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Responding to the Risk of Global Warming from an Air-Conditioning System by Using Refrigerant Blend

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Abstract

The use of air conditioning and refrigeration systems improved the standard of living. However, the system contributes to global warming by releasing potential global warming refrigerants directly and powering the system. There is an obligation, like UN Kyoto Protocol, EU MAC Directive and Japan METI Directive to find an alternative low-GWP refrigerant with excellent thermo-physical properties. In this paper, the global warming effect of an air-conditioning system is analyzed theoretically using few low-GWP refrigerant mixtures. New refrigerant mixtures are formed based on low GWP, high volumetric capacity, and refrigerating effect. After analyzing, refrigerant blends of R1234yf/R32 (40/60, 50/50, and 60/40 by wt%) and R1234ze/R32 (40/60, 50/50, and 60/40 by wt%) are found promising to replace the widely used R410A. The best performance of the refrigerant blend is found for R1234yf/R32 (40/60). These analyses are crucial for selecting suitable refrigerants for domestic air conditioning systems.

Keywords

Air-Conditioner, Coefficient of Performance, Mass Flow Rate, Volumetric Capacity, Warming Impact

1. Introduction

The air-conditioning (AC) systems ensure a comfortable environment inside the building concerning temperature and humidity. The AC system is designed based on the principles of thermodynamics, fluid mechanics, and heat transfer. It uses electrical energy and refrigerants to provide efficient heating and cooling to the room. Most of the refrigerants used in the system have high global warming potential (GWP). As a result, air conditioners collectively contribute to the greenhouse effect as well as global warming. The hot air released into the atmosphere causes more heat in the atmosphere. The total equivalent warming effect (TEWI) from an AC considers two types of warming effects (Tyagi et al., 2019; Uddin et al., 2019; Uddin et al., 2021). Firstly, direct global warming, which is due to the emission of refrigerants and other pollutants from the AC into the atmosphere. And secondly, indirect global warming, which results from the emission of equivalent carbon dioxide due to the combustion of fossil fuels (oil, natural gas, and coal) in the power plant to provide electricity in the AC system.

To address the threat of global warming due to anthropogenic greenhouse gas emissions, Kyoto Protocol (COP3) was signed in 1997, and successively; many signatory countries set their target to reduce greenhouse gas (United Nations 1998). The COP21 (UNFCC, 2015), on the other hand, emphasized holding the global temperature rise well below 2˚C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5˚C. The United Kingdom's most recent National Development Plan (NDP) pledges the country to lower emissions by at least 68 percent by 2030 compared to 1990 levels. The fundamental issue confronting COP26 is that the total NDCs of all countries are insufficient to fulfill the Paris Agreement's 1.5˚C targets. If all of the present intentions and commitments contained in the NDCs were combined, the global temperature would rise by 2.4˚C by 2100, and if actual emissions were taken into account, the global temperature would rise by 2.9˚C by 2100 (Pierrehumbert, 2014).

The legally binding Montreal Protocol amendment will require industrialized countries to reduce HFCs production and consumption by at least 85% compared to their yearly average values from 2011 to 2013 (Sciance, 2013). By the year 2045, a group of emerging countries, including China, Brazil, and South Africa, must reduce their HFCs use by 85% of what it was in 2020-22. By the year 2047, India and a few other developing countries—Iran, Iraq, Pakistan, and some oil economies like Saudi Arabia and Kuwait will have reduced their HFCs by 85% of their current levels in 2024-26 (Anon, 2019). **Figure 1** shows the HFC reduction goal by different countries.

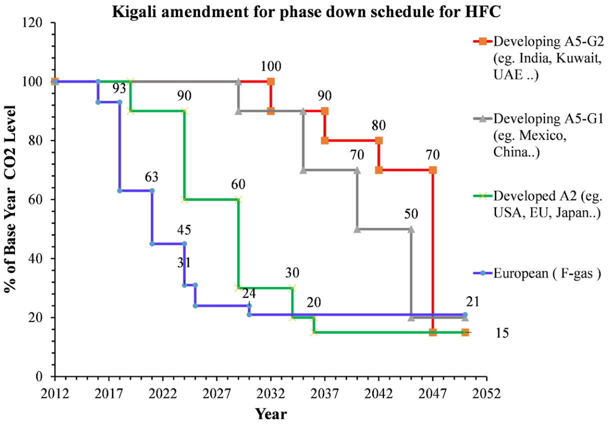

Figure 1. Phase-down schedule for HFCs by country group (Anon, 2019).

The refrigerant used in the air-conditioning system is mostly chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), etc. All refrigerants are harmful to the environment because of their high global warming potential (GWP) (i.e., R410A, R22) (Abas et al., 2018; Guilherme et al., 2022). To follow the international protocol, there is an urgent need to limit the use of CFCs, HCFCs, and HFCs refrigerants. Therefore, finding low GWP refrigerants with excellent energy efficiency has become an urgent task for the present generation. The fourth-generation refrigerants should have zero ODP and ultra-low GWP and should have a shorter lifetime in the atmosphere. Though technology has experienced a lot of advancement in the last few decades, a challenge is persisting in reducing the overall environmental impact of the system.

In the present study, the total equivalent warming impact from an air conditioning system will be assessed considering the AC systems used in the residential sectors (Li, 2015a, 2015b, 2017). New types of environmentally friendly refrigerant blends will be searched to fulfill the requirements of the international protocol by analyzing the thermodynamic efficiency of some low GWP refrigerants. Therefore, proposing new blends may provide a solution for low-GWP, zero ODP, and A2L safety class (ASHRAE) refrigerants.

