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The Impact of Hydrocarbon R290 Refrigerant on Air Conditioner Performance and Environmental Sustainability

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ABSTRACT

This study addresses the critical need for environmentally friendly refrigerants in residential air conditioning systems and explores the advantages of hydrocarbon R290 as an alternative to synthetic options. Given the indispensability of air conditioning for human comfort, the shift towards eco-friendly refrigerants becomes paramount. This research aims to demonstrate the superiority of natural refrigerants, particularly hydrocarbon R290, over conventional synthetic alternatives in air conditioning. Through a comparison of two similar air conditioners charged with R290 and R22 refrigerants, the study evaluates their performance and environmental implications. The initial phase involves a thorough analysis of hydrocarbon R290's physical properties and compatibility with synthetic refrigerants. The findings underscore its remarkable compatibility, directly replacing the environmentally harmful Hydrochlorofluorocarbon R22 refrigerant. Practical experiments and theoretical pressure-enthalpy chart analyses establish that R290-equipped air conditioners significantly enhance the coefficient of performance (COP). In practical applications, COP sees a 21.74% boost, while theoretical analysis indicates a 7.33% increase. Furthermore, adopting R290 contributes to a 17.5% reduction in CO_2 emissions through reduced power consumption. Environmental sustainability is a pivotal aspect of refrigerant evaluation; the study furnishes compelling evidence favouring hydrocarbon R290. The research demonstrates that R290 is approximately 1,383 times more environmentally friendly than R22 in terms of global warming potential and refrigerant mass. Safety, a paramount concern in adopting new refrigerants, is also addressed. R290's mass charge aligns with international standards, and its concentration remains 17.37% below the lower flammability limit, ensuring secure usage in confined spaces.

Keywords: Hydrocarbon R290, air conditioner, coefficient of performance, global warming potential, environmental sustainability, natural refrigerant

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INTRODUCTION

Global issues such as the energy crisis, the ozone-depleting threat, the impact of global warming and climate change require more public attention. How are these pressing issues interrelated to the heating, ventilation and air conditioning (HVAC) industry?

In the earlier stage of phasing out ozone-depleting substances, most appliances were replaced by non-ozone-depleting refrigerants, mainly formulated by fluorinated gases (F-gases), specifically hydrofluorocarbon (HFC), as an alternative to ozone-depleting refrigerants. However, Europe considers these F-gases powerful greenhouse gases (European Commission, 2022). As a result, some European countries have opted to switch from HFCs to other superior refrigerants or natural refrigerants.

The Kigali Amendment to the United Nations (UN) Montreal Protocol is another effort to reduce global temperature after the success of the UN Montreal Protocol program. It aims to continue addressing the climate change problem by eliminating powerful greenhouse gases and, if faithfully implemented, could control the full rise of 0.5 degrees Celsius in global temperature by the end of the century (United Nations Climate Change, 2016) (2100).

Malaysia ratified the Kigali Amendment to the UN Montreal Protocol on 21 October 2020 (Ministry of Environment and Water, 2020). As a result, Malaysia is obligated to phase down the high global warming HFCs based on the Malaysian Baseline. The first phase down of 10% is scheduled for 2029, with a further 20% of the balance from the baseline allowed for essential uses by 2045.

The hydrocarbon R290 refrigerant is highly flammable, but it is suitable for use as a conversion option for existing R22 refrigerant air conditioners without requiring major retrofitting of the existing system. The primary and only challenge with hydrocarbon refrigerants is their high flammability. However, this concern can be addressed through refrigerant mass charge control, and the HVAC design must comply with international A3-class refrigerant safety standards. Even though the hydrocarbon refrigerant air conditioners require such a safety design, the manufacturing cost is not significantly affected because the compressor is built with explosion-proof mild steel, the copper tubes are sparkless, and the system operates under an oxygen-free circuit. Moreover, the cost of natural refrigerants is much lower than that of synthetic refrigerants. The molecular mass of hydrocarbon R290 refrigerant is lighter than that of existing R22 refrigerant. However, it has a similar volumetric charge, which can further reduce the compressor power consumption and enhance lifespan.

Synthetic refrigerants are widely used in the market but significantly impact global warming. They are super greenhouse gases. These synthetic refrigerants also contribute to the pollution of freshwater sources through trifluoroacetate (TFA) in the atmosphere (Rusyanto, 2021). As scientists have reported, TFA is a chemical compound generated by the latest invented synthetic refrigerants known as hydrofluoric-olefins (HFOs).

Figure 1 shows global greenhouse gas emissions by variable types of gases. The source is the Intergovernmental Panel on Climate Change (IPCC) (2014), based on global emissions from 2010 (EPA, n.d.).

