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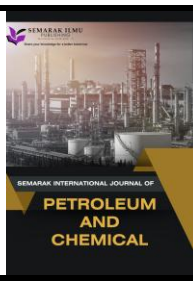

Investigation of New Refrigerant Blends as R410A Alternatives for Air-Cooled Split Air Conditioner

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ABSTRACT

The Kigali Amendment is an international agreement addressing the environmental impact of high-GWP (Global Warming Potential) refrigerants and reducing their contribution to climate change. High-GWP refrigerants are potent greenhouse gases that tightly trap heat in the Earth's atmosphere, resulting in an enhanced greenhouse effect and global warming. The amendment contributes significantly to advancing sustainable practices in the refrigeration and air conditioning industries by limiting the use of these potent greenhouse gases and encouraging the adoption of more environmentally friendly alternatives. As a result, the replacement refrigerants in this study must have lower GWP values than R410A, which aligns with the Kigali Amendment's goals. This study aimed to identify potential refrigerants to replace R410A in air-cooled split air conditioners while adhering to the Kigali Amendment's GWP requirements. By combining environmental indexes and thermodynamic properties, the study can evaluate and compare various refrigerant blends to identify those that are environmentally friendly, energy-efficient, and meet the Kigali Amendment's GWP requirement. The evaluation identifies promising R410A replacements, such as R446A for high-temperature applications and R32 for higher-temperature air conditioning. R447B, R452B, and R454B exhibit improved system performance and efficiency due to the slightest temperature glide during phase transition. R454B has the highest Coefficient of Performance (COP) and volumetric refrigeration capacity, indicating greater energy efficiency and a lower environmental footprint. These findings help select appropriate refrigerant alternatives, address environmental concerns, and adhere to Kigali Amendment regulations. This research promotes environmentally friendly refrigeration solutions and sustainable practices in the air conditioning industry.

1. Introduction

Over the last few decades, R-22, a hydrochlorofluorocarbon (HCFC), has become a common refrigerant in residential air conditioners, marking a significant advancement as the first non-flammable working fluid in the refrigeration cycle-a development that significantly improved the

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safety of air conditioning systems. However, in the 1980s, scientific revelations underscored the detrimental impact of chlorine, a constituent of Chlorofluorocarbon (CFC) and HCFC refrigerants, on the ozone layer. Consequently, R-22 was included in the list of ozone-depleting substances under the Montreal Protocol in 1987, marking the initiation of its gradual phase-out [1]. In response to the planned removal of ozone-depleting refrigerants from HVAC&R systems, the industry switched from R-22 to R410A. Not only is R410A good for the ozone layer, but it is also more energy efficient than its predecessor, R-22 [2,3]. It excels at heat absorption and release. However, R410A was later discovered to contribute to global warming, necessitating its phase-out. With growing global warming and climate change concerns, refrigerants with high global warming potentials (GWPs) must be phased down [4].

Addressing this issue, the Kigali Amendment to the Montreal Protocol is an international agreement explicitly designed to orchestrate the gradual reduction in hydrofluorocarbons (HFCs) with higher GWPs, such as R410A [5].

The refrigerant R410A, which has a significant GWP of 2088, is consistent with the principles of the Kigali Amendment and should be phased out of use. R410A's suitability in the split air conditioning market is diminishing, but it remains the preferred refrigerant for the A1 classification. The A1 classification is essential when looking into alternative solutions for structures reliant on R410A. Notably, the upcoming transition to low-GWP refrigerants differs markedly from previous instances. Unlike previous transitions in which all HVAC manufacturers adopted a single refrigerant, such as R-22 or R-410A, the current landscape lacks a consensus on a specific lower GWP refrigerant. R410A replacements are classified into single-component refrigerants and refrigerant blends, except for R32, as shown in Table 1 [13].