As a consequence, the various blend combinations presented in this work may be a good option for a sustainable air conditioning system as their performances are very similar to R410A (Guilherme et al., 2022; Kim et al., 2024; Zaki & Abdelaziz, 2024). Furthermore, their GWP is less than one-sixth of R410A. Considering the comparison of coefficients of performance (COP), pressure ratios, volumetric capacity of the tested refrigerants, and also the main environmental impacts on ozone layer depletion and global warming, the refrigerant blends of HFO-1234yf/HfFC and HFO-1234ze/HFC-32 are found to be suitable for the replacement of R410A.

2. Refrigerants selection criteria

To develop sustainable solutions, it is critical to find a low GWP refrigerant. The current low GWP single component refrigerant may increase energy consumption, pose a safety risk, and necessitate considerable system modifications in some cases (Emani et al., 2017). When compared to the current best refrigerants, a refrigerant blend can be an effective alternative for achieving sustainable building technology by reducing energy consumption and greenhouse gas emissions by 50% (Uddin et al., 2019).

Pure R32 has been available for last few years, it is not preferred used in AC systems since AC makers prefer R410A for their higher volumetric capacity (Uddin et al., 2021). R32 has the drawbacks of being categorized as a flammable fluid and having greater compressor discharge temperature than R410A. However, because of its reduced GWP value and good system performance, R32 is currently being examined (Mota-Babiloni et al., 2017). New R32 blends (combined with hydro-fluoro-olefins, or HFOs) are also being developed to provide even more GWP reductions and a trade-off between various properties.

The global warming effect from an air-conditioning system is theoretically analyzed using a cycle performance study of a new low-GWP refrigerant mixture. Few new refrigerant mixtures are formed with the desired characteristics. Conversely, the properties of a blend sometimes differ from their original constituents. The selection of mixture components, temperature glide, volumetric capacity, GWP, and cycle performance are the most important criteria for choosing binary blends. We have to select refrigerants that compromising environmental issues as well as other characteristics of refrigerants.

This study selected refrigerant blends that exhibit zero ODP and GWP of less than 400. To keep the volumetric capacity comparable to R410A, it is very difficult to reduce GWP level further. The flammability is considered A2L or less by ASHRAE (American Society of Heating, Refrigeration and Air Conditioning).

Highly desirable characteristics of refrigerants include:

- Environmental acceptability;
- Chemical stability;
- Materials compatibility;
- Refrigeration-cycle performance;
- Adherence to nonflammable and nontoxic guidelines;
- Boiling point.

2.1. Selection of Blend Components

R32 which has a high volumetric capacity, and medium GWP 675. On the other hand, Olefins (R1234yf & R1234ze) have negligible GWP but low cooling effect and volumetric capacity. Both R32 and HFO have low flammability and toxicity. So, it is convenient to mix them in different ratios to make binary blends.

The thermophysical properties of refrigerant mixtures in mechanical vapor compression systems have been considered in order to provide successful condensation and evaporation processes. Due to the high value of the heat transfer coefficient, the condenser and evaporator will operate effectively when the thermal conductivity of both the liquid and vapor phases of the refrigerant mixture is high (Lee et al., 2016; Mahmood et al., 2020). As a result, energy consumption will be reduced. The refrigerant charging amount is also influenced by some physical property.

Table 1 lists the properties of R410A, R32, R1234yf, and R1234ze refrigerants.

The thermodynamic analysis aids in predicting the performance of these refrigerants in systems as well as their environmental impact (Abas et al., 2018). This study employed ten different refrigerants i.e., R410a, R32, R1234yf, R1234ze, and their mixtures with R32 considering 40%, 50%, and 60% of R1234yf and R1234ze.

Table 1. Main characteristics of some individual refrigerants.

Refrigerant name	R32	R1234yf	R1234ze	R410A
Molar mass (kg/kmol)	52.02	114.04	114.04	72.59
Normal boiling point (˚C)	−51.7	−29.5	−19.0	−51.5
Critical temperature (˚C)	78.2	94.7	109.37	71.34
Critical pressure (MPa)	5.78	3.38	3.64	4.9
GWP (UNEP, 2016)	677	<1	<1	1900
Atmospheric lifetime	4.9 yrs.	11 d	18 d	17 yrs.
Flammability range (vol%)	13.3 - 29.3	6.2 - 12.3	7.0 - 9.5	None
Burning velocity (cm/s)	6.7	1.5	–	–
Safety class (ASHRAE)	A2L	A2L	A2L	A1

2.2. Global Warming Potential

GWP_{100} indicates the heat traps in a refrigerant in the environment compared to the heat trap by the same mass of CO_2 over the 100-year horizon. Figure 2 depicts that the refrigerant mixtures show low GWP compared with widely used R410A.