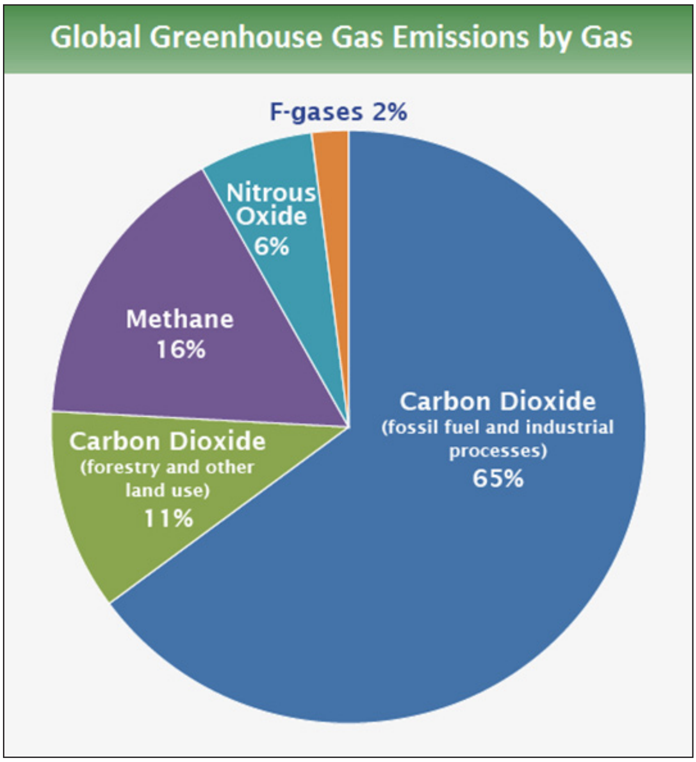

Figure 1. Global greenhouse gas emissions

The air conditioner industry is phasing out the ozone-depleting refrigerants and replacing them with newer alternatives. However, most of the refrigerants used today are high global warming substances. Surprisingly, just two per cent of F-gas refrigerants are the main contributors to Global Warming Source. The impact of this 2% from the F-gases can be significant. On the other hand, if natural refrigerants replace these refrigerants, the reduction in global warming could be substantial and beneficial for mankind. According to the Sustainable Energy Development Authority (SEDA) Malaysia's 2016 energy and CO_2 emissions report, Peninsular Malaysia's CO_2 emission coefficient rate is 0.639 kg per kWh of electrical usage (SEDA Malaysia, 2019).

As air conditioning systems have become essential for human comfort, the transition to eco-friendly refrigerants is becoming increasingly important. This research aims to demonstrate the superiority of natural refrigerants, specifically hydrocarbon R290, over traditional synthetic refrigerants in air conditioning applications.

MATERIALS AND METHODS

Preliminary prototype setups are required for a system with R290 refrigerant, and the other unit is charged with R22 Refrigerant for data findings and studying. Instruments to measure the temperature, pressure, airflow and electrical parameters are installed on the prototypes. The important part of prototype setup is ensuring the systems are free from leakage problems. Any faults should be rectified before being charged with refrigerant. Prototypes are vacuumed thoroughly and charged with R290 and R22 refrigerant, respectively. Once the systems have been completely functionally tested, the results will be observed and fine-tuned to meet the required discharge pressure, suction pressure, temperature, air flow rate and power consumption. Neither system should be undercharged nor overcharged with refrigerant. The data findings will further plot the pressure-enthalpy chart and compute the obtained cooling capacity. Subsequently, other related results will be derived via recorded raw data such as refrigerant mass flow, work done during compression, electrical power, CO_2 equivalent emissions and coefficient of performance.

The thermodynamic properties and compatibility study were obtained from the "Ener-Save Hydrocarbon Refrigerants Training Manual" (Ng, 2021). This information is essential to identify whether the existing domestic air conditioner is suitable for conversion into a Hydrocarbon natural refrigerant system or whether any modification is required to retrofit it.

Table 1 contains the basic information related to refrigerants' physical and chemical properties and related information on R290 refrigerant and R22 refrigerant. R290 refrigerant is an organic natural refrigerant; it is propane hydrocarbon with a chemical compound of C_3H_8, and the R22 refrigerant is a synthetic refrigerant with a chemical compound of hydrochlorofluorocarbon ($CHClF_2$). The R290 refrigerant is an environmentally friendly refrigerant with zero ozone-depleting potential and negligible global warming potential compared to the R22 refrigerant. The atmospheric life of R290 refrigerant is much shorter than that of R22 refrigerant, making it less harmful to the environment.

While the boiling point of R290 refrigerant is approximately the same as that of R22 refrigerant, due to its lower molecular weight, R290 refrigerant appears to be lighter than R22 refrigerant. The R290 refrigerant also has a higher heat absorption value than the R22 refrigerant, attributed to its latent heat of vaporization value at its boiling point.

Mineral oil is the compressor lubricant oil compatible with R290 and R22 refrigerants. This compatibility enables the conversion of existing R22 refrigerant domestic air conditioners to R290 refrigerant, in addition to the general compatibility with other elastomeric materials.

According to the safety classification from ASHRAE Standard 34, refrigerants are categorized into different safety classes based on their chemical characteristics (ASHRAE, 2022). R290 refrigerant is classified as A3 due to its lower toxicity and high flammability. On the other hand, the R22 refrigerant is classified as an A1 refrigerant with lower toxicity and non-flammability.

