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Energy and cooling performance of carbon-dioxide and hydrofluoroolefins blends as eco-friendly substitutes for R410A in air-conditioning systems

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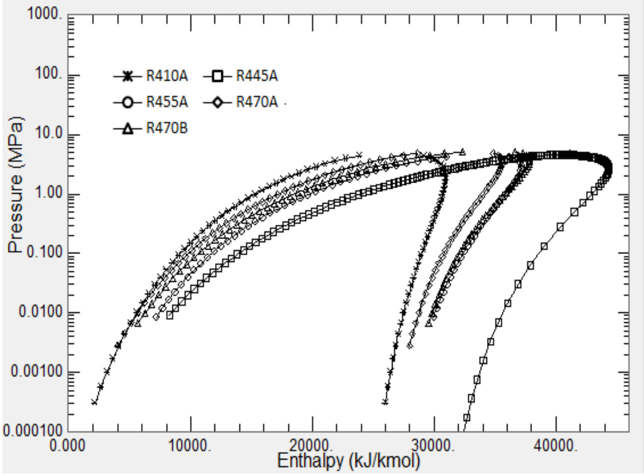

Highlights:

- Carbon dioxide and hydrofluoroolefin refrigerants as substitutes for R410A have been investigated.
- Four candidate refrigerants (R445A, R455A, R470B and R470A) showed better performance than R410A.
- The overall assessment revealed R455A as the best substitute refrigerant for R410A.

Abstract

Air-conditioning and refrigeration systems are electrical appliances that use a huge amount of energy and contribute indirectly to global warming. Also, R410A which was initially developed as a substitute for ozone-depleting refrigerants in the air-conditioning systems has been phase-out due to its high global warming potential (GWP) and the resulting harmful effect on the climate. In addition to the issue of refrigerant high GWP, energy consumption is a significant issue. The energy efficiency of new refrigerants must then be considered in the search for alternative refrigerants to ensure that they do not lead to an increase in greenhouse gas generation at the power source. Therefore, this paper investigates the energy and cooling performance of four new multi-components and ecologically friendly refrigerant blends that contained carbon dioxide and hydrofluoroolefins in their compositions as substitutes for R410A in air-conditioning systems. Relevant thermodynamic equations and REFPROP software were employed for the computational analysis. The results indicated that the new blends (R445A, R455A, R470B and R470A) exhibited a desirable low compression ratio and high heat transfer for cooling applications. The blends also exhibited low compressor energy input and low specific cooling energy. R455A has an average coefficient of performance (COP) of 24.6% above that of the reference refrigerant (R410A). The cooling capacity per unit volume for R470B, R455A and R470A across a temperature range of 253 to 293 K are higher by 1.3, 6.0, and 12.6%, respectively than that of R410A. Generally, among all the four new substitute blends, the overall assessment revealed R455A as the best replacement for R410A in air-conditioning systems due to its superior performance in terms of its low compression ratio, compressor energy and specific cooling energy. R455A also has the highest COP and relatively high cooling capacity per unit volume.

Keywords: Air-conditioning; CO_2; Cooling energy; Eco-friendly; R410A; Refrigerant blends

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1. Introduction

The air-conditioning and refrigeration systems are extremely important to civilization. They became well-known applications in the early years of the twentieth century. Refrigeration allows products to be preserved at low temperatures to prevent deterioration. Refrigeration's applications are found in the household and in many industries such as petrochemicals, cold chains, pharmaceuticals, food, and drinks [1]–[3]. Increased usage of air-conditioning and refrigeration equipment is indeed putting a major strain on power networks and increasing peak electricity consumption, particularly in nations with high ambient temperatures [4]. The vapour compression refrigeration method has dominated the refrigeration industry [5]. The method works by circulating a low-temperature fluid (refrigerant) around the material to be cooled, letting the fluid absorb and take away heat from the material. This approach is used to design a closed system that continually makes the refrigerant go through a series of phase transitions from liquid to vapour and back to liquid [6].

Heat pump, air-conditioning and refrigeration systems have two major environmental implications; the leaking of refrigerants into the environment, which can cause ozone depletion and contribute directly to global warming, and their energy consumption, which raises CO_2 emissions and contributes indirectly to global warming [7]. The Montreal Protocol, which banned the use of chlorofluorocarbons (CFCs) in 1987, addressed the issue of ozone depletion. Hydrochlorofluorocarbons (HCFCs), which are partly fluorinated hydrocarbons, are also ozone-depleting substances (ODS) and have a significant contribution to global warming. In terms of global warming potential (GWP), R22, the most frequently used HCFC, is about 2000 times more than the global warming potential (GWP) of carbon dioxide. Under the Montreal Protocol, HCFCs are prohibited from use in developed nations by 2020 and in developing nations by 2030 [8].