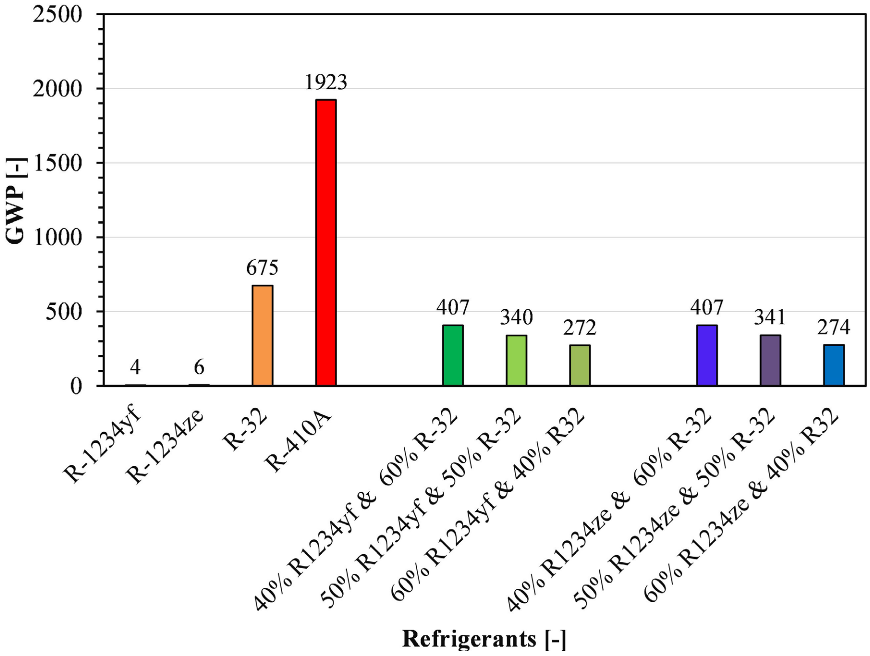

Figure 2. GWP of the selected refrigerants.

2.3. Cycle Performance

The coefficient of performance (COP) is calculated theoretically using the thermophysical properties found in REFPROP database (V 9.1). In this work, average temperatures for evaporation and condensation are considered 7˚C and 35˚C, respectively. The adiabatic compression efficiency is considered 0.85. Figure 3 shows the pressure-enthalpy diagram of different refrigerants with their thermodynamic cycle.

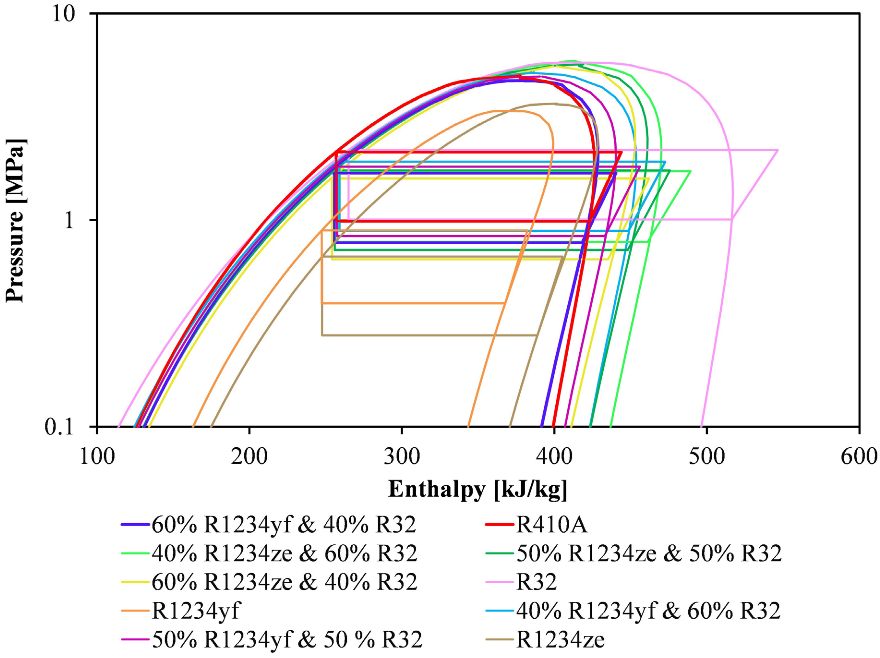

Figure 3. Thermodynamic cycle of Refrigerants.

The mathematical computations involved in the thermodynamic analysis are given. Isentropic compressor work is computed as

$$w_c = h_2 - h_1 \tag{1}$$

Refrigerating effect (Cooling effect) is calculated as

$$RE = h_1 - h_4 \tag{2}$$

Coefficient of performance (COP) is calculated as

$$COP = \frac{RE}{w_c} \tag{3}$$

Energy (Power) consumption by the compressor per ton of refrigeration is computed by

$$PPTR = \frac{3.5}{COP} \tag{4}$$

Refrigerant mass flow rate is computed by

$$\dot{m} = \frac{\dot{Q}}{RE} \tag{5}$$

The pressure ratio (PR), also referred to as the compression ratio or system pressure ratio is a dimensionless parameter. It is obtained as the ratio of the absolute condensing pressure (P_{cond}, MNm^{-2}) to the absolute evaporating pressure (P_{evap}, MNm^{-2}) :

$$P_R = \frac{P_{cond}}{P_{evap}} \tag{6}$$

The compressor discharge temperature (T_d) is computed using superheated property tables and interpolating for the degree of superheat corresponding to the entropy difference.

2.4. Volumetric Capacity

The Volumetric cooling capacity (VC, kJm^{-3}) is the refrigerating effect per unit volume of the refrigerant at the outlet of the evaporator. It is a value calculated from the vapor density (ρ, kgm^{-3}) at the compressor's inlet and the refrigerating effect (Q_{evap}, $kJkg^{-1}$)

Volumetric cooling capacity (Uddin et al., 2021) is calculated as

$$VC = \rho \times RE \tag{7}$$

3. Results and Discussion

3.1. Refrigeration Effect

Figure 4 shows the cooling effect of various refrigerants considering 35°C condensing temperature. A higher mass fraction of R32 in R32/HFOs blend shows good result but, in that case, GWP value increases. Therefore, the calculation of total equivalent warming impact helps to determine the proper mass fraction.