Table 1
Physical properties, chemical properties, and related information of R290 refrigerant and R22 refrigerant

Descriptions	**Column of Comparison**	
Refrigerant Type	R290	R22
Chemical Type	HC (Hydrocarbon)	HCFC (Hydrochloro- fluorocarbon)
Global Warming Potential (GWP), CO_2 = 1, 100 years basis	3	1,810
Ozone Depleting Potential (ODP)	0	0.055
Atmospheric Life	< 1 year	12 years
Boiling Point (^{o}C)	-42	-41
Molecular Weight,	44.1 g/mol	86.5 g/mol
Latent Heat of Vaporisation @ Boiling Point kJ/kg	426	233
Compressor Lubricant Oils	Mineral or Synthetic Oil	Mineral Oil Only
ASHRAE Standard 34 Refrigerant Safety Classification	A3 Lower toxicity, highly flammable	A1 Lower toxicity, Non-flammable
Leak Detection Method	Hydrocarbon	Halide
Autoignition (^{o}C)	480	NA
Lower Flammability Limit (LFL), kg/m^3	0.038	NA
Toxic Thermal Decomposition	None	Phosgene Gas

The air conditioning system consists of four major components that correspond to the Carnot refrigeration cycle (Cengel & Boles, 2015). These components include the expansion valve for the adiabatic expansion process, the evaporator coil for the isothermal expansion process, the compressor for the adiabatic compression process, and the outdoor condenser coil for the isothermal compression process. This closed-loop cycle uses refrigerant as a heat transfer medium, absorbing heat from the indoor area of the house and releasing it to the outdoor environment. It represents the typical usage of an air conditioner in hot climate countries.

Practically all the different types of refrigerants have different enthalpy properties. Equation 1 gives the relationship of enthalpy, h.

$$h = E_{int} + pv \qquad [1]$$

Where E_{int} is the total internal energy

Pressure-enthalpy charts will be plotted based on the actual performance of the prototype setup to simplify the determination of the work done for air conditioners using different refrigerants. This setup includes an R290 refrigerant air conditioner with pressure gauges, temperature displays, and a similar setup charged with R22 refrigerant. Figure 3 describes the plotting of the pressure-enthalpy chart; the temperatures and pressures are obtainable parameters from the prototype setup. The compressor drives the whole system as a main driver. Thus, the intention to determine the air conditioner's coefficient of performance will focus on the compression process as it will consume external energy to perform work internally. Even though the condenser fan motor and evaporative fan motor are used to transfer internal heat from the system out to the outdoor environment and from the external heat source of the indoor house to the internal refrigeration system, respectively, the energy of such fan motor is lesser than the energy consumed by the compressor. Therefore, the main focus of the study on the theoretical performance will be narrowed to the compression process, and the formula to obtain the work done during the compression of refrigerant is as Equation 2.

$$Q_c = m_R \times (h_2 - h_1) \quad [2]$$

Where m_R is the mass flow of refrigerant

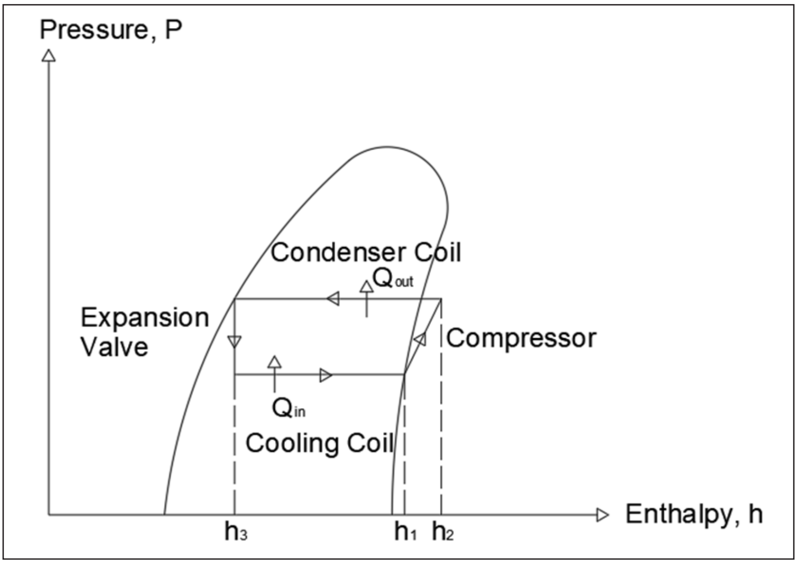

Figure 2. Pressure: Enthalpy diagram of the refrigeration system and the components involved

Ultimately, the coefficient of refrigerant performance in the system between natural R290 refrigerant and synthetic R22 refrigerant will be compared and calculated.

