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The Use of R290 as a Replacement for R404A in Block Ice Machines

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Abstract. *This study evaluates the performance of R290 refrigerant as an alternative to R404A in block ice-making machines based on vapor compression cycles. The method used is a quantitative experimental approach with direct testing of compressor power, condenser power, evaporator power, and coefficient of performance (COP) parameters. Test results indicate that R290 has lower power consumption and a higher COP compared to R404A, with a COP of 3.22 (R290) versus 2.48 (R404A). Additionally, R290 has a significantly lower global warming potential (GWP), making it more environmentally friendly. The more stable and efficient thermodynamic performance of R290 supports its effectiveness as an economical and sustainable alternative refrigerant for modern cooling applications.*

Keywords - *R290, R404A, refrigerant, energy efficiency COP, ice blocks*

INTRODUCTION

Indonesia is an archipelagic country located along the equator, characterized by a tropical climate with two main seasons: the rainy and dry seasons. The average ambient temperature in most regions reaches approximately 34°C, although highland cities such as Bandung experience relatively cooler temperatures ranging between 19°C and 30°C [1]. The prolonged high temperatures significantly increase the demand for refrigeration systems, not only in households but also in various industrial sectors such as food processing, pharmaceuticals, hospitality, cold-chain logistics, and storage facilities for perishable goods [2].

One of the most widely used cooling technologies is the vapor compression refrigeration system, which comprises four main components: compressor, condenser, expansion valve, and evaporator. This system operates by absorbing heat from a medium (e.g., a brine tank in block ice machines) via the evaporator and releasing it to the environment through the condenser [3]. This cycle dominates a wide range of applications, from domestic air conditioning and refrigeration to industrial cooling processes. Air conditioning systems play a vital role in ensuring thermal comfort and temperature control across residential and industrial settings, directly impacting energy efficiency and work productivity [4].

The performance of a refrigeration system is heavily influenced by the type of refrigerant used, as its thermophysical properties determine energy consumption, cooling capacity, and environmental impact. R404A is one of the most commonly used refrigerants, particularly in medium to low-temperature applications such as ice makers, cold storage, and commercial freezers. It is a near-azeotropic blend of HFC-R125, HFC-R143a, and HFC-R134a, developed to replace R502 [5]. Despite its favorable cooling performance, R404A has a very high Global Warming Potential (GWP) of 3922 and an Ozone Depletion Potential (ODP) of 0, making it environmentally detrimental. Due to this, it is targeted for gradual phase-out under global environmental regulations, including the Montreal Protocol and Kigali Amendment [6].

In response to the need for more sustainable refrigerants, R290 (propane) has emerged as a promising alternative. As a hydrocarbon-based natural refrigerant, R290 has a GWP of approximately 20 and an ODP of zero [7]. It exhibits excellent thermodynamic properties, including high thermal conductivity, low viscosity, and favorable specific heat, resulting in more efficient heat transfer and reduced compressor workload [8][6]. Research also indicates that R290 can reduce energy consumption by up to 31.4% compared to R404A [9]. However, it is classified as flammable, thus requiring strict adherence to safety standards such as IEC 60335 when used in refrigeration systems.

Global trends are increasingly shifting toward refrigerants that support low-carbon emissions, energy efficiency, and ozone protection. In this context, the exploration of alternative refrigerants such as R290 is particularly critical for applications like block ice machines, which are commonly used in fisheries and frozen food industries across Indonesia.

This study aims to evaluate the performance of R290 as a replacement for R404A in vapor compression refrigeration systems used in block ice machines. The evaluation adopts a quantitative experimental approach, measuring compressor power, condenser power, evaporator power, and the system's Coefficient of Performance (COP). The results are expected to contribute scientifically and practically to the development of more efficient, costeffective, and environmentally friendly refrigeration technologies, aligned with global energy conservation and emission reduction goals.

METHODS

The experimental research was carried out in a controlled indoor laboratory environment to minimize external influences and ensure repeatability of the results. The test aimed to compare the performance of R290 and R404A refrigerants in a vapor compression refrigeration system used for block ice production.