Hydrofluorocarbons are now the most extensively used alternative refrigerants in most air-conditioning and refrigeration applications. These refrigerants have no effect on ozone depletion yet they have a much greater impact on climate change than CO_2 as a result of the fluorine component in their molecules [9]. Climate change is increasingly acknowledged as a factual and serious threat to global development and humanity as reported in many scientific studies [10]–[12]. It has currently produced several issues, such as increased drought, rising sea levels and glacier melting, all of which have a worldwide impact on human life. As a result, it is very important to reduce global greenhouse gas (GHG) emissions [13].

In order to reduce greenhouse gas (GHG) emissions and safeguard the global environment, the refrigeration sector is returning to natural refrigerants that were employed before synthetic refrigerants were introduced. Natural refrigerants are so-called because they are present in nature and do not need to be manufactured in a laboratory [14]. Many studies have been conducted on the use of carbon dioxide (CO_2), a natural refrigerant, as a replacement for the conventional high-GWP refrigerants in some refrigeration applications. Cao *et al*. [15] examined the performance of CO_2 in a prototype liquid suction heat exchanger heat pump water heater. The study found that using CO_2 with a heat exchanger in the heat pump lowered the ideal discharge pressure. Also, a rise in the water input temperature and a drop in the ambient temperature reduces the system's working pressure.

Chen *et al*. [16] investigated the performance of CO_2 in a car refrigeration system employing compressors with intermediate cooling and a dual rotor. The findings demonstrated that the system with an intermediate cooler working with CO_2 as a refrigerant performed well under 35 °C ambient temperature. The highest COP increased by 12.8 per cent as compared to traditional working conditions. Likewise, Song *et al*. [17] studied the performance of CO_2 as an alternative to R407C refrigerant in the air-conditioning system of a train-vehicle. The air-conditioning system was analysed using simulation models based on a one-dimensional simulation of the thermodynamic cycle. The annual cooling and heating conditions were tested, and the results revealed that carbon dioxide performed poorly in cooling but very well in the heating application when compared to the system using R407C as a working fluid.

Carbon dioxide refrigerant has low GWP (as a reference point gas, GWP = 1) and has no ozone-depleting effect. However, like other natural refrigerants, it has its own limitation. The major disadvantage of using carbon dioxide as a refrigerant is that it has a higher operating pressure than synthetic and other natural refrigerants. Some studies considered mixtures of CO_2 with other refrigerants in order to mitigate its high working pressure. Zhang *et al*. [18] considered mixtures of CO_2 and R1270 as refrigerants in a cascade system. The performance of the mixtures was tested experimentally at different evaporating temperatures in a constructed cascade system with a semihermetic type of compressor. The results showed that when the evaporation temperature drops, the isentropic efficiency and coefficient of performance rise.

In the recent search for perfect substitute refrigerants, interest in refrigerant mixtures has grown. This is because by combining two or more refrigerants, a new working fluid with the desired properties can be produced. The use of refrigerant mixtures can lead to energetic improvements, an expansion of the application limits, and a continuous capacity control when compared to conventional refrigerants. Refrigerant blends may provide benefits when used with standard equipment in applications where one refrigerant may not quite produce the desired result [19], [20]. For instance, the vapour pressure of the final fluid can be modified to match that of the conventional refrigerants being replaced by changing the composition of a blend consisting of high-pressure and low-pressure refrigerants. Also, new blends that are non-flammable but still contain moderately flammable refrigerants can be made by blending different refrigerants. In other instances, blends are developed to enhance specific system characteristics, such as the temperature of the compressor discharge, or to enhance lubricant circulation by including a higher proportion of lubricant-miscible refrigerants in the blend, which will enhance the system's overall performance. Multi-component refrigerant blends give you more freedom to modify the final refrigerant's properties to get closer to the ideal refrigerant.

Yelishala *et al*. [21] analysed the performance of mixtures of carbon dioxide and hydrocarbons as working fluids in a mechanical refrigeration cycle. The mixtures were theoretically analysed using a gas cooler and evaporator of a refrigeration system under constant heat transfer. For the tested refrigerant combinations, the system performance in terms of refrigerating capacity and coefficient of performance was assessed under various operating settings. The results revealed that carbon dioxide and hydrocarbon blends performed well as refrigerants in the refrigeration system. Sun *et al*. [22] studied CO_2 and hydrofluoroolefin refrigerant mixtures as suitable working fluids in air-conditioning and refrigeration systems. The impacts of combining hydrofluoroolefin with CO_2 refrigerant on the critical pressure and temperature were theoretically investigated and compared to the usage of pure CO_2. The study discovered that changes in critical pressure and temperature of CO_2 depend on the type and the mass fraction of hydrofluoroolefin in the mixture.