Firstly, the refrigerating effect per kg, R_E, can be obtained from Equation 3 before calculating the mass flow of refrigerant.

$$R_E = h_1 - h_3 \quad [3]$$

After finding the RE value, Equation 4 shows the refrigerant's mass flow, m_R. The cooling capacity is the actual cooling performance of the air conditioner's evaporative blower.

m_R = cooling capacity / R_E

Thus,

$$m_R = \text{cooling capacity} / (h_1 - h_3) \quad [4]$$

and

The work done during refrigerant compression, Q_c (Equation 5), is the interesting part of identifying the work done on the air conditioner's compressor, as it is the main driver of the closed-loop thermodynamic process.

$$Q_c = m_R \times (h_2 - h_1) \quad [5]$$

Nevertheless, the theoretical coefficient of performance (COP) for the refrigerant can be obtained from Equation 6.

$$COP = (h_1 - h_3) / (h_2 - h_1) \quad [6]$$

Classically, the cooling capacity was calculated using the imperial unit in most applications; certain conversions are required to identify whether the calculated value matches within the range of design or not. Such as:

1 Watt = 3.412 btu/hour (Cooling Capacity) = 1 Joule/s
1 horsepower (hp) = 741 Watt (Electrical Power)
12,000 btu/hour = 1 refrigeration ton (RT)

Practically, the higher the specific power value, the lower the air conditioner's coefficient of performance. Higher specific power means the air conditioning system consumes more energy to produce a refrigeration ton of cooling. The specific power could be obtained from Equation 7.

$$\text{Specific Power} = \frac{\textit{Electrical Power}}{\textit{Refrigeration Ton}} \quad [7]$$

COP is always inversely proportional to a specific power, as shown in Equation 8.

$$\text{COP} = 12 / (\text{Specific Power} \times 3.412) \quad [8]$$

Specific heat at constant pressure (C_p) is required to raise the temperature of a unit mass of gas by one degree Celsius at constant atmospheric pressure (Khurmi & Gupta, 2008).

Total heat energy, Q, is equal to the mass of air multiplied by its specific heat at constant pressure with the differential temperature obtained, as shown in Equation 9.

$$Q = m\,C_p\,(T_{in} - T_{out}) \quad [9]$$

Where T_{in} enters air temperature (data collection from prototype), and T_{out} leaves air temperature (data collection from prototype). Hence, if the thermodynamic takes place, the derivation of heat energy Q is the cooling capacity from the evaporator and is derived in Equation 10.

$$\text{Cooling capacity, } dQ/dt = (m/dt)\,C_p\,(T_{in} - T_{out}) \quad [10]$$

Where the m/dt is the mass flow rate of air or M_f.

The mass of air is given by Equation 11.

$$\text{Mass of air, } m = \text{density of air} \times \text{volume of air} \quad [11]$$

However, the airflow from the evaporative blower is a dynamic property. The airflow rate from the evaporative blower must be measured to get the mass flow rate of air. Equation 12 is the formula to find the mass flow rate of air.

$$M_f = \text{density of air (kg/m}^3) \times \text{air flow rate (m}^3\text{/s)} \quad [12]$$

Therefore, the air conditioner's final and simplified cooling capacity can be estimated using Equation 13.

$$\text{Cooling capacity} = M_f \times C_p\,(T_{in} - T_{out}) \quad [13]$$

Figures 3 and 4 show a complete prototype setup with a temperature sensor, pressure gauge, power logger and air flow meter. One of the air conditioners is charged with 240 grams of R290 refrigerant, and the other is charged with 550 grams of R22 refrigerant for virtual comparison and data finding. Both systems switch on for approximately thirty minutes to achieve stabilisation before performing data collection.

Figure 3. Complete indoor evaporator blower setup with measurement gadget

Figure 4. Complete outdoor compression condenser unit setup with measurement gadget

Never forget to conduct the Hydrocarbon conversion according to the standard operating procedure (SOP) because the R290 refrigerant is hydrocarbon and highly flammable. Table 2 is the practical SOP for conducting the R290 refrigerant conversion in the R22 domestic air conditioner.

Table 2
Standard of procedure for R290 conversion

Working procedures	Instructions
Step 1	Perform a leak test after setting up the air conditioner system
Step 2	Estimate equivalent HC charge—Use conversion rate of R22 to R290
Step 3	Check the maximum practical charge limit and consult the MS2678:2017
Step 4	Ensure all tools and working areas are safe from fire hazards and prepare a fire extinguisher.
Step 5	Identify all potential sources of ignition that are out of range
Step 6	Vacuum the air conditioner system thoroughly
Step 7	Using the refrigerant mass charge method to charge in the estimated R290 refrigerant
Step 8	Put a temporary flammable zone at the drop-in working area
Step 9	Apply relevant system marking with a warning sign
Step 10	Switch on the air conditioner and fine-tune the system

The steps to identify the maximum allowable hydrocarbon refrigerant charge in a specific room are outlined in the standard, defined by the installation location. It is recommended that the Malaysian Standard MS 2678:2017 (MS2678 Working Group, 2017) be consulted, where the relevant charge size shall not be more than 20% LFL of hydrocarbon refrigerant charge. If the facility is below ground level, the maximum charge would be 1kg in all circumstances, but not more than 20% LFL of hydrocarbon refrigerants charge.

