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Investigation and Analysis of R438A as an Alternative Refrigerant to R22 with Lower Global Warming Potential

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ABSTRACT

This research presents the R438A refrigerant that non-flammable refrigerant and develop for retrofit to R404A. The hydrofluorocarbons/hydrocarbon (HFCs/HCs) R463A (GWP=2,265) was zeotropic mixture of R125 (45%), R134a (44.2%), R32 (8.5%), R600 (1.7%) and R600a (0.6%). The R463A refrigerants is no frame propagation class A1 and lower toxicity and used polyol ester oil (POE). The results will investigation and analysis of the environmentally friendly refrigerant for R22 replacement. All refrigerant properties in this research were based on results from the REFPROP and CYCLE_D-HX software of NIST under CAN/ANSI/AHRI540. The results of this work show that HCs R170, R290, R600, R600a, R601, R601a, R1150 and R1270 can be mixed in HFCs R417A, R417B, R422A, R422B, R422C, R422D, R424A, R437A, R438A and R453A and able to be further developed in the future. All refrigerants are non-flammable refrigerants, non-toxic and zero ODP. The R438A mixed with HCs R600 (1.7%) and R601a (0.6%) and is the refrigerant cooling coefficient of performance close to that of R22 refrigerant. In conclusion, it can be used as an environmentally friendly and energy efficiency replacement for R22. The result of R438A normal boiling was lower than R404A 4% that high cooling capacity and zero ODP. All refrigerants are also refrigerants that are matched with the 4th generation refrigerants with the use of natural refrigerants.

1. Introduction

Energy use in Thailand's business sector is ranked second among overall energy users in the country, and is thus being targeted for energy-saving options [1]. The number of convenience stores in Thailand numbered to more than 20,000 locations in 2019, and this continuously increases on an annual basis [2]. The majority are open 24 hours per day, so the retail sector is the fourth largest consumer of energy in the business sector, consuming more energy than residences do [3]. The components that contribute to energy consumption of convenience stores in Thailand, ranked from highest to lowest, are refrigeration systems, air-conditioning systems, electrical equipment, and lighting [4,5]. However, proportions of energy use in convenience stores in Taiwan were previously

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ranked as shown in Figure 1 below [6]. The best options for reducing energy consumption in convenience stores in Thailand are high energy efficiency and an efficient energy-management system. A good example of energy savings in refrigeration systems is shown in Figure 2 below [7]. Energy savings in refrigeration systems can be achieved through decreased power consumption of the compressor, as this is the component that utilizes the most energy.

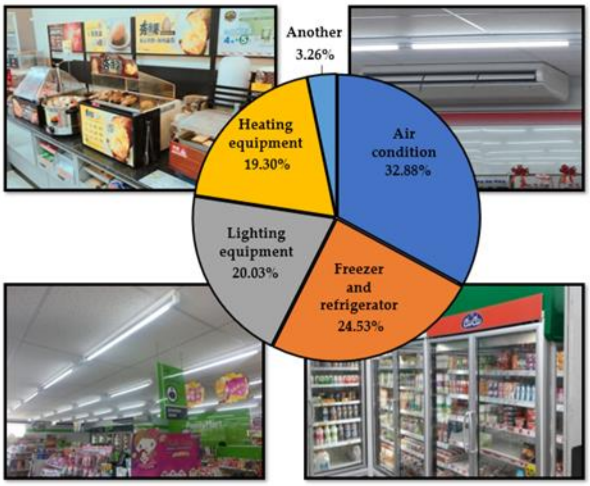


Fig. 1. Proportions of energy use in Taiwanese convenience stores [6]