Compared with R410A from Figure 4, it is found that the cooling effect of mixtures R1234ze with R32 is higher than other blends and HFOs.

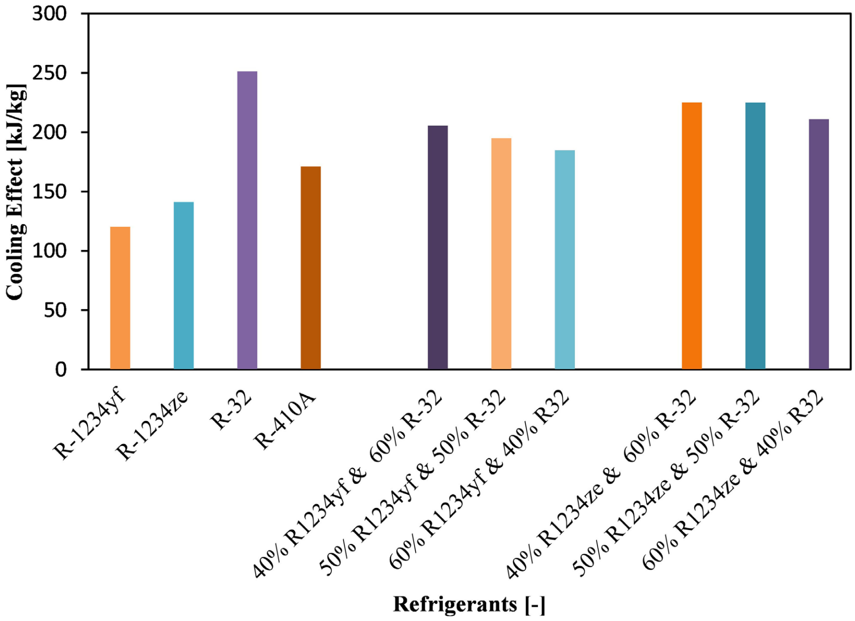

Figure 4. Cooling effect of various refrigerants at condenser temperature 35˚C.

3.2. Compressor Work

Figure 5 shows the compressor work for the mixtures. It is found that the compressor work is reasonable for R1234yf/R32 blends. The amount of R32 in the mixture helps to reduce the work done. 50% R32 with R1234yf shows less work done among the blends.

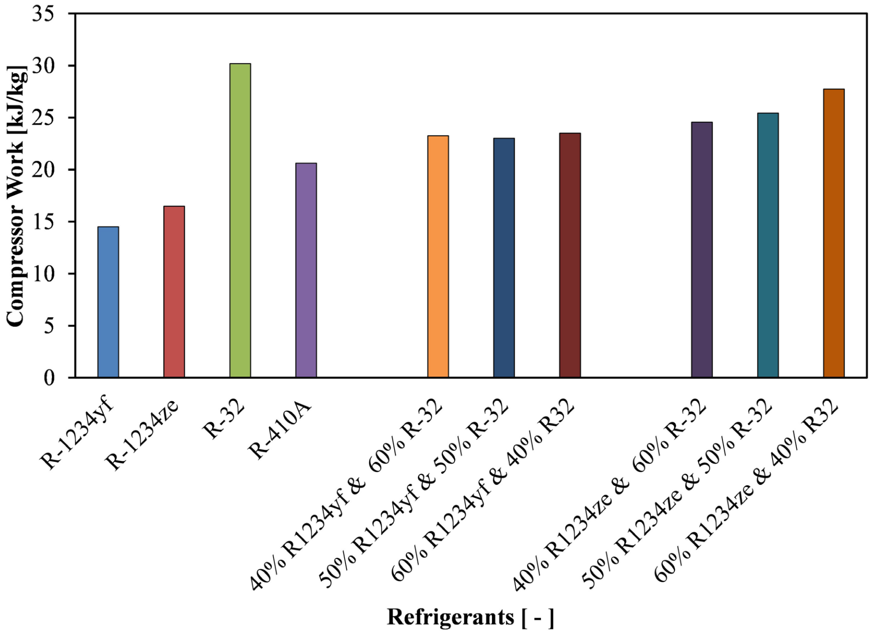

Figure 5. Compressor work of various refrigerants at condenser temperature 35˚C.

3.3. Coefficient of Performance

The high amount of COP is a crucial factor in selecting a refrigerant for a conventional air-conditioning system. It can be defined as the ratio of enthalpy difference in the evaporator and compressor sides (Yang et al., 2021). Here, the COP of mixtures 40% R1234ze with 60% R32 is 9.16, on the contrary, 60% R1234ze with 40% R32 is 7.60, the lowest among the studied refrigerants. Besides, 50% of R1234yf and R1234ze have more COP than R410A. In **Figure 6**, it may be perceived that by adding more R32 to the mixture, the value of COP is increased.