Equation 14 calculates the maximum hydrocarbon charge size per sealed system in a specific machinery room. Therefore, the gas leak will not trigger the ignition level five times lower than the LFL level. In all circumstances, the leakage event will not occur catastrophically in more than one compressor.

$$m_r = 0.20 \times (LFL) \times v_{room} \qquad [14]$$

Where,
LFL = lower flammability limit of refrigerant (kg/m^3) from Table 1,
v_{room} = room volume (m^3)
m_r = refrigerant mass (kg)

RESULTS AND DISCUSSIONS

The study uses the "ELIWELL" IDPlus974 Thermostat for temperature display. It is a dual sensor system consisting of temperature probes 1 (Pb1) and 2 (Pb2), as shown in Figure 5. The study uses the common air ambient temperature (Figure 6) and water medium temperature (Figure 7) to cross-check the sensible detection reading on temperature probes and both temperature displays and to determine the accuracy of both temperature detections. The temperature reading was observed and recorded in Table 3.

Figure 5. “ELIWELL” IDPlus974 Thermostat Schematic Diagram and Wiring Termination

Table 3
Temperature reading of the Pb1 and Pb2 in ambient air temperature and water medium temperature

Medium of Calibration	**Probe 1, Pb1**		**Probe 2, Pb2**	
	AC01 (R290)	**AC02 (R22)**	**AC01 (R290)**	**AC02 (R22)**
In Ambient Air (30/03/23, 10.05am)	30.2 °C	30.2 °C	30.1 °C	29.8 °C
In Water Medium (Trial 1, 30/03/23, 10.13 am)	29.4 °C	29.4 °C	29.3 °C	28.8 °C
In Water Medium (Trial 2, 30/03/23, 10.40 am)	29.4 °C	29.4 °C	29.3 °C	28.8 °C

Figure 6. Temperature sensor calibration check in ambient air

Figure 7. Temperature sensor calibration check in water medium

The temperature reading from the Probe 1 sensor is similar, either displayed from AC01 or AC02; thus, Pb1 is used as the main temperature sensor to observe the leaving air temperature. However, the Pb2 from AC01 is less than 0.1^{o}C. Therefore, a +0.1^{o}C calibration adjustment is required from the thermostat, but the AC02's Pb2 is required to adjust +0.4^{o}C to match the actual reading from the thermostat installed at AC02. The calibrations of the temperature reading will be hereafter.

Both air conditioners operated for approximately thirty minutes to keep the refrigeration cycle steady. The raw data are recorded in Table 4. The R290 refrigerants are natural organic compounds, and the R22 refrigerant is synthetic.

Table 4
Air conditioners' operating parameter

Descriptions	**R290 Refrigerant Air Conditioner AC01**	**R22 Refrigerant Air Conditioner AC02**
Refrigerant Mass Charge in 9,000 btu/hr air conditioner	240 grams	550 grams
Suction Pressure in 9,000 btu/hr air conditioner	6.0 Bar/ 0.60 MPa	6.0Bar/ 0.60 MPa
Discharge Pressure in 9,000 btu/hr air conditioner	16 Bar/ 1.6 MPa	18 Bar/ 1.8 MPa
A/C Temperature Set Point (^{o}C)	25	25
Entering Air Temperature ^{o}C, T_{in} (Calibrated)	31.5 + 0.1 =**31.6**	31.2 +0.4 = **31.6**
Leaving Air Temperature ^{o}C, T_{out}	22.8	22.6
Evaporator Blower, airflow speed, m/s	4.3	4.2
Instant Voltage Reading, V	235.9	236.3
Instant Current Reading, A	3.21	3.92
Power Supply Frequency, Hz	50.1	50.0
Instant Real Power, kW	0.735	0.893
Instant Power Factor, PF	0.970	0.965
Instant Reactive Power, kVar	0.186	0.244

Referring to Table 4, the refrigerant mass charge for the R290 refrigerant air conditioner is 240 grams, while for the R22 refrigerant air conditioner, it is 550 grams. It demonstrates that the refrigerant used in the R290 air conditioner is 56.36% lighter than the R22 refrigerant. The R290 system operates at a low head pressure of approximately 1.6 MPa, despite having a similar suction pressure of 0.6 MPa for both systems. The combination of low head pressure and lighter molecular weight contributes to a reduction in compressor torque power. These characteristics further explain the ability of R290 to enhance energy savings, as the compressor requires less energy to operate the air conditioning system.