Table 1
Main R410A replacements [6-12]

Refrigerant	Composition (mass %)	Safety Class	GWP AR4
R410A	R32/R125(50/50)	A1	2088
R32	R32(100)	A2L	677
R446A	R32/R1234ze(E)/R600 (68/29/3)	A2L	470
R447A	R32/R125/R1234ze(E) (68/3.5/28.5)	A2L	570
R447B	R32/R125/R1234ze(E) (68/8/24)	A2L	710
R452B	R32/R125/R1234yf (67/7/26)	A2L	676
R454B	R32/R1234yf (68.9/31.1)	A2L	466
R466A	R32/R125/R131I (49/11.5/39.5)	A1	733
R470A	R744/R32/R125/R134aR/1234ze(E)/R227ea (10.0/17.0/19.0/7.0/44.0/3.0)	A1	909

Schultz [7] compared the performance parameters of R466A and R410A under different conditions, including heating and cooling for residential split heat pump systems. The results showed that R466A is a viable substitute for R410A. Pardo and Mondot [14] investigated the performance of five alternative refrigerants—R459A, R454B, R447A, HPR2A, and R32—compared to R410A in a 10-kW air-to-water reversible heat pump. Their findings revealed performance parameters within ±10% of R410A, with the heat pump functioning normally under limited conditions. While R32 can directly replace R410A, its higher discharge temperature may limit the system's operating range. Notably, the relative performance advantages of R454B and R459A are clear. Kujak and Schultz [15] compared the performance of five refrigerants—R410A, R466A, R452B, R454B, and R32—based on thermodynamic properties using NIST software, REFPROP. The results showed that the COP values of the latter three refrigerants are nearly equal to or slightly higher than R410A, with cooling and heating capacities slightly lower than R410A, except for R32. R452B and R466A are considered direct replacements for

R410A, requiring only minor equipment modifications. These alternatives outperform R410A regarding environmental performance because their GWP values are less than 750. Most alternatives are classified as A2L, except R466A and R470A, classified as A1. The saturated pressure curves of all alternative refrigerants are very similar to those of R410A.

A thorough review of the literature reveals that current alternative refrigerants for R410A are classified into two types: pure refrigerants and refrigerant mixtures. ASHRAE Standard 34, or ISO 817, classifies R32, a pure refrigerant, as A2L or slightly flammable. R-32 is prominently featured as a critical refrigerant in current refrigerant blends designed by researchers to replace R410A in air conditioning systems [16-18]. Table 1 details the remaining alternatives, which are mixtures classified as A2L. Recognising the safety limitations imposed by EN378, which specifies the refrigerant charge limit for A2L refrigerants, efforts to develop new HVAC systems face challenges in quickly resolving the R410A replacement issue, especially with the Kigali Amendment taking effect in January 2019[19,20]. This research focuses on A1 and A2L refrigerants to overcome refrigerant charge limitations in mini-split air conditioner systems soon. The study looks at two A1 refrigerants, R466A and R470A, classified as non-flammable by ASHRAE Standard 34. The investigation also includes seven other refrigerants: R32, R446A, R447A, R447B, R452B, R454B, and R455A, all of which fall under the A2L classification according to ASHRAE Standard 34, indicating that they are mildly flammable refrigerants. The study examines these refrigerants' thermodynamic and heat transfer properties, shedding light on their suitability and safety considerations in various applications within the HVAC industry.

2. Performance Evaluation of Simplified Thermodynamic Model

In this study, a thorough thermodynamic analysis of R410A and its alternatives is based on the examination of multiple parameters, with a focus on four critical comparisons: coefficient of performance (COP), volumetric capacity (Q_{OV}), compression ratio, and discharge temperature of the compressor. Simulations are run to evaluate the performance of the chosen refrigerants in an air-cooled split air conditioning system using the ideal single-stage vapour compression cycle conditions outlined in Table 2.

