the evaporating temperature is -42.0 ˚C [3], while at a suction pressure of 1.2 bar for R290, the evaporating temperature is -40.0 ˚C [3]. Based on the test, it was found that replacing R404A with R290 in the freezer increased the evaporating temperature by 2ºC.

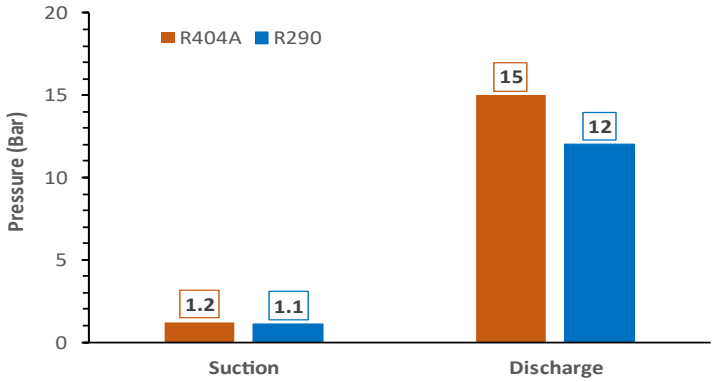

Fig. 3. Suction and discharge pressure of R404A and R290

The freezer cabin temperature depends on the evaporating temperature. Evaporating temperatures of -42.0 ˚C for R404A and -40.0 ˚C for R290 result in cabin temperatures, as shown in Fig. 4. The freezer cabin temperature with R404A is -40.1ºC and 38.0ºC for R290. This means the freezer cabin temperature is approximately 2ºC higher than the evaporation temperature, whether using R404A or R290. This relatively small increase in temperature will not have much impact on the function of the freezer, which is generally used to store products at a temperature of around -30 ˚C.

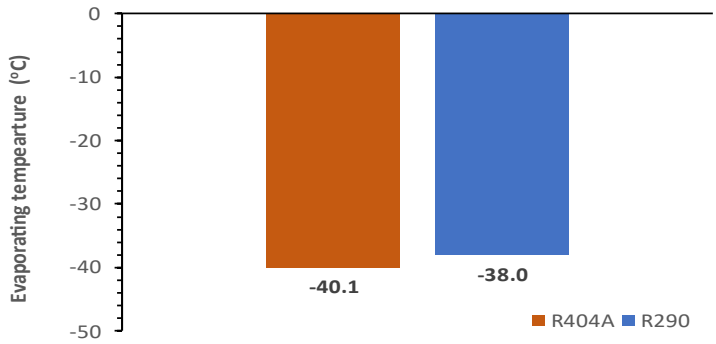

Fig. 4. Cabin temperature of R404A and R290

3.2 Energy analysis

3.2.1 Cooling capacity

Energy analysis was performed using Eqs. (1) to (3), i.e. calculating the cooling capacity produced by the evaporator, the power consumption by the compressor and the COP of the freezer. The cooling capacity generated by the evaporator is calculated using Eq. (1), and the quantity of cooling capacity is shown in Fig. 5. The figure shows that the cooling capacity using R290 is greater than that of R404A, 591.1 W, compared to 557.0 W. In other words, replacing R404A with R290 resulted in a 6.1% increase in cooling capacity. Since cooling capacity is the ability of the evaporator to absorb heat [4, 25], this increase in cooling capacity causes the temperature of the product stored in the freezer to cool faster.