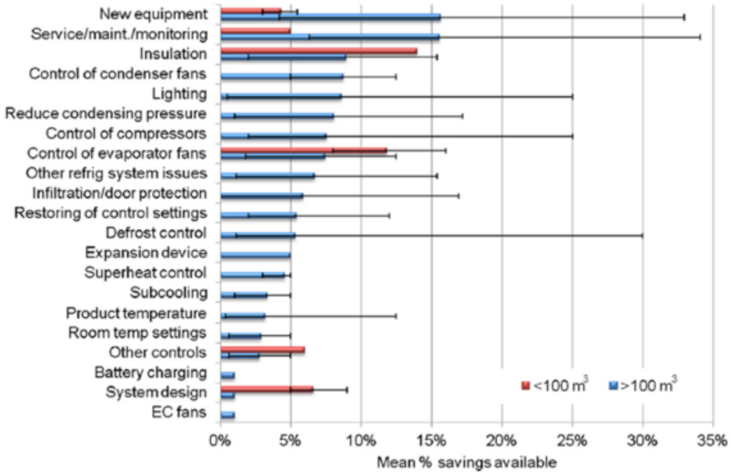


Fig. 2. Examples of energy savings in refrigeration systems [7]

Refrigerant trends in Thailand have shown improvements through increased energy efficiency and decreased global warming potential (GWP), as shown in Figure 3 [8,9], which is related to the hydrofluorocarbon (HFCs) phase-down schedule, as shown in Figure 4 [10]. First- and second-generation refrigerants are composed of natural refrigerants and hydrocarbons (HCs), both of which do not impact the environment, have low GWP, and have zero ozone-depletion potential (ODP) [11–13]. R744 operates under high pressure and is highly toxic and flammable [14–16]. Following the second generation, third-generation refrigerants are composed of chlorofluorocarbons (CFCs) [17–19] and hydrochlorofluorocarbons (HCFCs) [20–22], which are easy to use, can operate under low pressure, and are non-toxic. However, they have high GWP and ODP, contributing to ozone depletion and global warming. Therefore, in the development of refrigerants, significantly decreased ODP and GWP are highly desirable. Moreover, third-generation refrigerants (i.e., CFCs and HCFCs) were further developed into hydrofluorocarbon (HFCs) refrigerants that possessed low GWP and zero ODP

[23–25]. Fourth-generation refrigerants are mainly hydrofluoroolefins (HFOs) with low GWP and low capacity [26–28]. These refrigerants are generally a mixture of HFCs [29–31], HFOs [32–34], and HCs [35–37]. Natural refrigerants are low-GWP, zero ODP, high-capacity, low-pressure, and non-toxic [38–40].

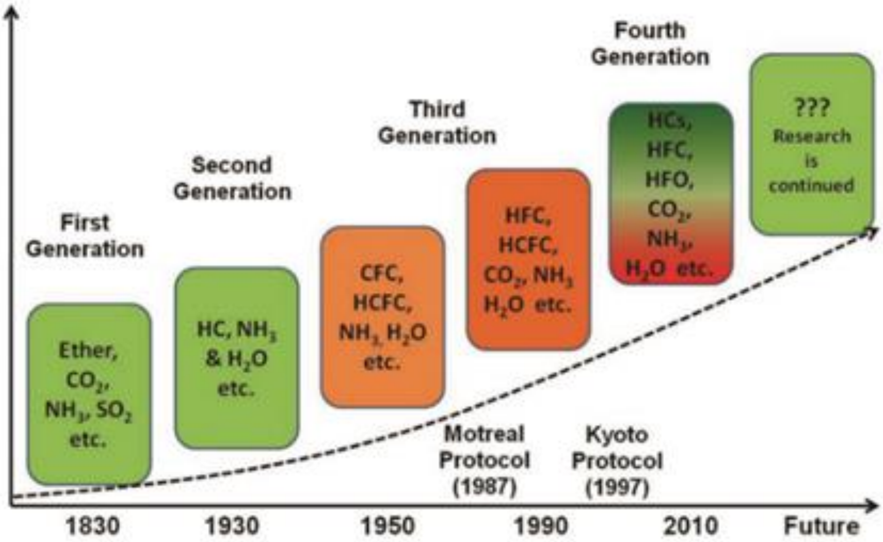


Fig. 3. Evolution of refrigerants [8,9]