During the entire testing process, environmental conditions were maintained within a stable temperature range of 26°C to 28°C, and relative humidity was kept between 65% and 70%**.** These settings were selected to simulate realistic tropical operating conditions, particularly reflective of climates in Indonesia. The ambient conditions were continuously monitored using a Benetech GM1361 digital thermo-hygrometer, which offers reliable temperature and humidity measurement with ±0.5°C and ±3% RH accuracy, respectively. Each refrigeration cycle was operated continuously for a total duration of 660 minutes (11.5 hours)**.** Throughout this period, data collection was conducted at fixed intervals of every 30 minutes, allowing for 24 complete data points to be obtained for each refrigerant configuration. This data frequency ensured that both short-term variations and long-term trends in system performance could be accurately captured.

Electrical power consumption of the compressor was measured using a Watts Up Pro digital power meter, which records real-time power usage, voltage, and current with high accuracy. Meanwhile, system pressures and temperatures were measured at strategic points—before and after the compressor, condenser, and evaporator—using Type K thermocouples and digital pressure gauges, allowing for precise monitoring of thermal and pressure dynamics in the cycle. All enthalpy values required for heat transfer calculations were derived using the CoolPack-v150, which provides accurate refrigerant property data based on the latest equations of state.

To ensure the reliability and safety of the testing, especially when using the flammable R290 refrigerant, the experiment followed the IEC 60335-2-40 safety standard, which outlines specific safety procedures for household and similar electrical appliances using flammable refrigerants. These procedures included proper ventilation of the workspace, fire extinguisher readiness, and leak detection prior to system startup.

By adhering to these technical and safety standards, the experimental procedure ensured that the performance data obtained for both refrigerants—R290 and R404A—were accurate, repeatable, and conducted under equivalent and realistic operating conditions.

Figure 1 shows a P-h diagram of a vapor compression refrigeration system consisting of four main components, namely a compressor that functions to compress or increase the pressure of the refrigerant, a condenser as a place for condensation or heat release from the refrigerant to the environment, an expansion as a place for the expansion process or reduction of refrigerant pressure, and an evaporator as a place for the evaporation process or heat absorption from the controlled cabin [10].

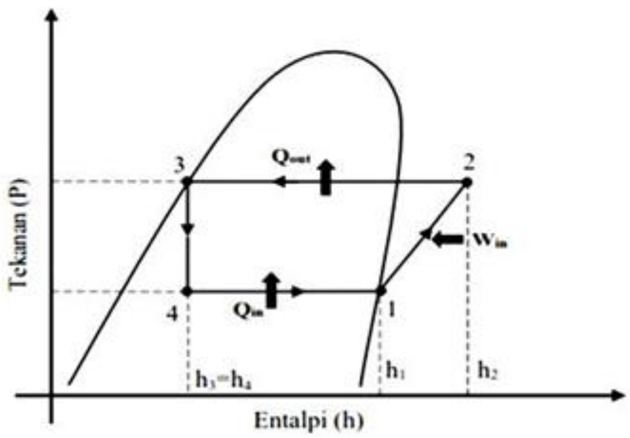

Figure 1. P-h Diagram of a Vapor Compression Refrigeration System [11]

Compression Process (1-2)

The compression process is the process of increasing the pressure of the refrigerant, which occurs isentropically (constant entropy) [12]. The initial condition of the refrigerant when it enters the compressor is saturated vapor at low pressure, and it exits as high-pressure vapor. To determine the amount of work done by the compressor.

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

Where:
q_w = Amount of heat in the compressor process (kJ/kg)
h1 = Enthalpy of refrigerant leaving the evaporator and entering the compressor (kJ/kg)
h2 = Enthalpy of refrigerant when leaving the compressor - entering the condenser (kJ/kg)

Condensation Process (2-3)
The condensation process is a process in which the refrigerant releases heat to the environment inside the condenser. In this stage, the refrigerant changes from a vapor to a saturated liquid. This process also occurs isobarically (at constant pressure) [13]. To determine the amount of heat released in the condenser, we use the following formula.

$$q_c = h2 - h3 \quad (2)$$

Where:
q_c = Amount of heat released in the condenser (kJ/kg)
h3 = Enthalpy of refrigerant when leaving the condenser (kJ/kg)