Table 2
Cycle working conditions

T_C(°C)	T_E(°C)	T_{SUP} (K)	T_{SUB}(K)
47	5	5	3

For the sake of simplicity, this study assumes that the compression process is isentropic, while the expansion process is considered isenthalpic. Furthermore, all frictional pressure drops in the system are disregarded, and heat transfer is limited to the evaporator and condenser. The operating temperatures for evaporation (T_E) and condensing (T_C) follow the guidelines outlined in AHRI Standard 210-240. Eqs. (1) and (2) define the evaporation pressure (P_O) as the vapour-saturated temperature and the condensing pressure (P_C) as the liquid-saturated temperature, respectively (2).

$$P_O = f(T_E) \quad (1)$$

$$P_C = f(T_C) \quad (2)$$

As outlined by Prayudi *et al.,* [21], the degree of superheat in the evaporator, denoted as T_{SUP}, is determined by the variance between the exit temperature of the evaporator ($T_{(E.OUT)}$) and the saturated temperature corresponding to the evaporating pressure ($T_{(E,SAT)}$). Similarly, the degree of subcooling in the condenser, labelled T_{SUB}, is calculated as the temperature difference between the condenser exit ($T_{(C.OUT)}$) and the saturated temperature linked to the condenser pressure ($T_{(C,SAT)}$). This relationship is expressed through Eqs. (3) and (4) respectively.

$$T_{SUP} = T_{E.OUT} - T_{E,SAT} \tag{3}$$

$$T_{SUB} = T_{C.OUT} - T_{C,SAT} \tag{4}$$

The enthalpy (h_{2is}) and temperature of compressor discharge (T_{2is}) are related to entropy (S_{2is}) and condenser pressure. These relationships are expressed using Eqs. (5) and (6).

$$h_{2is} = f(P_C, T_{2is}) \tag{5}$$

$$T_{2is} = f(P_C, S_{2is}) \tag{6}$$

The Coefficient of Performance (COP) is defined as the ratio of the refrigerating effect, represented by the difference in enthalpy at the evaporator's outlet and inlet ($h_{E,\,out}$ - $h_{E,\,in}$), to work required by the compressor, expressed as the difference in enthalpy at the compressor's outlet and inlet ($h_{(com,out)}$ -$h_{(com,in)}$), as well as the corresponding volumetric capacity, Q_{OV}. Q_{OV}, or volumetric capacity, represents the refrigeration effect per unit volume of vapour refrigerant (V_1) at the evaporator outlet. Eq. (7) capture these relationships (8).

$$COP = \frac{h_{E,out} - h_{E,in}}{h_{com,out} - h_{com,in}} \tag{7}$$

$$Q_{OV} = \frac{h_{E,out} - h_{E,in}}{V_1} \tag{8}$$

The calculation procedure uses the NIST Program - REFPROP, with the thermodynamic properties of the mixtures retrieved internally from the most recent version of REFPROP, version 10 s shown in Table 3. Table 3 shows the critical properties and latent heat st 5ºC of the investigated refrigerants: R410A, R32, R446A, R447A, R447B, R452B, R454B, R455A, R466A, and R470A.

Table 3
Working fluids selected in this study and their main properties

Refrigerant	Latent heat at 5ºC (kJ/kg)	T_{cri} (°C)	P_{cri} (kPa)
R410A	215	71.3	4901
R32	307	78.1	5782
R446A	240	88.5	5404
R447A	234	86.3	5286
R447B	229	84.0	5240
R452B	215	73.9	4805
R454B	237	83.3	4585
R455A	179	90.7	3787
R466A	132	94.0	6211
R470A	175	89.8	4479

Latent heat refers to the amount of heat required to change the refrigerant from liquid to vapour (or vice versa) at a constant temperature. A higher latent heat value generally indicates better cooling capacity. The critical temperature is the temperature above which the refrigerant cannot exist as a liquid, regardless of pressure. It is an important parameter for determining the operating limits of the refrigerant. The critical pressure is the pressure required to liquefy the refrigerant at its critical temperature. It is crucial for designing refrigeration systems and ensuring their efficiency and safety.

3. Results and Discussion

The results and discussions cover a wide range of thermodynamic performance parameters for the ten refrigerants under consideration, including coefficient of performance (COP), compressor discharge temperature, compression ratio, and volumetric capacity.

The COP is widely used in various applications, particularly air conditioners and heat pumps. In the context of air conditioners, COP represents the cooling efficiency, or the ratio of cooling the unit delivers to the energy input required for its generation. A higher COP indicates increased energy efficiency in the equipment.