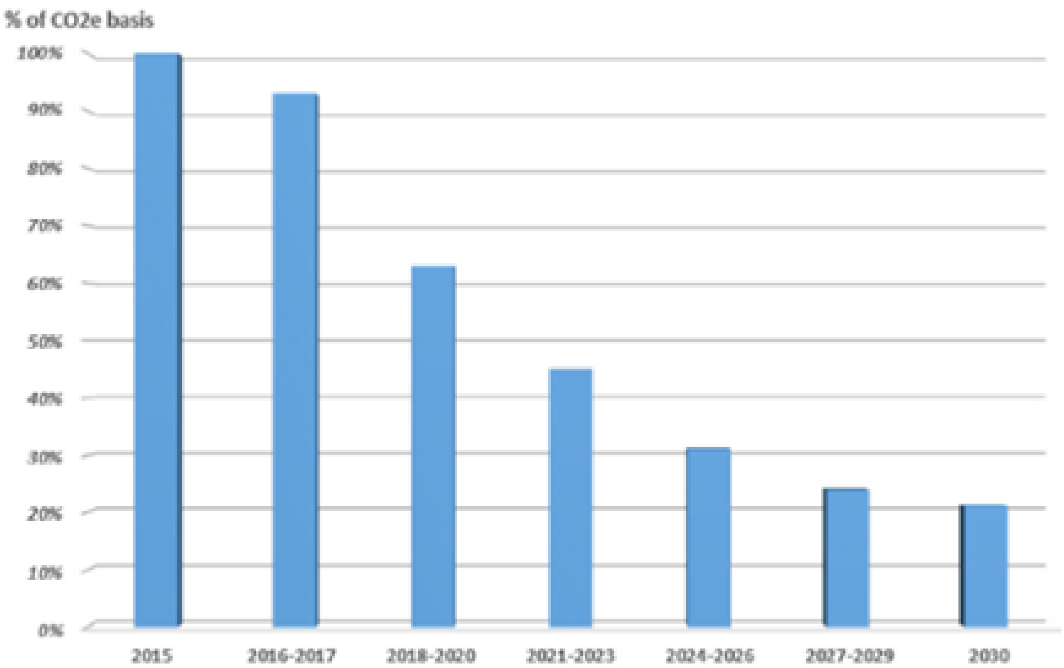


Fig. 4. Hydrofluorocarbon (HFCs) phase-down schedule (Co2e %) [10]

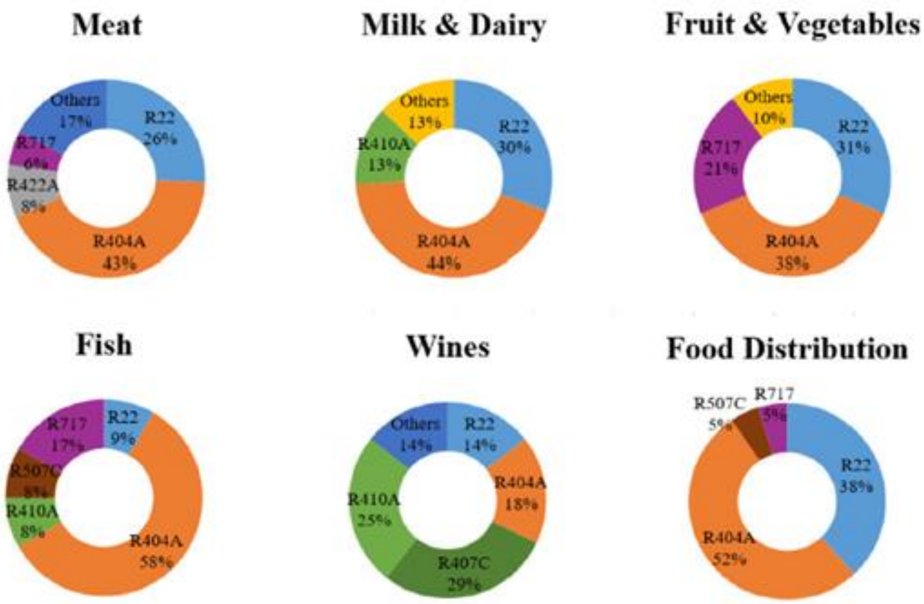


Fig. 5. Top refrigerants in the food industry [9]