Expansion Process (3-4)
The expansion process is a decrease in refrigerant pressure caused by flow resistance in the expansion device (throttling device) [14]. This process occurs isenthalpically (constant enthalpy). Because the process is isenthalpic, it can be concluded that.

$$h_3 = h_4 \quad (3)$$

Where:
h3 = Condenser outlet enthalpy (kJ/kg)
h4 = Evaporator inlet enthalpy (kJ/kg)

Evaporator Process (4-1)
The evaporation process is the stage where heat is absorbed from the conditioned cabin/room [15]. During this process, the refrigerant changes form from water to saturated vapor. This process occurs isobarically (at constant pressure). To determine how much heat is absorbed during the evaporation process, we use the following formula.

$$q_e = h_1 - h_4 \quad (4)$$

Where:
q_e = Amount of heat absorbed in the evaporator (kJ/kg)

Basically, the working principle of a cooling system or refrigeration system of ice block machine is to transfer heat from a brine tank to the outside environment, resulting in a decrease in temperature inside brine tank. A refrigeration system consists of four main components, namely a compressor, condenser, expansion device, and evaporator. In a vapor compression refrigeration system, the compressor compresses the refrigerant to increase its pressure and temperature after the refrigerant has performed the refrigeration effect brine tank [16]. Table 1 below explain the specification of the main components of a refrigeration system.

Table 1. Main Components in a Refrigeration System

No	Device	Type
1	Compressor	Kulthorn aw2495zk
2	Condenser	Kewely fnf-2.8/13
3	Expansion Valve	Termostatik Expansion Valve
4	Evaporator	In lined Copper pipe, dia. 9.52mm, total length 24.8 m.
5	MotorDrive	Single Phase Electric

The vapor compression refrigeration cycle is the most commonly used cycle in vapor compression refrigeration systems. Its ability to produce a cooling effect is the main point, so a working fluid that undergoes repeated phase changes from gas to liquid and vice versa throughout the process is required [17]. Figure 2 shows an overview of the vapor compression refrigeration cycle.

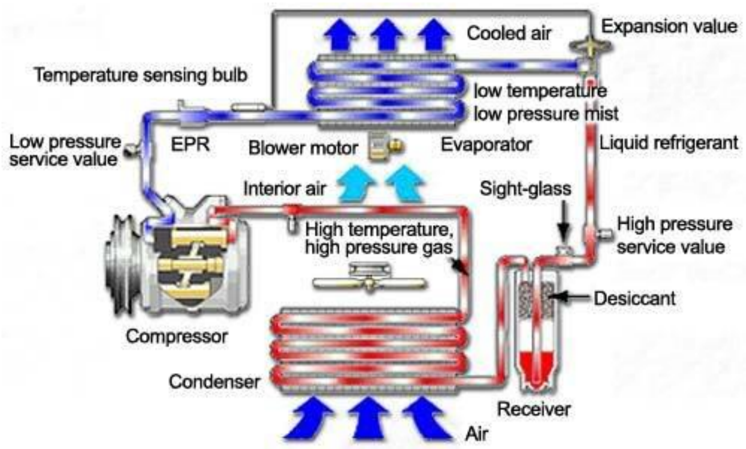

Figure 2. Vapor Compression Refrigeration Cycle [18]

The image above illustrates a schematic of a vapor compression refrigeration system, which is the most commonly used cooling cycle in domestic and industrial applications, including refrigerators, air conditioners, and block ice machines. The diagram clearly shows the flow of refrigerant through the four main components compressor**,** condenser**,** expansion valve and evaporator with red lines representing the high-pressure side and blue lines representing the low-pressure side of the system.

Process Stages Explained:

1. **Compressor**
   The refrigerant enters the compressor as a low-pressure saturated vapor and is compressed isentropically, resulting in a high-pressure, high-temperature vapor (represented by the red line). This stage requires mechanical energy input, labeled as “compressor work.”
2. **Condenser**
   The high-pressure vapor flows into the condenser, where it releases heat to the surrounding environment (heat rejection) and condenses into a high-pressure liquid. This process is often assisted by air or water as the cooling medium.
3. **Expansion Valve**
   The high-pressure liquid refrigerant then passes through the expansion valve, which reduces its pressure isenthalpically (at constant enthalpy). This produces a low-pressure liquid-vapor mixture.
4. **Evaporator**
   In the evaporator, the refrigerant absorbs heat from the space or medium to be cooled (heat absorption), causing it to completely evaporate into a low-pressure vapor. This evaporation process provides the actual cooling effect. After exiting the evaporator, the low-pressure vapor refrigerant returns to the compressor, thus completing the cycle.