Hydrofluoroolefins (HFOs) have been studied as an environmentally substitute for conventional refrigerants. HFOs are ecologically friendly refrigerants that are chemically produced to be prospective substitutes for R134a in various air-conditioning and refrigeration applications. Gil and Kasperski [23] used a one-dimensional model to investigate the performance of the HFO refrigerants in the ejector refrigeration system at various levels of evaporation and condensation temperatures. The study found that the HFO refrigerants achieve high ejector system efficiency at low vapour temperatures.

In a cold region, Li *et al*. [24] evaluated the performance characteristics of R1234yf (a HFO refrigerant) as a substitute for R134a in a heat pump system under various settings. At 40 °C condensing temperature, the COP of R1234yf is 20% lower than that of R134a, according to the study. In addition, when condenser temperature rises, the specific mass flow rate of R1234yf drops. Saleem *et al.* [25] looked into the performance of another HFO refrigerant, R1234ze(E), as a substitute for R410A in a refrigeration system with a fin-and-tube evaporator coil. The simulations were conducted with segment-by-segment heat exchanger models. The findings revealed a 2.5% loss in capacity and recommended further improvements in the heat exchanger design by conducting a comprehensive evaluation of the heat exchanger configuration for the HFO refrigerant.

R410A was created to replace the ozone depleting R22 refrigerant. R410A has proven to be the most effective substitute for working fluid in residential and commercial air-conditioning systems [26]. When the Montreal Protocol intended to eliminate refrigerants with ozone-depleting potential (ODP), the global warming potential (GWP) of alternative refrigerants was not considered. As a result, several of the refrigerants created in response to the Montreal Protocol have high GWP, making them ecologically hazardous. R410A is completely harmless to the ozone layer, but it has a relatively high GWP of 1890. It has been regulated under the Kyoto Protocol, the Kigali amendment to the Montreal Protocol and F-gas Regulations due to its harmful influence on the climate [27], [28]. Therefore, there is a need for a suitable and ecologically friendly refrigerant for R410A replacement in the residential and commercial air-conditioning systems.

Aside from the direct impact of air-conditioning and refrigeration equipment on global warming, it also contributes indirectly through greenhouse gas emissions caused by the energy used to power the equipment. Research must concentrate on lowering the refrigeration system's energy consumption to reduce the indirect contribution to global warming in order to increase the system's eco-sustainability. This could be achieved by ensuring that the new alternative working fluids in the refrigeration systems possess energy efficiencies that are comparable to or greater than those of the conventional refrigerants they are replacing. As a result, the energy performance of the suggested alternatives to R410A must also be established in analysis to define whether the adoption of the new refrigerants in the existing R410A system will necessitate the system's redesign or modification. Therefore, this paper investigates the energy and cooling performance of four new multi-component low-GWP blends that contained carbon dioxide and hydrofluoroolefins refrigerants in their compositions as substitutes for R410A in air-conditioning systems.

2. Methods

2.1. Refrigerants Under Consideration

The reference refrigerant, R410A, is a hydrofluorocarbon (HFC) class refrigerant made of equal parts of R32 and R125. Its primary application is in residential and commercial air-conditioning systems. R410A saves energy since it absorbs and releases heat more efficiently than the ozone-depleting R22 refrigerant it was designed to replace in air-conditioning systems [29]. The fundamental disadvantage of R410A that prompted the quest for a suitable alternative is its high GWP. The four new refrigerant blends under consideration are designated by ASHRAE as R445A, R455A, R470A and R470B [30]. As shown in **Table 1**, all the alternative mixtures contained carbon dioxide (R744) and hydrofluoroolefins (R1234yf and R1234ze) for the purpose of reducing the GWPs of the blends. R32 and R134a are contained in three of the mixtures to adjust their properties toward that of conventional refrigerant (R410A) while R125 and R227ea are contained in two of the blends to mitigate flammability. The physical and ecological properties of the studied refrigerant blends are shown in **Table 2**.

The four blends belong to the zeotropic group of refrigerants, which is designated by ASHRAE with the 400 series of refrigerant numbers [31]. Zeotropic blends do not maintain the same composition of the liquid and vrapour phases during any point of the vapour-liquid equilibrium state. As a result, they display temperature glides when the condenser and evaporator go through a phase transition. The difference in temperature between saturated liquid and saturated vapour at constant pressure is known as the temperature glide. The temperature glides of R445A, R455A, R470A and R407B are 21.5, 12.8, 8 and 4.1 K, respectively [32], [33]. Two issues associated to the zeotropic mixtures' phase-changing process are composition shift and temperature glide. However, these features are employed for increasing the energy efficiency and capacity of vapour compression refrigeration systems through careful system designs and selection of operating parameters. High temperature glide mixtures can improve system performance and energy effectiveness by balancing the temperature differences of the heat transfer fluid and the refrigerant. This process, known as glide matching, lowers the irreversibility of heat transfer thereby enhancing the system's performance [34].