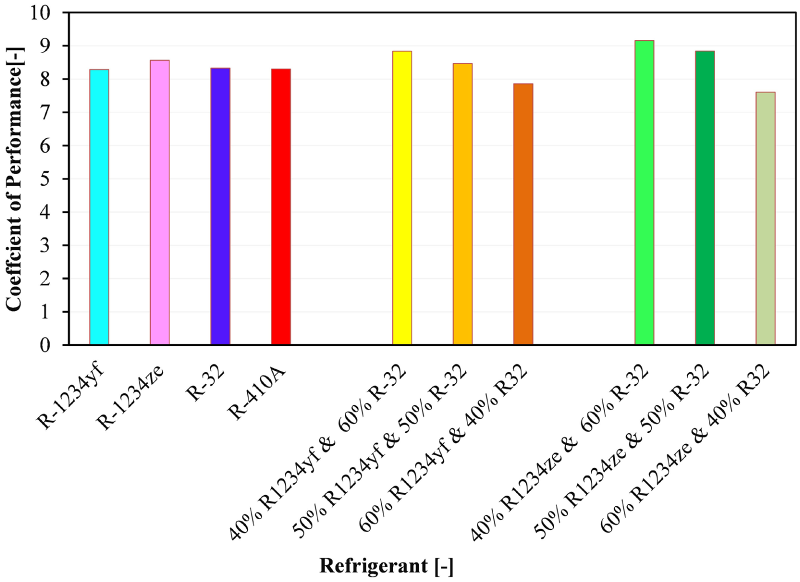

Figure 6. Coefficient of performance of various refrigerants at condenser temperature 35˚C.

3.4. COP Changes with Evaporation Temperature

The change of COP with change of evaporation temperature is shown in Figure 7. It is observed that with the increase in evaporation temperature, the COP increases. The foremost performance parameter of the conventional vapor compression system is COP which represents the overall cycle performance (Bolaji, 2020). 40/60 ze/R32 mixture shows the highest COP among all the studied refrigerants.

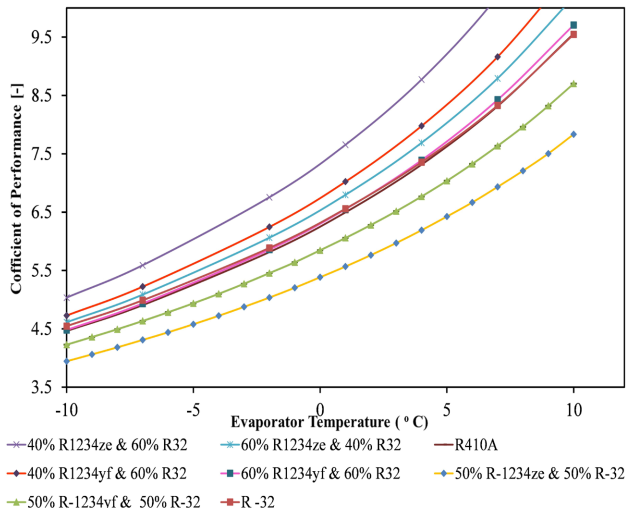

Figure 7. Coefficient of performance of different refrigerants at various evaporation temperatures.

3.5. Volumetric Cooling Capacity

Volumetric refrigeration capacity is influenced by the fluid's refrigeration properties and the density of the refrigerant vapors. Figure 8 shows that the volumetric capacity of R1234yf and R1234ze is lower, which requires a broad-size compressor for the refrigerants. Since R32 has a higher volumetric capacity, the compressor needs to be redesigned or shortened to handle it. 60% of R32 in the mixture is good for the drop-in replacement.

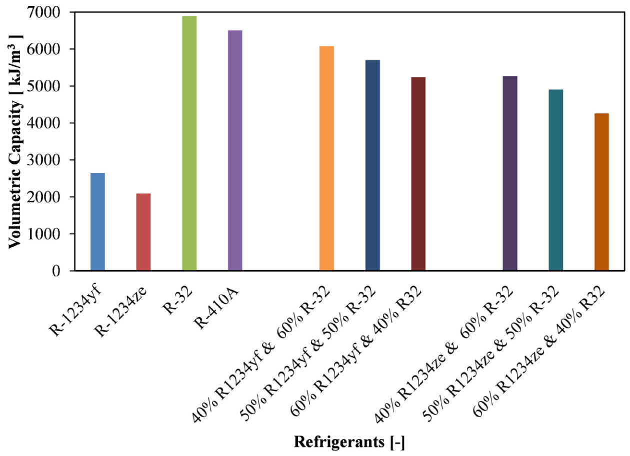

Figure 8. Volumetric cooling capacity of various refrigerants at evaporation temperature 7˚C.

3.6. The effect of Volumetric Capacity on COP

The volumetric capacity of the refrigerant improves COP significantly for each refrigerant. Actually, the rise in the evaporator temperature of the blends induces the enhancement of volumetric capacity. COP of refrigerants exhibits an upward trend when the volumetric capacity is increased as shown in **Figure 9**. The 40/60 ze/R32 shows the highest COP among the blends even in the same volumetric capacity.

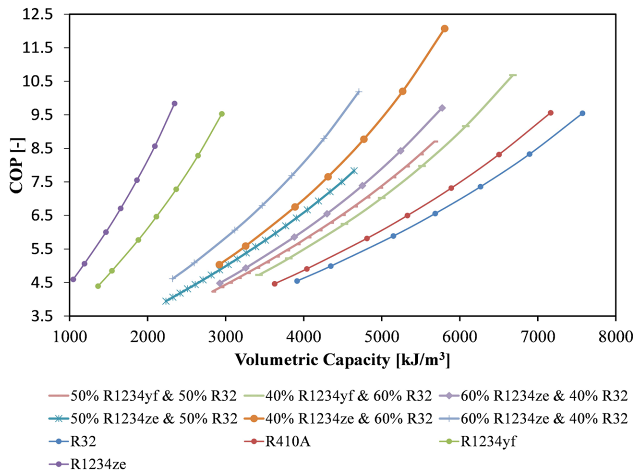

Figure 9. COP at different volumetric capacities.