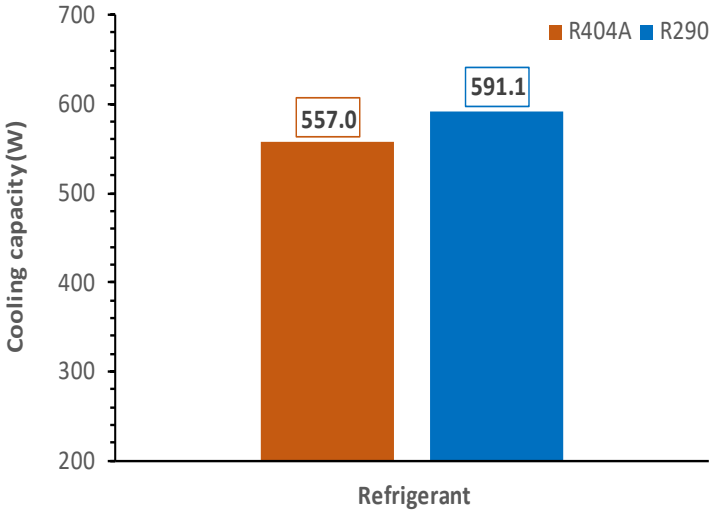

Fig. 5. The cooling capacity of R404A versus R290

3.2.2 Power consumption

The second parameter in the energy analysis is the power consumption by the compressor. Power consumption calculation uses Eq. (2), which is obtained from direct measurement of the electric current and voltage entering the compressor. The power consumption of the freezer when using R404A and R290 is shown in Fig. 6. The figure shows that the power consumption of R290 is lower than that of R404A, which is 434.1 W compared to 460.2 W. This means that replacing R404A refrigerant with R290 in the freezer results in a 6.0% decrease in power consumption. The lower power consumption in R290 is due to the lower charging mass of R290 refrigerant compared to the charging mass of R404A, which is 62.9 g compared to 170 g. As a result of the smaller charging mass, the compressor work will be decreased. Lower power consumption also results in lower operating costs for the freezer. This decrease in power consumption results in a decrease in the indirect contribution of the refrigeration sector to global warming [14-16].

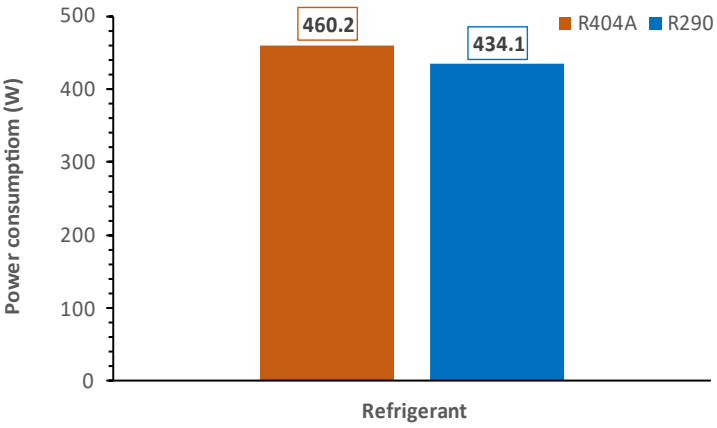

Fig. 6. Power consumption of R404A versus R290

3.2.3 Coefficient of performance

In energy analysis, the COP value is used as the main parameter to determine the advantages and disadvantages of refrigerant replacement in the refrigeration system. In addition to reducing the negative environmental impact, refrigerant replacement is also expected to increase the COP value. Based on Eq. (*3*), COP is the ratio of cooling capacity to power consumption. Since there is an increase in cooling capacity and a decrease in power consumption, the increase in COP will be higher than the increase in cooling capacity. Fig. 7 shows the COP comparison of R404A with R290. The figure shows that the COP of 290 is higher than R404A, which is 1.36 compared to 1.21, or an increase of 12.4%. This increase in COP means that the freezer will decrease its operating costs by 12.4% when replaced with R290 for the same ambient and cabin temperatures.

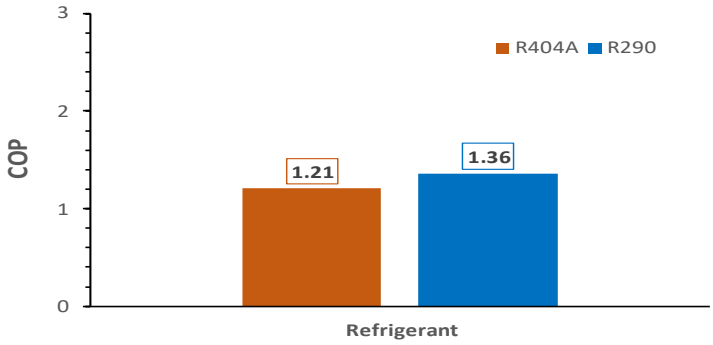

Fig. 7. Coefficient of performance of R404A versus R290

3.3 Exergy analysis

The energy analysis that has been carried out can calculate the quantity of heat absorbed by the evaporator and the power consumption by the compressor. Meanwhile, the energy analysis can calculate the irreversibility of each component in the freezer due to the increase in entropy in the process. This exergy analysis calculates the irreversibility in the four main components in the freezer: the compressor, condenser, capillary tube and evaporator.