The conversion to R290 and the use of R290 refrigerant in R22 domestic air conditioners comply with safety standards. A typical 9,000 BTU/hr air conditioner is installed in a

36-cubic-meter room (3m × 4m × 3mH). The concentration of R290 refrigerant from a 9,000 BTU/hr air conditioner in the room is determined by dividing the refrigerant mass charge per sealed system by the room volume. In the case of a 9,000 BTU/hr R290 air conditioner in a room of 36 cubic meters, the concentration is 0.0066 kg/m³ in the event of refrigerant leakage. This concentration adheres to the standard that does not exceed 500g and is less than 20% of the lower flammability limit (LFL) charge limit. In fact, it is 17.37% lower than the LFL charge limit.

Cooling Capacity of R290 Air Conditioner and R22 Air Conditioner

The air conditioners were set to a temperature set point of 25°C. The set point does not affect the constant airflow temperature of the indoor evaporator since the testing site is open to the outdoor ambient air. The outdoor ambient temperature thoroughly influences the indoor temperature, thus consistently maintaining the entering air temperature above the set point. As a result, the compressor operates at a 100% load.

From the Equation 13, cooling capacity = $M_f \times C_p\,(T_{in} - T_{out})$
Specific heat of air at constant pressure, C_p = 1.000kJ/kg.°C
Density of air at 25°C, ρ = 1.1839 kg/m³

M_f can be obtained from Equation 15; the cooling capacity is calculated separately for the R290 and R22 systems. The airflow rate of the evaporator blower is V_f.

$$V_f\,(m^3/s) = L \times H \times \text{air-flow speed (m/s)} \qquad [15]$$

L = length of evaporator blower = 0.675m
H = height of evaporator blower = 0.080m
The airflow speed is recorded in Table 4

Cooling Capacity of R290 System

The system converted to R290 refrigerant is not working 100% to the designed cooling capacity. Calculating the actual cooling capacity is required to identify the air conditioner's performance. Thus, the parameters required to calculate the cooling capacity are taken from the data collections.

The R290 refrigerant air conditioner is currently operating at 8,254.0 BTU/hr, which is 8.29%, slightly below the designed specification of 9,000 BTU/hr. The cooling capacity falls within an acceptable range, meeting the criteria of being within plus or minus 10% of the 9,000 BTU/hr design.

Cooling Capacity R22 System

The R22 refrigerant system is not working 100% to the designed cooling capacity. Calculating the cooling capacity is required to notify the conditioner's performance air. Thus, the parameters required to calculate the cooling capacity are taken from the data collections.

The R22 refrigerant air conditioner is currently operating at 8,245.4 BTU/hr, which is 8.38%, slightly below the designed specification of 9,000 BTU/hr. The cooling capacity falls within an acceptable range, meeting the criteria of being within plus or minus 10% of the 9,000 BTU/hr design.

Refrigeration Cycle State Analysis

Figure 8 illustrates the operation flow of a refrigeration cycle involving pressure measures. It will then plot the ideal refrigeration cycle in a pressure-enthalpy (p-h) chart. Table 5 summarizes the data found in the p-h chart for every state.

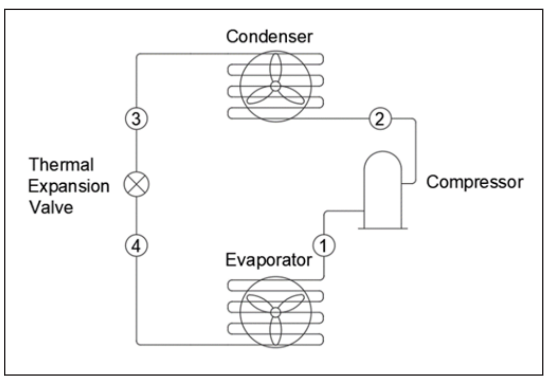

Figure 8. The simple refrigeration cycle diagram involves processes in states 1, 2, 3 and 4. It is a closed-loop cycle from state 1 to state 4 and back to state 1

Table 5
Ideal refrigeration cycle state and data finding summary

Descriptions	**State 1**	**State 2**	**State 3**	**State 4**
R290 Refrigerant Cycle	p_1 = 6.0 Bar/ 0.60MPa T_1 = 13.46°C h_1 = 479kJ/kg	p_2 = 16 Bar/ 1.60Mpa T_2 = 49.68 °C h_2 = 529kJ/kg	$p_3 = p_2$ T_3 = (T_2 – Subcooling) $h_3 = h_4$ = 228kJ/kg	$p_4 = p_1$ T_4 = (T_1 – Superheat) $h_4 = h_3$ = 228kJ/kg
R22 Refrigerant Cycle	p_1 = 6.0 Bar/ 0.60Mpa T_1 = 10.98°C h_1 = 407kJ/kg	p_2 = 18Bar/ 1.80Mpa T_2 = 49.06 °C h_2 = 438kJ/kg	$p_3 = p_2$ T_3 = (T_2 – Subcooling) $h_3 = h_4$ = 262kJ/kg	$p_4 = p_1$ T_4 = (T_1 – Superheat) $h_4 = h_3$ = 262kJ/kg

Mass Flow of Refrigerant, Work Done and COP

From the pressure-enthalpy chart plotted in Figures 9 and 10, the refrigerating effect per kg could be obtained from Equation 3.