3.7. Mass Flow Rate

In a refrigeration system, the mass flow rate plays a significant role in measuring how fast the fluid flows in the evaporator. By changing the compressor operation, this value can be modified (Emani et al., 2017). A high mass flow rate of refrigerants ensures producing high cooling capacity. **Figure 10** shows the mixture of R1234yf/ R32 (60/40 by %wt) require the largest mass flow rate 1.082 kgs^{-1} and R1234ze/ R32 (40/60 by %wt) require the smallest mass flow rate, which is 0.8887 kgs^{-1}.

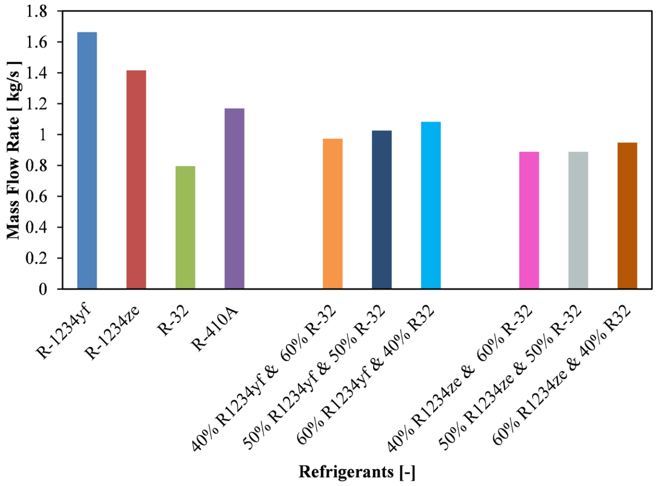

Figure 10. Variation of the mass flow rate of different refrigerants.

3.8. Mass Flow Rate Versus Evaporator Temperature

Figure 11 shows that the mass flow rate decreases with the increase in evaporation temperature. This is happening due to the increase of evaporation enthalpy at higher temperatures. The mixtures show better result than the widely used R410A.

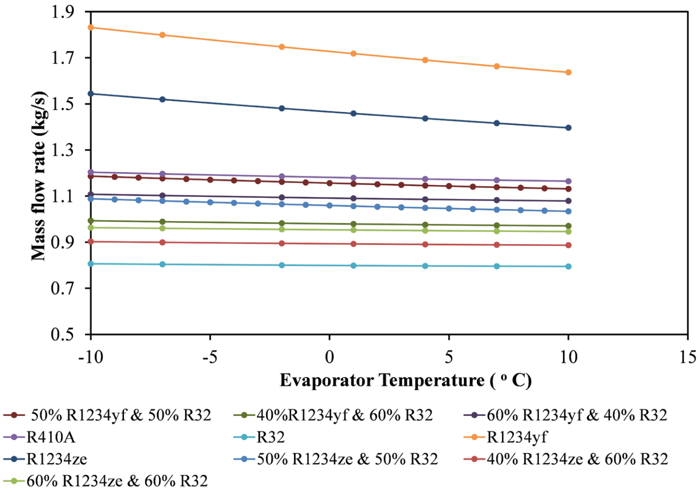

Figure 11. Variation of the mass flow rate of the refrigerant with evaporator temperature.

3.9. Pressure Ratio between Condenser and Evaporator

A lower pressure ratio is desirable because the volumetric and isentropic efficiencies are expected to increase at pressure ratio. Figure 12 illustrates the relative pressure of R32/R1234ze and R32/R1234yf blends are more advantageous than R32/1234yf (40/60). Hence, the higher-pressure ratio means the reduction of compressor efficiency (Uddin et al., 2019). Figure 12 delineates the operational pressure for R-32/R1234ze blend is slightly higher than that of R410A. Higher pressure ratio requires more compressor work to lift the evaporation pressure to the condensation pressure (Pal et al., 2018).

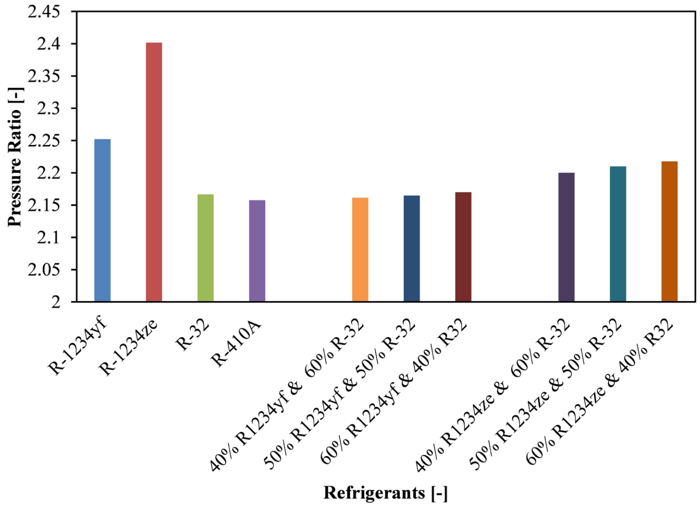

Figure 12. Pressure ratio between condensing and evaporating condition.

3.10. Compressor Discharge Temperature

It is crucial to investigate the stability and lifespan of the compressor before adding the new refrigerant to the system. Figure 13 shows the compressor discharge temperatures of all the investigated refrigerants. It is noticeable that compressor discharge temperatures of blends are higher. 40% R1234yf with 60% R32 shows lower discharge temperature among the blends.