Table 1. The safety group and the constituents of the mixtures under consideration [30], [35]

Blends	Blend's constituents	Mass fraction (%)	Safety Group
R410A	R32/R125 (conventional refrigerant)	50.0/50.0	A1
R445A	R744/R134a/R1234ze	6.0/9.0/85.0	A2L
R455A	R744/R32/R1234yf	3.0/21.5/75.5	A2L
R470A	R744/R32/R125/R134a/R1234ze/R227ea	10.0/17.0/19.0/7.0/44.0/3.0	A1
R470B	R744/R32/R125/R134a/R1234ze/R227ea	10.0/11.5/11.5/3.0/57.0/7.0	A1

Table 2. Environmental and physical properties of the studied refrigerant mixtures [30], [32]

Properties	Refrigerants				
	R410A	R445A	R455A	R470A	R470B
Molar mass (kg/k.mol)	72.6	66.2	87.4	84.4	89.7
Vapour phase density, kg/m^3 at 25 ^{o}C	65.9	20.3	39.2	44.1	38.3
Liquid phase density, kg/m^3 at 25 ^{o}C	1058.6	915.4	1050.1	1082.9	1102.0
Critical density (kg/m^3)	459.1	367.7	440.2	472.1	475.2
Critical pressure (MPa)	4.9	5.0	4.5	4.8	4.7
Critical temperature (^{o}C)	71.3	109.4	91.9	84.3	90.1
Global Warming Potential (GWP)	1890	118	146	909	717
Ozone Depleting Potential (ODP)	0	0	0	0	0

2.2. Basic Air-Conditioning System

Most air-conditioning systems operate based on thermodynamics law and employ a vapour compression refrigeration system to move heat from a lower temperature enclosed space to the open air outside the system at a higher temperature. **Figure 1** is a schematic representation of an air-conditioning system. It is made up of four major parts: an expansion valve, an evaporator, a reciprocating compressor, and a condenser. These four basic components are linked in a closed-loop system by tubes of adequate size to circulate the refrigerant with optimal thermodynamic and ecological qualities. The principal goal of the evaporator coil is to remove heat from the interior air and transfer it to the refrigerant. It also collects water particles in the air and drains them down the drain line. The primary duty of the condenser coil is to remove heat from the refrigerant and discharge it to the outside air. As a result, heat is transferred from the interior air to the outside air, and the internal space is cooled. The air-conditioning system also includes cooling fans to distribute airflow and air filters to eliminate dust particles. The pressure–volume (p–h) diagram for the cycle is shown in **Figure 2**. As depicted in the diagram, process 1-2 is compression, 2-3 is condensation, 3-4 is expansion or throttling, and 4-1 is evaporation.

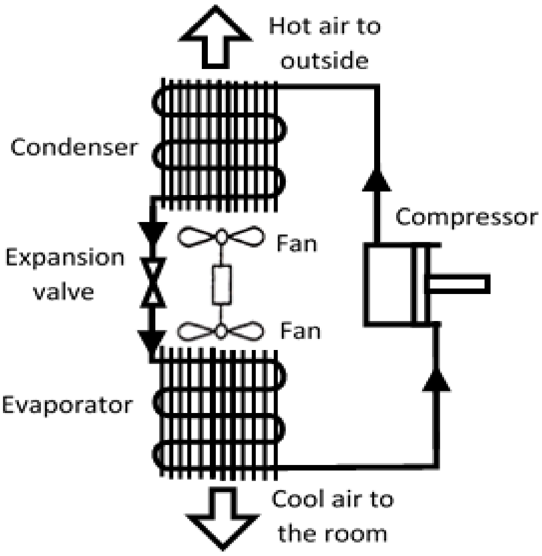

Figure 1. Schematic diagram of a basic air-conditioning system

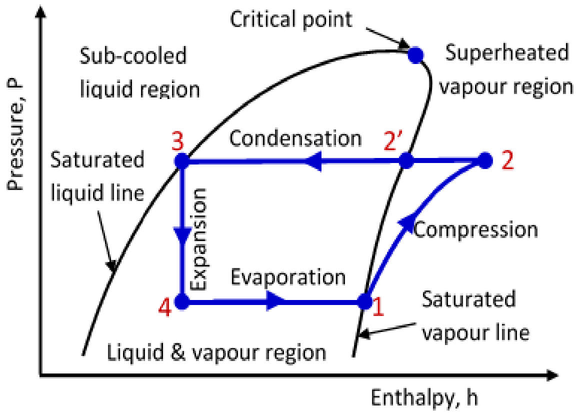

Figure 2. Basic refrigeration cycle on the pressure-enthalpy diagram

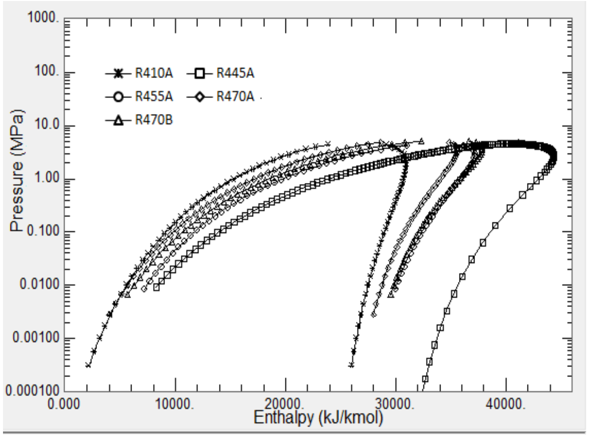

Figure 3. The pressure-enthalpy curves for the refrigerants (REFPROP)