Refrigerant is a working fluid used in cooling devices to absorb heat from the product being cooled in the evaporator and release that heat into the environment through the condenser [19]. In this study, there are two types of refrigerants, namely R404a and R290, as explained below.

R404A Refrigerant

R404a refrigerant is one of the most commonly used refrigerants in cooling systems. This type of refrigerant belongs to the HFC group [20]. It can be used in medium-temperature cooling systems and low-temperature cooling systems. Table 2 shows data on the characteristics of R404a refrigerant.

Table 2. R404a Refrigerant Characteristics [21]

No	Parameter	Value
1.	Temperature NBP	-46.2°C
2.	Freezing Point	-117.5°C
3.	Critical pressure	37.29 Bar
4.	Liquid density (0°C)	1150.01 kg/m^3
5.	Vapor density (25°C)	3.99 kg/m^3
6.	Specific heat liquidCp (25°C)	1.5423 kJ/kg.K
7.	Specific heat vaporCp (25°C)	1.2214 kJ/kg.K
8.	Global Warming Potential (GWP)	3922
9.	Ozone Depletion Potential (ODP)	0

R290 Refrigerant

According to [7] Refrigerant R290 (Musicool-22) or R-290 (propane) belongs to the hydrocarbon category because it has low ODP and GWP (ODP = 0 and GWP = ~20 [d]). R-290 has the chemical compound formula CH3CH2CH3 with a Normal Boiling Point (NBP) of - 42°C which makes it flammable. One of the R-290 products available on the market is Musicool from PT Pertamina. Musicool (MC22) is an environmentally friendly refrigerant and is designed to be a replacement for potentially environmentally damaging refrigerants, such as R-12 (CFC), R-22 (HCFC), and R-134a (HFC). The data on the characteristics of R-290 refrigerant is presented in Table 3 below.

Table 3. R290 Refrigerant Characteristics

No	Parameter	Value
1.	Properties	C_3H_8
2.	Molecular Mass (g/mole)	44.09
3.	Boiling Point (°C)	-42.11
4.	Freezing Point (°C)	-187.62
5.	Critical Temperature (°C)	96.74
6.	Critical Pressure (kPa)	4251.2
7.	Critical Density (kg/m3)	220.4

The method applied in this research is an experimental method with a quantitative approach to analyze the use of R290 refrigerant as a substitute for R404a refrigerant in ice block making machines [22]. From a quantitative point of view, the purpose of research is to test a theory, present a fact and to develop a concept or an existing understanding. Figure 3 below shows the research stages used in this testing process.