Figure 1 shows a discernible trend in the relative COP values and R410A is the baseline refrigerant. R32 is exhibiting the highest relative COP at 104%, surpassing R410A by 4 percent. In contrast, the two lowest values are attributed to R466A and R470A, which show a 25% and 26% reduction in COP when compared to R410A. R452B exhibits a relative Coefficient of Performance (COP) of 96%, indicating a 4% drop in efficiency compared to R410A. Both R454B and R455A have a relative COP of 93%, each demonstrating a 7% reduction in efficiency. R447B shows a relative COP of 90%, resulting in a 10% decrease in efficiency, while R447A has a relative COP of 88%, marking a 12% efficiency drop. Lastly, R446A has the lowest relative COP at 87%, reflecting a 13% decrease in efficiency compared to R410A. Overall, the chart suggests that among the refrigerants studied, R32 offers a higher efficiency compared to R410A, while R466A and R470A have significantly lower efficiencies.

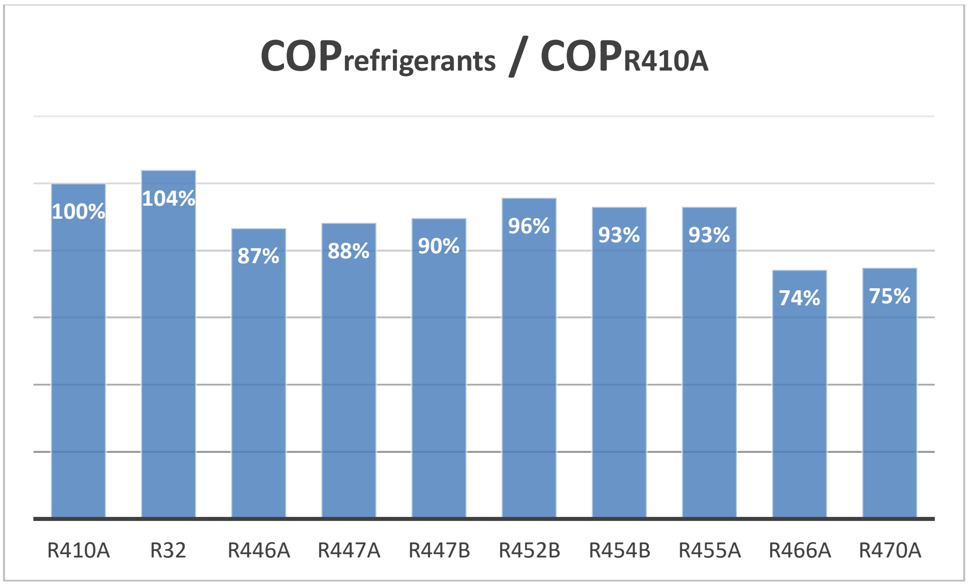

Fig. 1. Ratio of COP refrigerants to COP of R410A

Figure 2 depicts the compressor discharge temperatures for all ten refrigerants under consideration. Eight refrigerants have higher discharge temperatures than R410A, with only R455A being 14 percent lower. R32 and R466A exhibit discharge temperatures of 95.5ºC and 96.5ºC, respectively. Notably, the discharge temperature of R466A is 24% higher than that of R410A, while

R32 has a 23% increase over R410A. It is critical to emphasise that elevated discharge temperatures can shorten the compressor's lifespan due to prolonged operation in a high superheat mode.