A versatile refrigerant database software program, REFPROP (version 10.0) was used for the investigation [30]. It has the potential to compute the thermodynamic and physical properties of pure fluids and blends in a wide range of fluid states, including the supercritical, subcritical, and saturated phases of liquid and gas. The REFPROP generated saturation lines on p-h diagram for the studied refrigerants are shown in **Figure 3**. The performance characteristics of the refrigerant blends in the basic vapour compression air-conditioning system were computed using the heat transfer across the major components. The compressor energy (*CE*) per unit mass of refrigerant and refrigerating effect (*RE*) are determined using Eq. (1) and Eq. (2).

$$CE = h_2 - h_1 \qquad (1)$$

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

where h_1, h_2 and h_4 are the refrigerant's enthalpies per unit mass at the outlet of the evaporator, compressor, and expansion device, respectively. Then, the coefficient of performance (*COP*) and the compression ratio (*CR*) for the system are computed by Eq. (3) and Eq. (4).

$$COP = \frac{RE}{CE} \qquad (3)$$

$$CR = \frac{P_{out}}{P_{in}} \qquad (4)$$

where P_{out} and P_{in} are the pressures of the refrigerant at the outlet and inlet of the compressor, respectively. Then, the specific cooling energy (*SCE*) is determined by by Eq. (5). Finally, the cooling capacity of a system reflects how much heat it can remove from a confined space or room over time. It is the same as the difference in refrigerant's specific enthalpy in the evaporator produced by the cooling load multiplied by the refrigerant's mass flow rate. Hence, the cooling capacity per unit volume (*CCPV*) of refrigerant is computed by multiplying the vapour density at the compressor's inlet (ρ_1) by the refrigerating effect (*RE*), as presented by by Eq. (6).

$$SCE = \frac{3.5CE}{RE} \tag{5}$$

$$CCPV = \rho_1.(RE) \tag{6}$$

3. Results and Discussion

Figure 4 illustrates the vapour pressure profiles of R410A and its four substitute blends at varying temperatures. The closeness between refrigerants' vapour pressures within the range of operating temperatures is an important criterion for determining whether they may replace one another in a refrigeration system. As seen in **Figure 4**, vapour pressure increases with temperature for R410A and its substitute refrigerant blends (R445A, R455A, R470A and R470B). The vapour pressure trends for the four substitute blends closely resemble and match those of the standard refrigerant (R410A), this is the main reason while they were selected for the study. The ability of the refrigerant blends to replace R410A in air-conditioning systems was demonstrated by the similarities between their temperature and pressure characteristics.

Figure 5 shows the variations in compression ratio regarding the evaporation temperature for the five refrigerants under study. The figure indicates that a rise in evaporation temperature reduces the compression ratio for each of the five refrigerants. A refrigeration system's ability to function effectively is hampered by a high compression ratio because it puts additional strain on the compressor and lowers the system's performance. All the investigated alternative refrigerant blends had a desirable low compression ratio. The average compression ratio of R445A, R470B, R470A and R445A are 11.9, 13.0, 15.4 and 21.7 per cent lower, respectively than that of R410A.

Figure 6 depicts the relationship between the degree of superheat and the evaporation temperature for the refrigerants under evaluation. The difference between the compressor discharge temperature and the condensing temperature is the degree of refrigerant superheat at the compressor output. A superheat that is too high raises the heat of compression and causes the temperature at the discharge valves to increase. The compressor will become damaged if the temperature rises above its safe operating temperature. Therefore, better performance is achieved when the degree of superheat of refrigerant at compressor outlet is between 0 and 20 degrees. At high levels