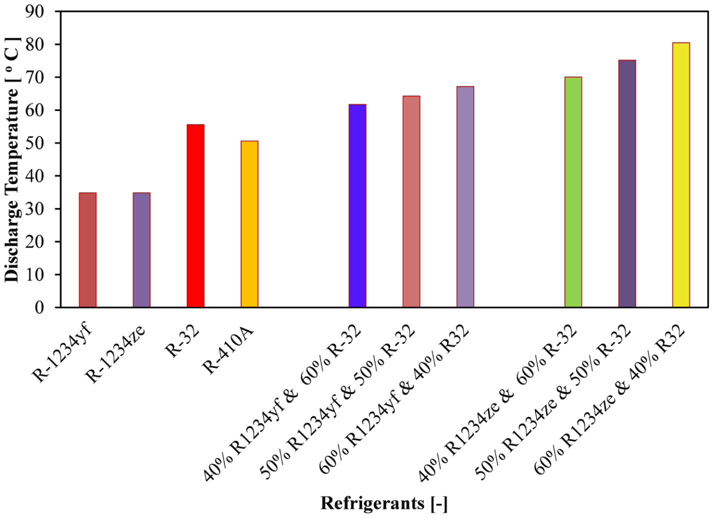

Figure 13. Discharge temperature of various refrigerants at condenser pressure.

3.11. Power Perton of Refrigeration

The power per ton of refrigeration for the refrigerants demonstrates how much electrical work is put into producing one ton of refrigeration by the compressor. In Figure 14, it can be shown that, among the ten examined refrigerants, mixture of 40/60 R1234ze/R32 uses the least amount of compressor energy per ton of refrigeration.

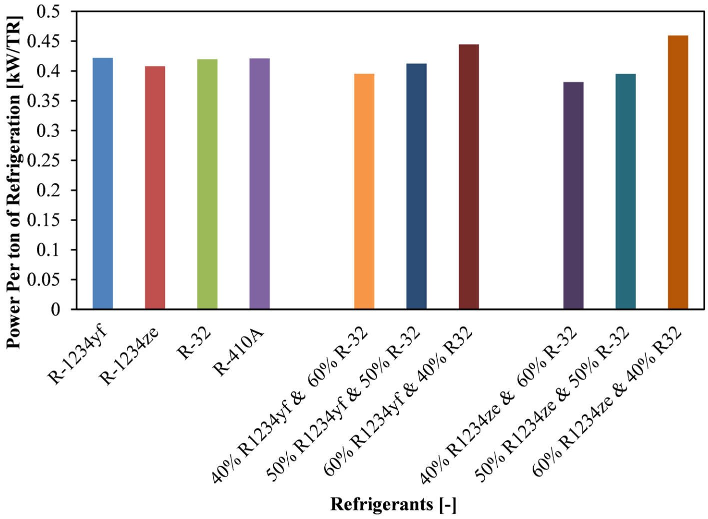

Figure 14. Power Per ton of refrigeration of various refrigerants at 35˚C.

3.12. Total Equivalent Warming Impact

The environmental impacts of the air-conditioning and refrigeration system for its lifetime can be calculated by TEWI (Total Equivalent Warming Impact). TEWI is the result of direct and indirect emissions (Uddin et al., 2019). The required time when the compressor runs on, as well as the coefficient of performance (COP) of refrigerant are the key parameters. The temperature at which cooling is required, for instance, application service, or process temperature of the space, along with the ambient temperature at which heat will be rejected is necessary to measure the TEWI. Each of the above variables can vary hour by hour and on a seasonal basis. It is therefore almost always necessary to use an Annual Load Model to calculate compressor energy consumption.

The electricity used to power cooling systems (Deutsch & Harris, 2013) is primarily derived from fossil fuel-based power plants (such as coal and natural gas), which primarily emit global warming gases like CO_2 (Craig, 2016). The GWP resulting from on-site electricity consumption is classified as an indirect emission (Pierrehumbert, 2014).

The indirect emissions are influenced by the coefficients of performance. In the case of supermarkets, refrigerant leakage is a more serious source of emissions (Islam et al., 2017). Its impact is correctly classified as a direct source of global warming gases (Yang et al., 2021). Leakage rates are currently around 10% - 15% of on-site stock per year (Uddin et al., 2021). This study calculated the TEWI value using the following equations (Uddin et al., 2021):

$$TEWI = Direct\ Emission + INndirect\ Emission \tag{8}$$

$$DE = GWP \times M \times \left[1 - \left(1 - \frac{a}{100}\right)^{y}\right] + GWP \times M \times \left(1 - \frac{a}{100}\right)^{y} \times \left(1 - \frac{b}{100}\right)^{y} \tag{9}$$

$$IDE = c \times Y \times CC \times \frac{t_c}{COP_c} \tag{10}$$

The system's lifetime has been chosen as 10 years. The system is used in cooling mode for 3285 hours per year. The refrigerant charge amount is considered 0.75 kg for all refrigerants. The leakage rate is 2 percent per year and the recovery rate is 30 percent. CO_2 emissions to produce per kWh of electricity is 0.599 kg per kWh.

Rated cooling capacity was used at 2 KW for all refrigerants. The energy consumed by the refrigeration compressor(s) depends on various parameters (Uddin et al., 2021; Uddin & Saha, 2022).

Figure 15 shows the direct emission for R410A is higher than all the studied refrigerants. Among the mixtures, R1234yf and R32 (40/60) show the highest amount of direct emission. TEWI is also the highest for refrigerant R410A. And among the blends R1234yf and R32 (40/60) show the lowest TEWI which is shown in **Figure 16**.