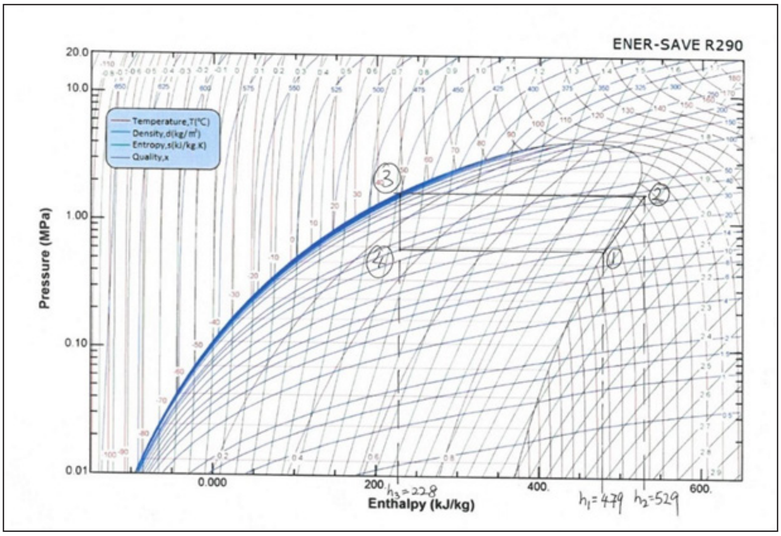

Figure 9. Pressure-enthalpy plotting of R290 air refrigeration system

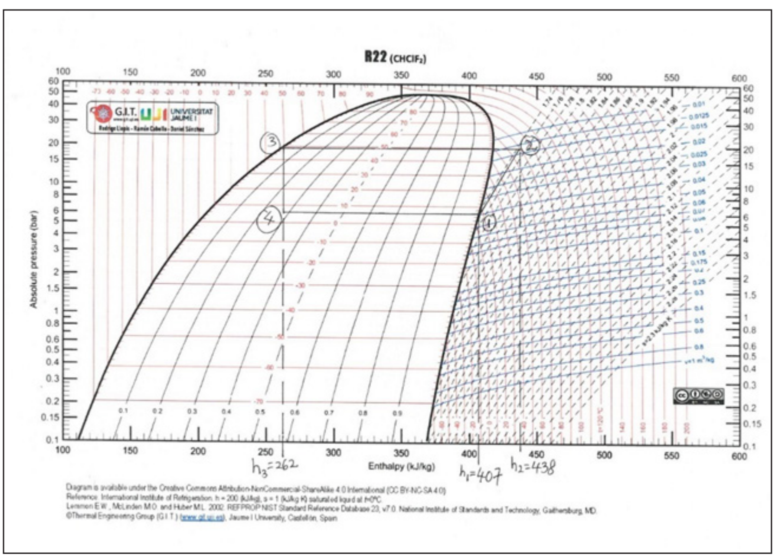

Figure 10. Pressure-enthalpy plotting of the R22 refrigeration system

The mass flow of the refrigerant, m_R, can be obtained from Equation 4. The whole process relies on the compressor's external power. Therefore, the work done during the compression cycle is significant in identifying the performance of the refrigeration cycle, as the other states' work was merely the same. Work done during refrigerant compression can be obtained from Equation 5; subsequently, the coefficient of performance, COP, can be calculated from Equation 6. The work done on the compression cycle and refrigeration COP are calculated and shown in Table 6.

Table 6
Work done on compression cycle and refrigeration COP in theory

Refrigerant Type	Work Done During Compression Cycle	COP
R290	482 Watt	5.020
R22	517 Watt	4.677

Apparently, the R290 system draws less power for the compression cycle if compared to the R22 system. Furthermore, the COP of the R290 refrigeration cycle shows a 7.33% increase in the R22 system in the theoretical approach.

Energy Saving Verification and System COP in Practical Case Study

Electrical data collection and observation were conducted concurrently. The practical operating comparison is based on each air conditioner's operating power and cooling performance.

From Table 4, the R290 refrigerant air conditioner consumes instantaneous real power at 0.735 kW with a cooling capacity of 0.688 refrigeration tonnage (RT). The specific power value effectively illustrates its efficiency in terms of how much electrical power is used to generate one RT of cooling capacity. The specific power can be derived using Equation 7. In this study, the specific power of the R290 refrigerant air conditioner is calculated to be 1.068 kW/RT, while the specific power of the R22 refrigerant air conditioner is 1.300 kW/RT. Based on specific power, the R290 refrigerant air conditioner is 17.85% more efficient than the existing R22 refrigerant air conditioner.

From the specific power obtained, the COP in practical operation could be derived from Equation 8. Hence, the COP of an R290 refrigerant air conditioner in practical operation is 3.293, and the COP of an R22 refrigerant air conditioner in practical operation is 2.705. It shows a 21.74% increase in COP after converting to R290 natural refrigerant.