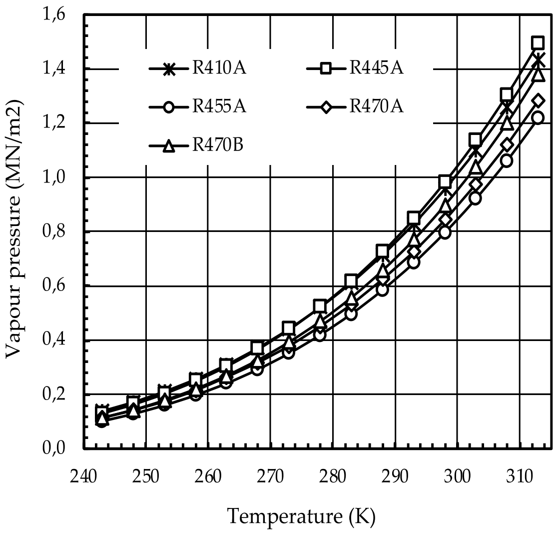

Figure 4.
Vapour pressure versus temperature

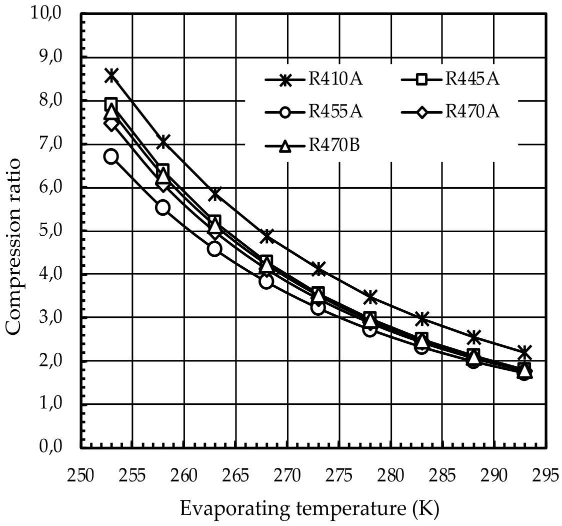

Figure 5.
The effect of evaporation temperature on the compression ratio

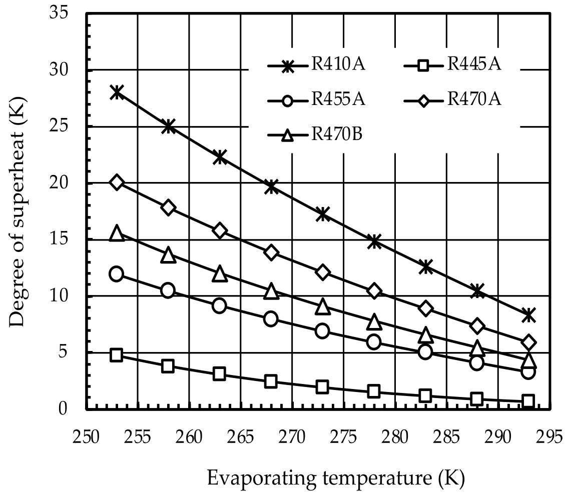

Figure 6. The changes in the degree of superheat with respect to evaporation temperature

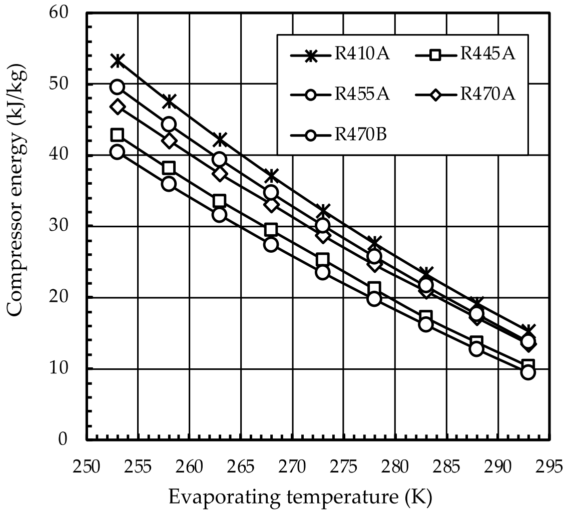

Figure 7. The curves of the compressor energy at varying evaporation temperature

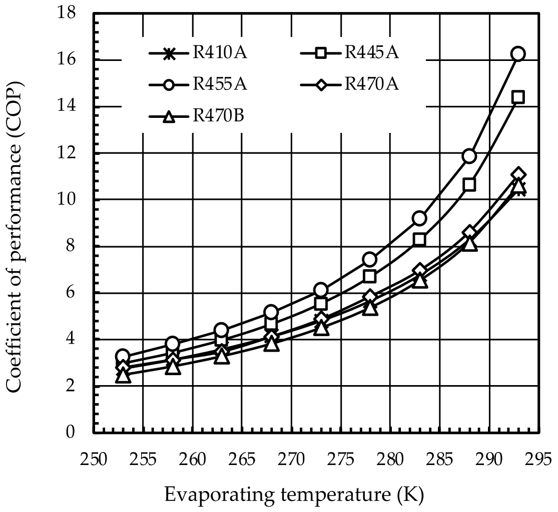

Figure 8. The COP at varying evaporation temperature

of superheat, the system's performance deteriorates considerably. As a result, refrigerants having a low degree of superheat at the compressor discharge are extremely desirable in refrigeration systems. As seen in the figure, the degree of superheat decreases as the evaporation temperature rises. Compared to R410A, all the four new refrigerant blends under evaluation demonstrated a low degree of superheat. The average superheat temperature of R470A, R470B, R455A and R445A blends are 5.1, 8.2, 10.4 and 15.4 K below that of the standard refrigerant, respectively.