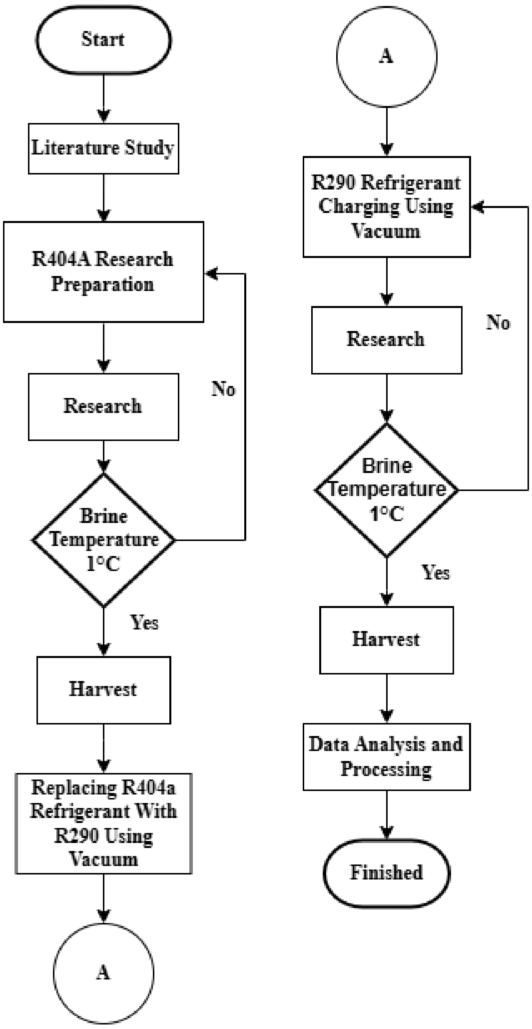

Figure 3. Flowchart of Testing Process of Refrigerant R404A and Refrigerant R290

RESULTS AND DISCUSSION

Based on the compression power graph figure 4, data was obtained on the power consumption of two types of compressors, namely compressors with R404A refrigerant and compressors with R290 refrigerant, measured against operating time. The graph shows that the electrical power consumption of the R404A compressor at the start of the test (minute 0) was around 1550 watts, then gradually decreased as operating time increased. At minute 660, the electrical power consumption of the R404A compressor dropped to approximately 1120 watts. Although there were minor fluctuations at certain points in time, the overall trend in power consumption showed a decreasing tendency.

Meanwhile, the R290 compressor exhibited different power consumption behavior. At minute 0, the R290 compressor had a power consumption of around 800 watts, and during the testing process, the power consumption remained stable with very small fluctuations in the range of 750–800 watts. There is no significant decrease as observed in the R404A compressor. The stability in power consumption demonstrated by the R290 indicates more consistent performance throughout the operational period.

The difference in power consumption between the two types of compressors can be attributed to the thermodynamic properties of each refrigerant. R290 refrigerant has higher energy efficiency than R404A, as evidenced by the lower power requirement needed to achieve the same cooling process. This indicates that the compressor works more efficiently when using R290 compared to 404A. Additionally, R290 has a significantly lower Global Warming Potential (GWP) compared to R404A, making its use more environmentally friendly. The following is a graph of the test results comparing the compression power between R404A refrigerant and R290 refrigerant.

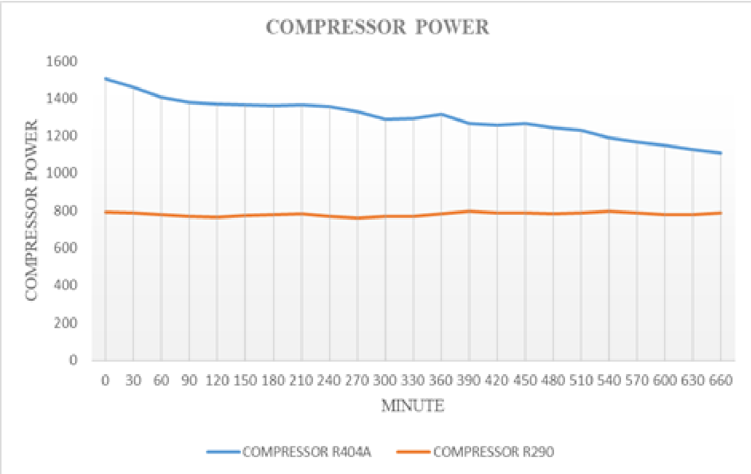

Figure 4. Comparison graph of the power of R404a and R290 refrigerant compressors

Meanwhile, Figure 5 shows the comparison of condenser performance between refrigeration systems using R404A and R290 refrigerants is based on the amount of heat released by the condenser over the operating time. From the test results, it can be seen that the condenser with R404A refrigerant has a relatively high initial heat release value, which is around 5800 watts at minute 0. As operating time increases, this value shows a gradual decrease, reaching approximately 3,500 watts at minute 660. At certain points in time, particularly around minute 300, there is a slight spike, but overall, the trend remains downward. In contrast, the condenser using R290 refrigerant shows an initial heat release value of around 3700 watts, with a more stable and gradual decrease compared to R404A. The heat release value of the R290 condenser at the end of the test (minute 660) is around 3100 watts. Fluctuations in the R290 condenser were also relatively smaller, indicating the stability of the heat release process during operation.