Using Eqs. (5) to (8), the irreversibility of the four main components in the freezer was obtained. Fig. 8 displays the irreversibility of the four main components in the freezer when using R404A and R290. The figure depicts that the irreversibility of the three main components, namely the compressor, capillary tube and evaporator, using R404A is higher than that of R290. However, in the condenser, the irreversibility of R404A is lower than that of R290, which is 73.7 W compared to 85.0 W. The higher irreversibility of R290 than R404A is due to the condenser dimensions for R404A being less suitable for R290. The dimensions of the R290 condenser should be increased slightly to allow for longer subcooling than in the existing condenser [3]. In other words, based on the exergy analysis, when replacing the refrigerant in the freezer from R404A with R290, it is better to increase the dimensions of the condenser to get the optimal performance improvement. However, if no dimensional changes are made to the condenser, replacing the R404A refrigerant with R290 still results in improved performance, as the energy analysis explains.

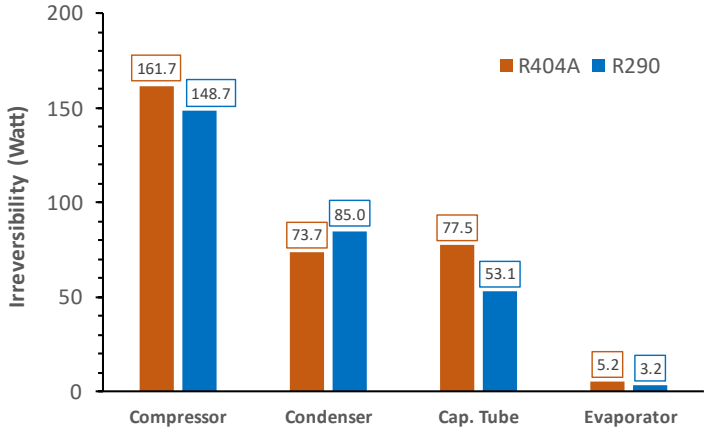

Fig. 8. Irreversibility on each freezer component when using R404A and R290

Fig. 8 shows the irreversibility of each major freezer component, while the total irreversibility, which is the sum of the irreversibility of the four components, is shown in Fig. 9. The values in the figure are based on Eq. (9), and from the figure, it can be seen that the total irreversibility for R404A and R290 are 318.1 W and 289.8 W, respectively. This means that the replacement of R404A with R290 results in a decrease in irreversibility, which is 9.8%. This irreversibility decrease means the system works more efficiently [24, 25]. As explained earlier, this decrease in irreversibility will be greater if the dimensions of the condenser are increased so that the irreversibility that occurs in the condenser decreases.

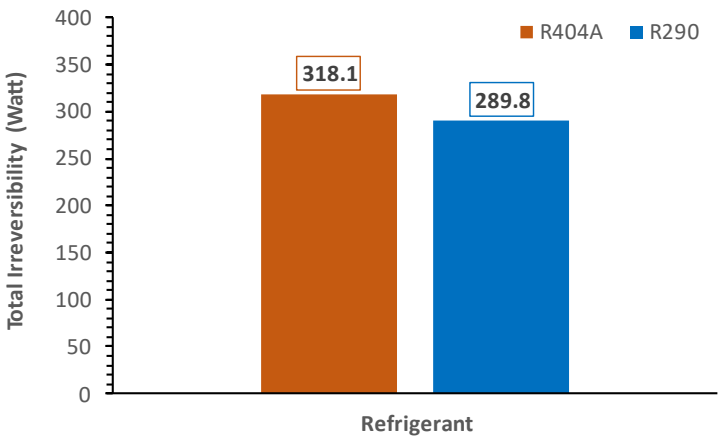

Fig. 9. Total irreversibility on freezer components when using R404A and R290

Fig. 10 shows the percentage of irreversibility in the four freezer components. It can be seen in the figure that the highest percentage of irreversibility occurs in the compressor, which is 50.8% for R494A and 51.3% for R290. This result is similar to studies conducted by several researchers [21, 24, 25], where the largest percentage of irreversibility also occurs in the compressor. The high irreversibility in the compressor is due to the high discharge temperature of the compressor due to the irreversible process. One method to reduce this irreversibility is to lower the discharge temperature by reducing the friction loss between the piston and the cylinder wall.