In conjunction with the Malaysian Department of Environment program and based on the SEDA 2016 report, the CO_2 equivalent emissions per hour of air conditioner power consumption are calculated by multiplying the total power consumption per hour by Peninsular Malaysia's CO_2 emission coefficient rate of 0.639 kg per kWh of electrical usage. Thus, the R290 refrigerant air conditioner would produce 0.509 kg of CO_2 equivalent emissions per usage hour (0.735 kW × 1 hr × 0.639 kg/kWh). In comparison, the R22 refrigerant air conditioner would produce 0.617 kg of CO_2 equivalent emissions per usage hour (0.893 kW × 1 hr × 0.639 kg/kWh). The CO_2 emissions equivalent produced by the R290 air conditioner are 17.5% lower than those produced by the R22 refrigerant air conditioner. The R290 refrigerant air conditioner is more energy efficient.

Lastly, the direct impact of refrigerants on global warming is determined by multiplying the amount of refrigerant mass charge per air conditioner by the refrigerant's GWP. The direct CO_2 equivalent for R290 refrigerant equals 240 grams multiplied by three (R290 refrigerant has a GWP of 3). For R22 refrigerant, the direct CO_2 equivalent equals 550 grams multiplied by 1810 (as R22 refrigerant has a GWP of 1810). The release of R290 refrigerant from a 9,000 BTU/hr air conditioner will result in a CO_2 equivalent impact of 0.72 kg. Releasing R22 refrigerant from a 9,000 BTU/hr air conditioner will result in a CO_2 equivalent impact of 995.50 kg. Therefore, the R290 refrigerant air conditioner is 1,383 times more environmentally friendly than the R22 refrigerant air conditioner.

CONCLUSION

The hydrocarbon (HC) R290 refrigerant exhibits a lower molecular weight and the highest latent heat of vaporization at its boiling point. It is compatible with both mineral compressor oil and synthetic compressor oils. The lower molecular weight reduces the torsion power required by the compressor, while the higher latent heat of vaporization aids in absorbing more heat within the R290 refrigerant. The compatibility with both compressor oils allows R290 to be effectively converted for use in existing domestic air conditioners. This approach offers an economical solution to address environmental concerns related to transitioning from ozone-depleting and global-warming refrigerants to natural refrigerants. Remarkably, the results of using R290 refrigerant in existing R22 air conditioners indicate a 17.69% reduction in instantaneous power consumption.

From a technical perspective, the hydrocarbon R290 refrigerant enhances the air conditioner's coefficient of performance (COP) by 21.74% in practical terms and by 7.33% in theoretical analysis based on the pressure-enthalpy chart. This increase in COP leads to energy savings through reduced power consumption by the R290 air conditioner.

In terms of environmental impact and global warming, adopting the natural refrigerant R290 in domestic air conditioners significantly reduces the impact to 720 grams CO_2 equivalent for each R290 system conversion, given its GWP of 3. It starkly contrasts the 995.5 kilograms CO_2 equivalent emitted by an R22 system with a GWP of 1810. It equates to a 1,383 times reduction in CO_2 equivalent released into the environment over one day when an air conditioner is disposed of in a garbage disposal area.

Safety is paramount when adopting new refrigerants, and we assess the safety aspects of R290. The HC air conditioner's safety compliance, verified through refrigerant mass charge safety verification, and the application of the R290 natural refrigerant air conditioner have been confirmed. The system's flammability is five times lower than the lower flammability limit (LFL) of R290, making it safe for household use and compliant with international standards. However, certain safety precautions are essential to educate users and installers, such as avoiding installation of the R290 system near ignition sources. Electrical components need to be switched to solid-state components; for instance, glass-type fuses are recommended to be replaced with ceramic types on the printed circuit board. Overcoming flammability concerns involves adopting good practices and designs.

Furthermore, to mitigate carbon emissions through the use of HC in domestic air conditioners, refrigerants like synthetic R22 need to be recovered into empty cylinders for recycling, reclamation, and reuse. According to Table 4, each R290 conversion from an existing R22 system (9000 BTU/hr) can directly reduce CO_2 equivalent impact by 994.78 kg due to the refrigerant's global warming potential, making it 1,383 times greener. The projected reduction in carbon dioxide from electricity savings is estimated at about 17.5%, potentially leading to a reduction of up to 0.108 kg of CO_2 emissions per hour of usage for each air conditioner.

Considering the scenario of converting 200,000 units of R22 air conditioners to R290 natural refrigerant instead of replacing them with other high global warming type air conditioners, it could result in a reduction of up to 198.956 million kg of CO_2 equivalent from refrigerant direct impact and 21,600 kg of CO_2 reduction per hour of electricity usage. Environmental sustainability is a critical factor in evaluating refrigerants, and our study presents compelling evidence in favour of hydrocarbon R290. By adopting natural refrigerants, we have the potential to mitigate climate change by reducing the usage of high global warming substances found in traditional synthetic refrigerants. Embracing this change on a larger scale could substantially impact the environment and help address the challenges of global warming.

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