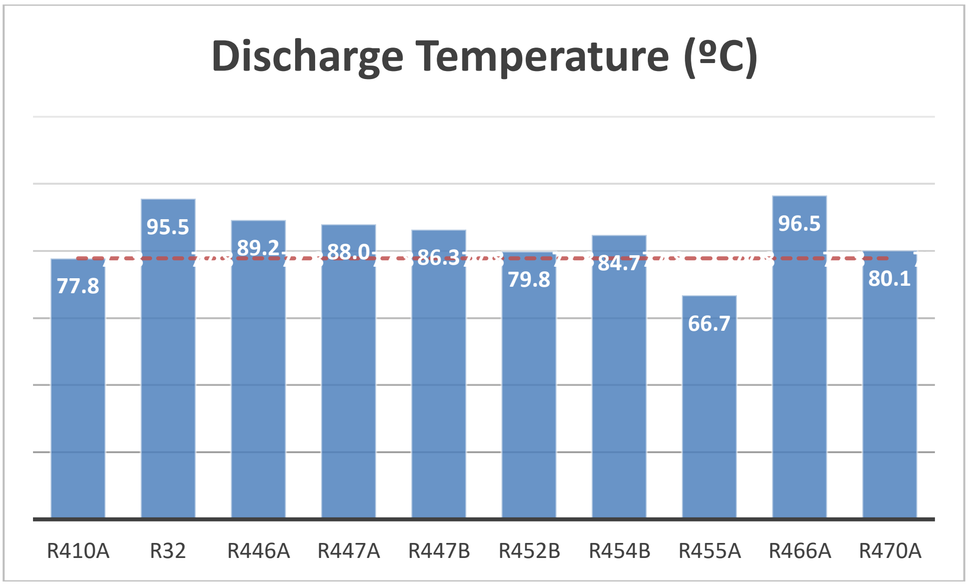

Fig. 2. Discharge temperature of Refrigerants compares with R410A

The compression ratio stands out as a critical factor, and the inclusion of several other variables is required due to their effect on discharge temperatures. Figure 3 depicts the relative compression ratios for R410A and its nine alternatives. The findings show that all the alternatives have higher compression ratio values than R410A, except for R32, which has a comparable compression value. The results show that R470A has the highest compression ratio, surpassing R410A by 57%, while R452B has the smallest increase, only 6% more than R410A. It is important to note that the increase in vapour temperature during compression is significantly influenced by the amount of work done on it. This involves the process of increasing pressure and density, and a more significant change in pressure and density results in a higher final temperature for the vapour under a given suction condition—though this aspect is not explicitly addressed in this study.

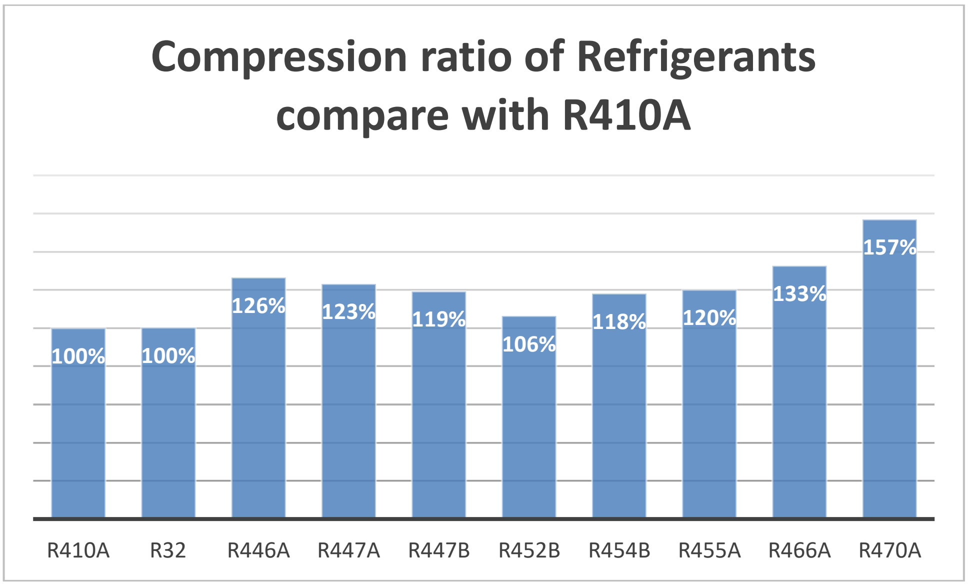

Fig. 3. Compression ratio of R410A, R466A, and R470A

Figure 4 depicts the volumetric capacity of various refrigerants relative to R410A. Volumetric capacity is determined by the specific volume of the refrigerant in the vapour stage and the refrigeration effect it produces. This metric represents the cooling capacity per unit volume of refrigerant vapour exiting the evaporator and the volume of refrigerant displaced by the compressor within the system. As shown in Figure 4, the volumetric capacity of eight refrigerants is lower than that of R410A. As a result, these refrigerants require a larger compressor capacity, necessitating the redesign or selection of a larger compressor size in an air conditioner to achieve the same cooling capacity as R410A. Only R32 has a volumetric capacity that outperforms R410A by 12%. This refrigerant required a smaller compressor than R410A.