Figure 7 depicts the influence of evaporation temperature on compressor energy for five evaluated refrigerant blends. The figure illustrates how compressor energy drops as evaporation temperature rises. This is because when the evaporator's temperature rises, the compressor inlet temperature rises as well, reducing the amount of energy required for compression. The four alternative refrigerants had lower compressor energy than R410A. However, R455A is the most energy efficient among the four substitute blends under consideration; its average value is 26.9 per cent lower in comparison with the reference refrigerant (R410A). The Coefficient of Performance (COP) indicates the performance of the cycle and is the primary driver for deciding on a new refrigerant as a replacement. Figure 8 depicts the relationship between COP and evaporation temperature for R410A and the four alternative blends. As demonstrated in the figure, the COP increases as the evaporating temperature rises. Three of the alternative blends had higher COPs, whereas R470B has a lower COP than the reference refrigerant. Again, this study identified R455A as the substitute blend with the highest application performance. It has an average COP of 24.6 per cent above that of the reference refrigerant (R410A).

Most of the energy required to power air-conditioning and refrigeration systems comes from the combustion of fossil fuels. Reducing the energy usage of the systems will thus provide a considerable chance to minimize the systems' greenhouse gas emissions. Figure 9 depicts the specific cooling energy for R410A and its four substitute refrigerant blends at varied evaporation temperatures. As seen in the figure, the specific cooling energy drops as the evaporation temperature rises for all the blends. This is brought on by an increase in the amount of refrigerant vapour leaving the evaporator. Blends that require lower specific cooling energy are more energy efficient and better for the environment and the air-conditioning system. Analysis of the results

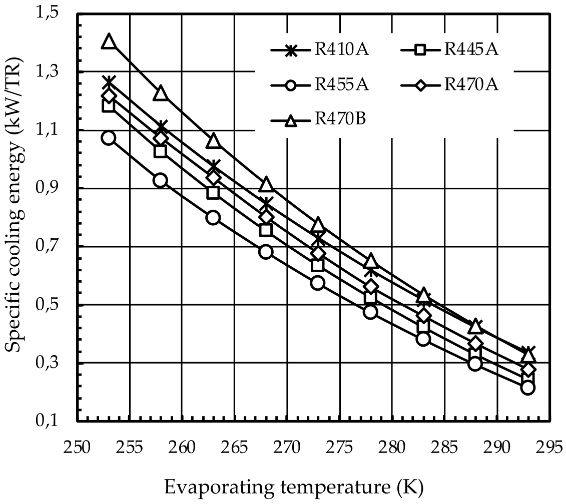

Figure 9. The specific cooling energy at different evaporation temperature

revealed that three of the substitute blends required less energy and R455A emerged as the most energy-efficient refrigerant among all the five refrigerants. In comparison to R410A refrigerant, the average energy required per unit cooling for R470A, R445A and R455A are 6.4, 12.0 and 20.6 per cent lower, respectively, whereas the average cooling energy required for R470B is 7.6 per cent higher.

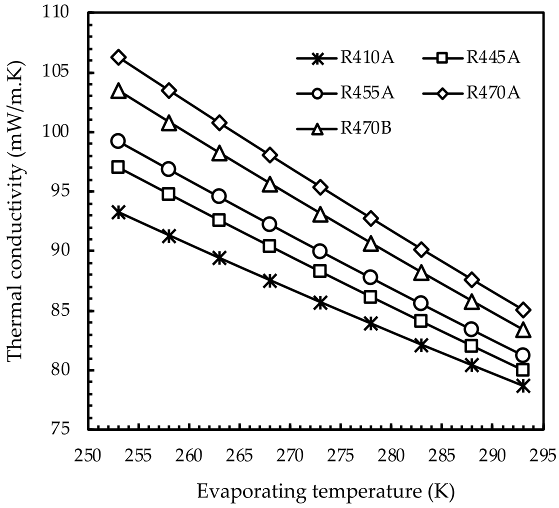

Figure 10. The thermal conductivity at different evaporation temperature

Figure 10 depicts the thermal conductivities of the evaluated refrigerant blends at various evaporation temperatures. A refrigerant's thermal conductivity is a measure of its capacity to transmit heat in the evaporator and condenser of the air-conditioning and refrigeration systems. Heat transmission takes place at a faster rate in high thermal conductivity refrigerants than in low thermal conductivity refrigerants. As a result, refrigerants with high thermal conductivity are highly desirable in the systems. The thermal conductivities of the refrigerants drop as the evaporation temperature rises. The four substitute refrigerant blends exhibited a higher rate of heat transfer for cooling or heating than the reference refrigerant (R410A). The average thermal conductivities of R445A, R455A, R470B and R470A within the most common air-conditioning working temperature range (253 to 293 K) are 3.0, 5.0, 8.7 and 11.3% higher, respectively than the value obtained for the reference refrigerant.