These differences in heat release patterns are closely related to the thermophysical properties of each refrigerant. R404A has a larger cooling capacity but lower condenser thermal efficiency compared to R290. This causes the R404A condenser to work harder at the start of operation to dissipate heat, which then gradually decreases as stable operating conditions are achieved. Meanwhile, the R290 refrigerant, which has better thermal conductivity and specific heat capacity, is able to maintain heat dissipation at a more stable and efficient level. The following graph compares the condensers for R404A and R290 refrigerants in Figure 5 below.

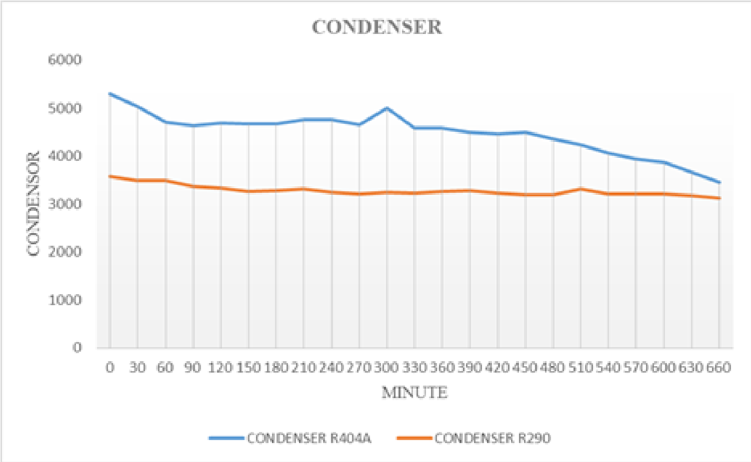

Figure 5. Comparison chart of R404a and R290 refrigerant condensers

Finally, the evaporator illustrates the cooling capacity characteristics of the evaporator for two types of refrigerants, namely R404A and R290, measured using 30-minute intervals, similar to the comparison of compressor and condenser power. Based on the graph, it can be seen that the evaporator with R404A refrigerant has an initial cooling capacity of 4200 watts at minute 0. As time progresses, this cooling capacity decreases gradually, with occasional fluctuations, such as a spike at minute 300 reaching approximately 3700 watts, before eventually decreasing again to around 2400 watts at minute 660.

On the other hand, the evaporator using R290 refrigerant showed an initial cooling capacity of 2,900 watts, which also decreased gradually. However, compared to R404A, the decrease in R290's cooling capacity tends to be more stable and consistent. At the end of the testing period (minute 660), the cooling capacity of the R290 evaporator was recorded at around 2300 watts, with relatively small fluctuations throughout the testing.

The performance difference between these two refrigerants can be explained by their thermodynamic properties and heat transfer characteristics. R404A refrigerant does have a higher cooling capacity, providing greater cooling power at the start of operation. However, R290 is more stable in maintaining cooling performance throughout the operating cycle. This is due to R290's higher thermal conductivity and heat transfer coefficient, meaning that despite its lower initial capacity, its cooling process is more consistent and efficient over the long term. Figure 6 shows a comparison graph of evaporators for both refrigerants.

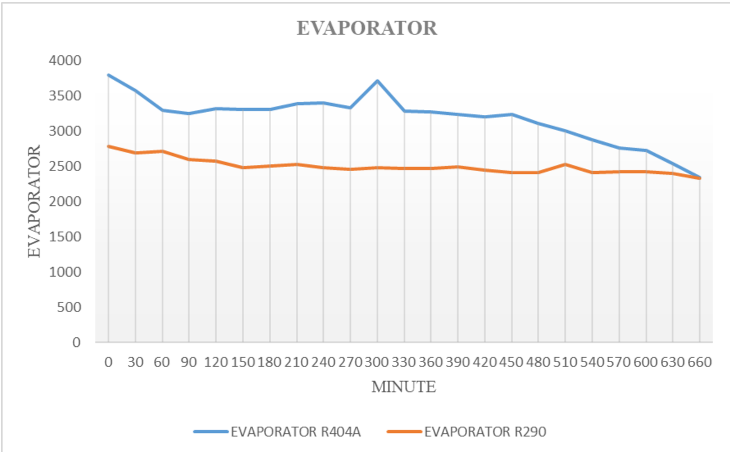

Figure 6. Comparison graph of R404a and R290 refrigerant evaporators

In addition to comparing the power of the compressor, condenser, and evaporator, there is also a performance coefficient graph comparing the two refrigerants to see in detail the overall differences between R404A and R290 refrigerants. The following is a graph of the performance coefficient values between the two refrigerants shown in Figure 7 below.