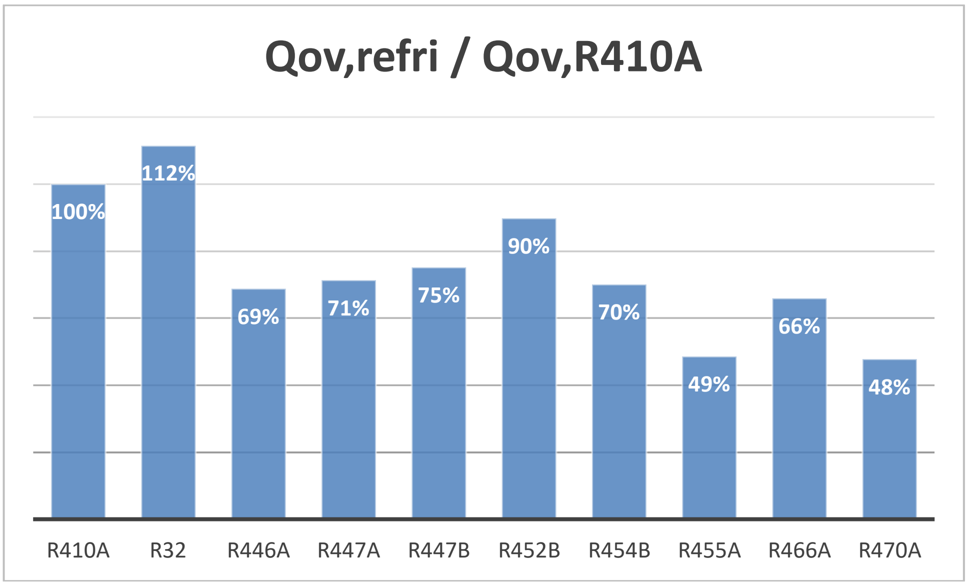

Fig. 4. Comparison of volumetric capacity of R410A and its alternatives

4. Conclusion

In this study, the theoretical performance of ten refrigerants—R410A, R32, R446A, R447A, R447B, R452B, R454B, R455A, R466A, and R470A—was investigated within a basic vapour compression refrigeration cycle. The study used a condensing temperature of 47ºC, the evaporating temperature of 5ºC, compressor suction superheat of 5K and condenser subcooling of 3K. Based on the analysis and discussion of the results, the following conclusions can be reached:

i. R455A, R454B, and R446A have significantly lower GWPs than R410A, with reductions of 98%, 77.7%, and 77.5%, respectively. This suggests a potential contribution to reducing the overall impact of global warming.
ii. R455A, R466A, and R470A are refrigerants with higher critical temperatures and pressures than R410A, which is advantageous for increased heat transfer at a constant temperature.
iii. Five refrigerants, R32, R446A, R447A, R447B, and R454B, have refrigeration effect higher than R410A in the air conditioner refrigeration cycle.
iv. R446A, R447A, R447B, R452B, R454B, R455A, R466A, and R470A all have lower volumetric capacities and COPs than R410A.
v. R32, R446A, R447A, R447B, R452B, R454B, R455A, R466A, and R470A have a higher compression ratio than R410A does.

vi. The discharge temperature of the compressor for R32, R446A, R447A, R447B, R452B, R454B, R466A, and R470A is higher than R410A. Only R455A is less than R410A.

vii. In conclusion, R455A is environmentally friendly, with lower GWPs and a COP value comparable to R410A. The drawback is that the refrigerant is classified as A2L. It is important to note that these alternatives may not serve as direct replacements for R410A in air conditioners due to differences in volumetric capacity, compression ratio, and compressor discharge temperature.

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