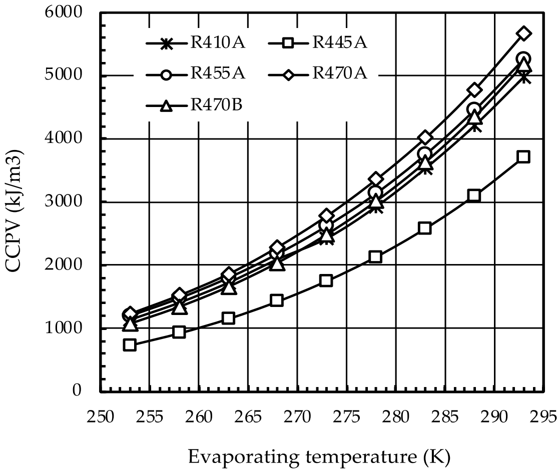

Figure 11. The cooling capacity per unit volume (CCPV) at different evaporation temperature

A refrigerant's cooling capacity indicates how much heat it can remove from a refrigerated space over time. Figure 11 presents the cooling capacity per unit volume (CCPV) curves for the refrigerants under investigation at various evaporation temperatures. As demonstrated in the figure, the CCPVs of all the five refrigerants rise as the evaporating temperature rises. A rise in the temperature of the refrigerant in the evaporator increases the volume of the vapour refrigerant at its departure, which improves the cooling capacity. R470A has the highest CCPV, and in comparison, to R410A, the average CCPVs for R470B, R455A, and R470A across a temperature range of 253 to 293 K are higher by 1.3, 6.0, and 12.6%, respectively, whereas the value for R445A is 28.3% lower. In addition to this investigation, a thorough literature search was conducted for all potential direct and indirect R-410A replacement candidates with relation to zero ODP and low GWP in running air conditioning systems [36]. Researchers concur that developing substitutes for R-410A in small capacity chillers, split air conditioners, and portable AC units is crucial for combating climate change [37]–[40].

4. Conclusion

R410A is a refrigerant primarily developed as a substitute for ozone-depleting refrigerants in residential and commercial air-conditioning systems. Although R410A is completely harmless to the ozone layer, it has a harmful influence on the climate due to its high GWP of 1890. Also, refrigeration systems are electrical appliances that use a huge amount of energy and hence contribute indirectly to global warming. This study investigated the energy and cooling performance of four new multi-components low-GWP blends that contained carbon dioxide and hydrofluoroolefins refrigerants in their compositions as eco-friendly substitutes for R410A in air-conditioning systems. The followings are the conclusions drawn from the study:

a. The similarities of temperature and pressure characteristics of the refrigerant blends with those of R410A show their ability to replace R410A in air-conditioning systems.
b. The four new substitute blends (R445A, R455A, R470B and R470A) exhibited desirable low compression ratio and high heat transfer for cooling or heating application with the average thermal conductivities of 3.0, 5.0, 8.7 and 11.3% higher, respectively, than that of the reference refrigerant (R410A).
c. The average superheat temperature of R470A, R470B, R455A and R445A blends are 5.1, 8.2, 10.4 and 15.4 K below that of the R410A, respectively.
d. Compared to R410A, all the four evaluated substitute blends exhibited lower compressor energy input with the lowest value obtained from using R455A as a refrigerant.
e. Three of the substitute blends exhibited a high coefficient of performance (COP) and once again R455A emerged as the blend with outstanding COP having an average value of 24.6% higher than that of the R410A.
f. With reference to R410A, the specific cooling energy required for R470A, R445A and R455A are 6.4, 12.0 and 20.6 per cent lower, respectively, whereas the average energy required for R470B is 7.6 per cent higher.
g. The cooling capacity per unit volume for R470B, R455A and R470A across a temperature range of 253 to 293 K are 1.3, 6.0, and 12.6%, respectively, above that of the reference refrigerant (R410A).

In general, the four new substitute blends performed better than R410A. The overall assessment revealed the R455A blend as the best replacement for R410A in air-conditioning systems due to its superior performance in terms of low compression ratio, compressor energy and specific cooling energy. It also has the highest COP and relatively high cooling capacity per unit volume.

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Authors' Declaration

Authors' contributions and responsibilities - First Author: Bukola Olalekan Bolaji, is the Corresponding Author, and the originator of the research ideas, he formulated the research goals and aims. He contributed substantially in all aspect of the research. Second Author: Deborah Olufunke Bolaji, she developed the research methodology and also contributed in the data analysis using the computer software (REFPROP). Third Author: Semiu Taiwo Amosun, he is the research collaborator from other institution. He made a critical revision of the article for important intellectual content.

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