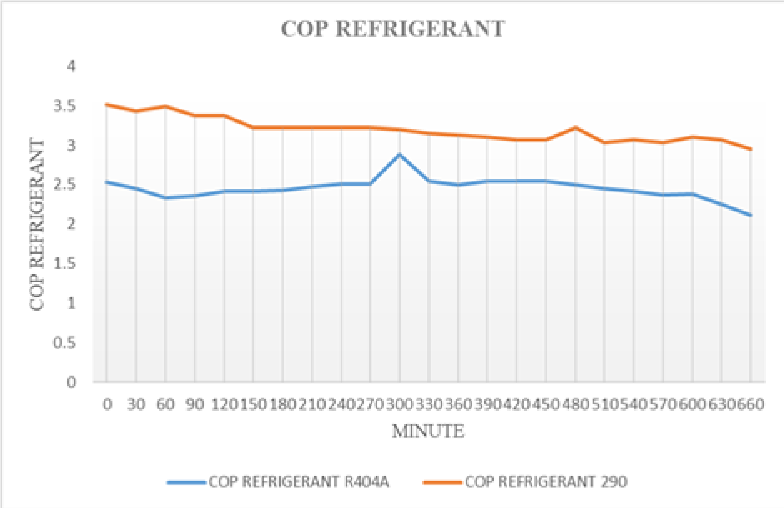

Figure 7. Comparison graph (COP) for refrigerants R404a and R290

The graph above shows a comparison of the Coefficient of Performance (COP) values between two types of refrigerants, R404A and R290, during a 660-minute cooling system operation. COP is an important parameter that describes the efficiency of a refrigeration system, where a higher COP value indicates a more efficient cooling process. Based on the graph, the COP of R290 refrigerant consistently shows better performance compared to R404A. At the start of the test (minute 0), the COP of R290 refrigerant was around 3.6, then gradually decreased and stabilized between 3.0 and 3.2 throughout the test duration. This decrease was relatively smooth with minimal fluctuations, reflecting the stability of the R290-based refrigeration system's performance.

In contrast, the COP of R404A refrigerant started at around 2.7 and experienced a more significant decrease over the observation period, reaching approximately 2.1 by the end of the testing period (minute 660). There was one instance where the COP increased at minute 300, with the R404A COP rising close to 2.9, but it quickly decreased afterward. This sharper decrease in COP indicates that the R404A refrigeration system experienced a faster decline in efficiency compared to R290.

This performance difference is evident in the graph displayed. R290 (propane) has better heat transfer properties, lower density, and lower viscosity compared to R404A, thereby supporting more efficient heat transfer processes and resulting in a higher COP. Figure 8 and figure 9 below show the comparison graph of the P-h diagram of R404A and R290 for each average result