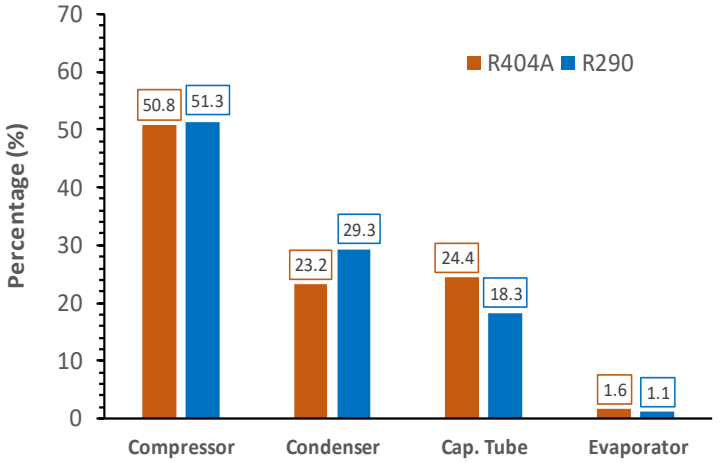

Fig. 10. Percentage of irreversibility on each freezer component when using R404A and R290

In contrast to the irreversibility quantity shown in Fig. 8, where the irreversibility in R404A compressor is higher than R290, but in terms of percentage, the percentage of irreversibility in R404A compressor is lower than R290, which is 51.3% compared to 50.8%. This is because the compressor used was originally designed using R404A, not R290. Therefore, when using R290, the compression process will experience more irreversible processes, likely one of the causes of the compressor lubricant [27]. Generally, lubricants used in compressors with R404A are synthetic [1, 27], while lubricants for R290 are often used as mineral lubricants [28]. The replacement of lubricant in the compressor when replacing R404A with R290 will impact the compressor's life [29].

The second Law of efficiency can be used to determine the degree of efficiency of the refrigeration machine. This means that the greater the Second Law efficiency value, the more efficient the refrigeration machine. To determine the Second Law of freezer efficiency in this study, Eq. (10) was employed. Fig. 11 depicts the Second Law efficiency values of R404A and R290, which are 30.9 and 33.2, respectively. It can be seen in the figure that the Second Law value of R290 efficiency is higher than R404A, which increases

by 7.5%. This means that replacing R404A with R290 in freezers and lower power consumption will drastically reduce greenhouse gas emissions. This is because the GWP of R404A is much higher than that of R290, which is 3922 compared to 3, as shown in Table 1 [5, 6]. The smaller the GWP value of the refrigerant used in the refrigeration system, the less emission of gases that cause global warming.

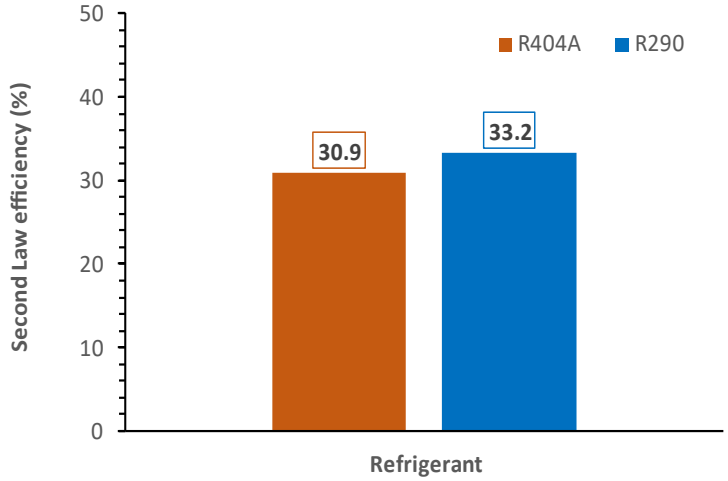

Fig. 11. Second Law efficiency of the freezer when using R404A and R290

4 Conclusions

This research confirms that R290 is a viable low-GWP alternative to R404A in freezer applications. Energy analysis shows that R290 improves system performance by increasing cooling capacity by 6.1% and reducing power consumption by 6.0%, leading to operational cost savings. Exergy analysis further indicates a reduction in system irreversibility, with total irreversibility decreasing from 318.1 W (R404A) to 289.8 W (R290), and Second Law efficiency improving from 30.9% (R404A) to 33.2% (R290). The results demonstrate that replacing R404A with R290 can enhance system efficiency while significantly lowering environmental impact, given its GWP reduction from 3922 to 3. However, to fully optimize the performance of R290-based systems, changing the lubricant of the compressor is recommended to ensure compatibility with the new refrigerant.

Acknowledgements

We would like to thank the Refrigeration & Air Conditioning Engineering Department, Politeknik Negeri Bandung, for allowing us to use the facilities for this research.

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