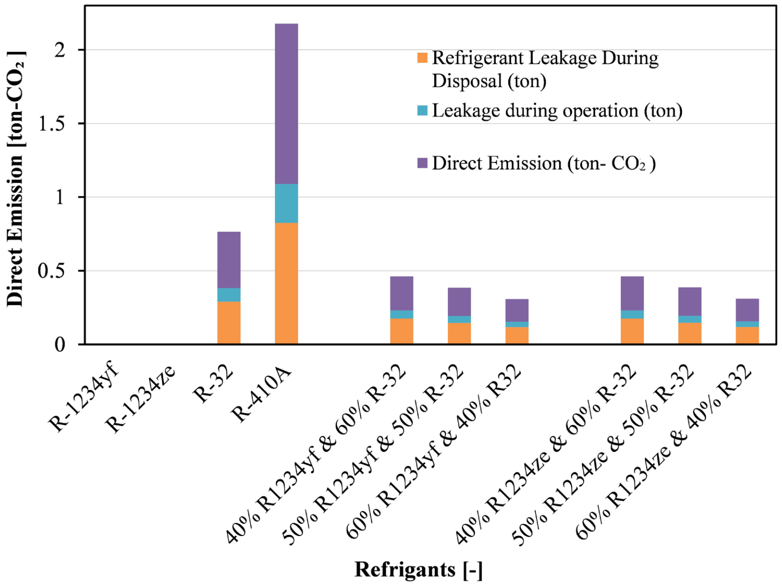

Figure 15. Direct CO_2 equivalent emissions for pure and mixture refrigerants.

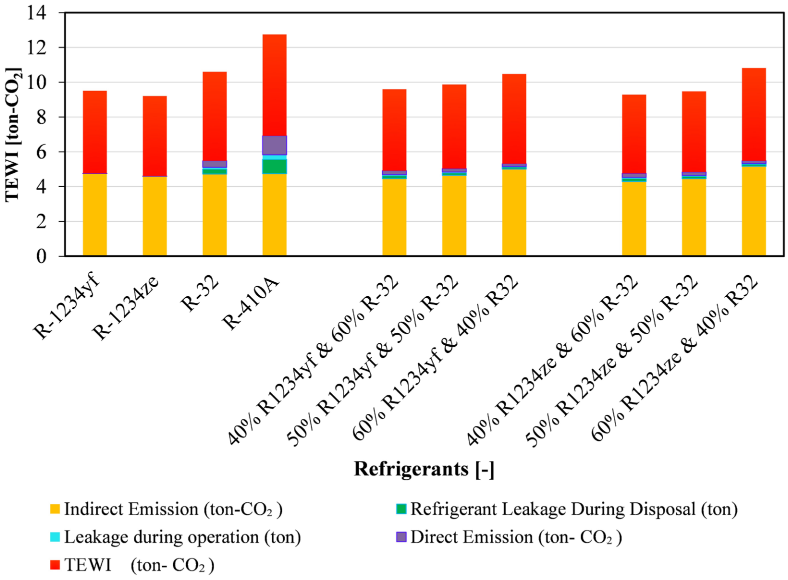

Figure 16. TEWI for refrigerants in comparison with R410A.

4. Conclusion

This study attempted to propose environmentally sustainable refrigerants for the next generation air conditioning system compared to the widely used refrigerant R410A. It is found that low GWP refrigerants with higher volumetric capacity are the key parameters to influence performance of the system.

The findings of this study can be summarized as follows:

- Pure HFOs are not suitable as an alternative to R410A, but the addition of R32 to HFOs is one of the promising methods to find a low GWP refrigerant as an alternative to R410A.
- R32 presents good performance compared to R410A in the cooling mode, but

its flammability and discharge temperature is the main concern. The mixture of R32 with other HFOs always shows promising performance.

- The highest PPTR (0.460 kW/TR) and mass flow rate (1.082 kg/s) are found for blend R1234yf/R32 (40/60).
- All the blends studied in this work show lower TEWI compared with pure R32 and R410A.
- The maximum volumetric capacity of refrigerants and the lowest pressure ratio between evaporator and condenser chamber are profitable to select a gas for the air conditioning system. Both crucial properties have been found suitable for the blend of R1234yf/R32 (40/60). In addition to that considering major thermophysical characteristics, 40% R1234yf displays an excellent performance. It also shows that the studied blends have less TEWI (4.683ton-CO_2) with respect to R410A and R32.

Considering the analytical results, the performance for R1234yf/R32 (40/60) as well as R1234ze/R32 (40/60) are found to be promising binary mixtures. The abovementioned properties are essential to analyze the blends for the development of a next-generation air conditioning system.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Nomenclature

C	Temperature [˚C]
COP	Coefficient of performance [-]
Comp	Compression
GWP	Global warming potential
H	Enthalpy [kJ kg^{-1}]
P	Pressure [kPa]
T	Temperature [K]
VC	Volumetric capacity [kJ m^{-3}]
P	Density [kg m^{-3}]
Yr	Year
d	Day
TEWI	Total equivalent warming impact [ton CO_2]
DE	Direct emission [ton CO_2]
IDE	Indirect emission [ton CO_2]
a	Annual refrigerant leak rate [%/year]
b	Refrigerant recovery rate (based on residual refrigerant at disposal) [%]
c	Carbon dioxide emission coefficient [kg-CO_2/kWh]
CC	Rated cooling capacity [kW]
LE	Refrigerant leakage during disposal [kg-CO_2]
LL	Lifetime refrigerant leakage [kg-CO_2]
M	Refrigerant charge amount [kg]
t_c	System use in cooling mode [h/year]
Y	System lifetime [year]
subscript	
evap	Evaporator
c	Cooling
cond	Condenser
h	Heating
liq	Liquid
vap	Vapor