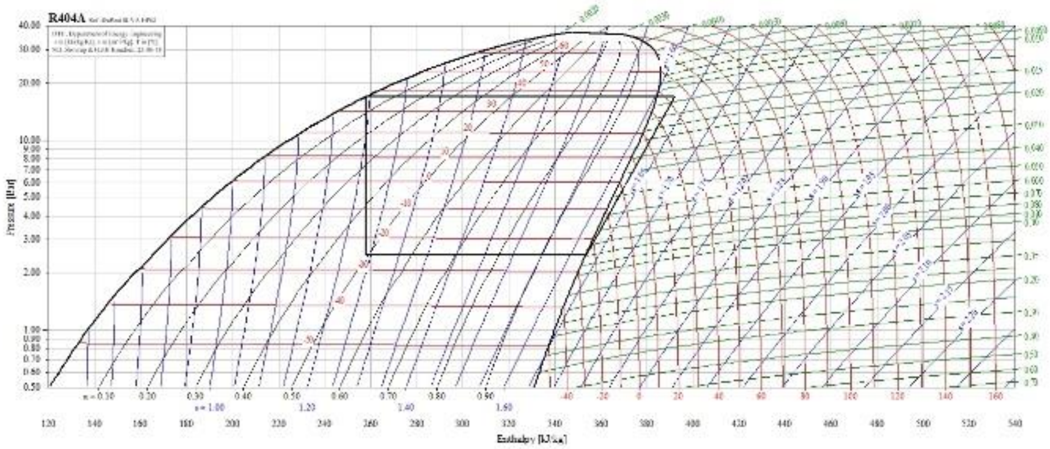

Figure 8. P-h diagram of the average values from testing refrigerant R404A

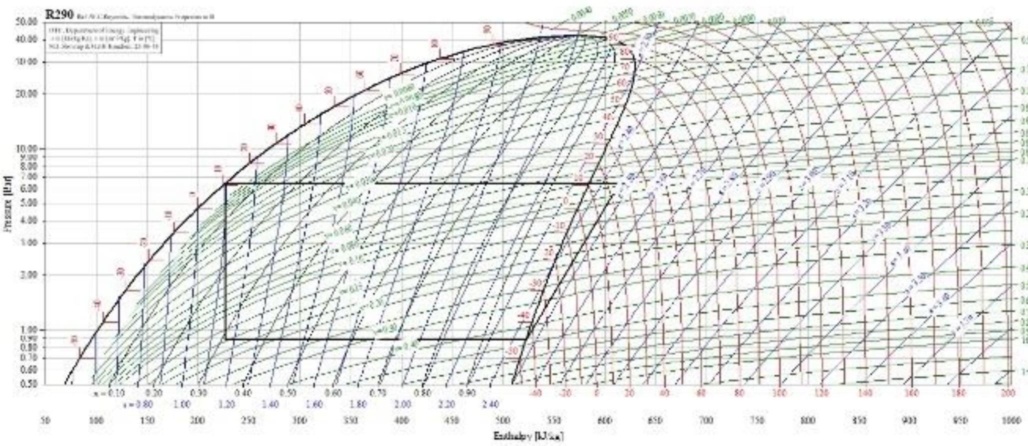

Figure 9. P-h diagram of the average values from testing refrigerant R290

A comparison of Figures 8 and 9 above shows that the working pressure of R290 is lower than that of R404A. In addition, the characteristics of R290, which has a simpler molecular structure and a lower boiling point, cause its evaporation enthalpy to be greater than that of R404A.

CONCLUSIONS

Based on the analysis of the overall graphs covering compressor power, condenser power, evaporator power, and Coefficient of Performance (COP) values, it can be concluded that refrigeration systems using R290 refrigerant show better thermodynamic performance than systems using R404A refrigerant. This is consistently demonstrated by lower power consumption and higher efficiency in various system components. In the compressor power graph, it can be seen that the compressor with R290 refrigerant requires lower electrical power compared to R404A throughout the testing period. A similar phenomenon also occurs in condenser power and evaporator power, where the R290-based system shows lower energy requirements to run the condensation and evaporation processes. This indicates that the use of R290 can reduce the overall workload of the cooling system, directly leading to better energy efficiency.

Additionally, performance comparisons based on the Coefficient of Performance (COP) further reinforce the superiority of R290 refrigerant. The general COP value for R404a ranges from 1.5 to 2.5, while the COP for R290 ranges from 2 to 3.5. In the study conducted, the COP for R404a was found to be 2.48, while the COP for R290 was 3.22. The COP of R290 refrigerant is consistently higher than that of R404A, meaning that cooling systems using R290 can achieve greater cooling effects with lower energy consumption. The stable COP value of R290 also indicates the operational stability of cooling systems over the long term.

The advantages of R290 are not only in terms of energy efficiency but also from an environmental perspective. With a Global Warming Potential (GWP) that is significantly lower than R404A, the use of R290 supports efforts to reduce greenhouse gas emissions, aligning with principles of sustainability and energy conservation. R404A is commonly used in commercial refrigeration systems such as freezers and cold storage. However, its use is beginning to be phased out in some countries due to its high GWP value. Despite this, R404A is still used in older systems because of its higher safety profile (it is less flammable), even though its COP is lower than that of R290. Therefore, overall, R290 is a more efficient, economical, and environmentally friendly refrigerant alternative compared to R404A, making it a worthy consideration as a replacement refrigerant in modern refrigeration system applications.

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