Refrigerants need to be low-GWP, zero -ODP, high-capacity, low-pressure, and non-toxic, and should, thus, be mixed with HCs and HFOs; however, current refrigerants are still highly flammable and have low capacity. An alternative is to incorporate other HFCs. R32 is low-GWP, zero ODP, high-capacity, and non-toxic, but operates under high pressure and is flammable; in contrast to R134A, which possesses highly similar properties but can operate under low pressure and has low capacity. Current refrigeration systems use R22 [41], as well as R417A [42], R417B [43], R422A [44], R422B [45], R422C [46], R422D [47], R424A [48], R433A [49], R437A [50], R438A [51], and R453A [52], all of which were developed as alternatives to R22 and which are mixed with HCs and HFCs, as shown in Table 1–4. The lowest normal boiling points (of R422A and R422C) are -46.80 °C and -46.20 °C, respectively, lower than that of R22 by 12.82% and 11.69%. This is due to the presence of hydrofluorocarbon (HFCs) R125 in their composition (85.1% and 82.0%, respectively), consistent with those of R410A and R507, which have boiling points of -51.6 °C and -46.74 °C, respectively, and are considered attractive as alternative refrigerants to R134A and R404A, due to their HFCs R125 content of 50%. The boiling point of R125 is -48.1 °C, with a high GWP value (3,450); leading to R422A and R422C having the high GWP values of 3,143 and 3,185, respectively. R422A and R422C also have hydrocarbon (HCs) R601a in their composition (3%). The boiling point and GWP of R601a are 0 and -11.73 °C, respectively, the effect of which is reducing the GWP and increasing the boiling point of refrigerant mixtures it is contained in. The lower GWP, compared with R22 f R453A and R437A (1,765 and 1,805, respectively) is due to hydrofluorocarbon (HFCs) R134a (53.8% and 78.5%) in their composition and hydrofluorocarbon (HFCs) R32 (20%) in the composition of R453A; this is consistent with R407A, R407H, and R407F, which combine R134a and R32 with R744 in contents of 6% and 3%, respectively, in their compositions. The boiling point and GWP naturally change when adjusting the composition of the refrigerant. The refrigerant effect and heat rejection of R453A were found to be higher than those of R22, due to the presence of hydrofluorocarbon (HFCs) R32 (20%). R453A also has the hydrocarbon (HCs) R600 (0.6%) in its composition. The lowest refrigerant work was found for R422A, which possesses HCs R600a (3%) in its composition.

Table 1
Properties of R22, R417A, and R417B

Condition	LT	MT	HT	LT	MT	HT	LT	MT	HT
Refrigerant	R22			R417A			R417B		
Composition	R22			R125/R134a/R600			R125/134a/600		
Mass percentage	100			46.6/60/3.4			79/18.3/2.7		
Boiling point (°C)	-40.80			-39.10			-45.20		
Critical Pressure (kPa)	4,990			4,036			3,737		
Critical Temperature (°C)	96			87			74		
ODP	0.055			0			0		
GWP	1,600			1,950			3,027		
Class	A1			A1			A1		
Lubricant type	MO			MO/AB/POE			MO/POE		

Table 2
Properties of R422A, R422B, and R422C

Condition	LT	MT	HT	LT	MT	HT	LT	MT	HT
Refrigerant	R422A			R422B			R422C		
Composition	R125/R134a/R600a			R125/R134a/R600a			R125/R134a/R600a		
Mass percentage	85.1/11.5/3.4			55/42/3			82/15/3		
Boiling point (°C)	-46.80			-41.59			-46.20		
Critical Pressure (kPa)	3,665			3,857			3,696		
Critical Temperature (°C)	72			82			72		
ODP	0			0			0		
GWP	2,530			2,526			3,085		
Class	A1			A1			A0		
Lubricant type	MO/AB/POE			MO/POE			MO/POE		

Table 3
Properties of R422D, R424A, and R437A

Condition	LT	MT	HT	LT	MT	HT	LT	MT	HT
Refrigerant	R422D			R424A			R437A		
Composition	R125/R134a/R600a			R125/R134a/R600/R600a/R601a			R125/134A/R600/R601		
Mass percentage	62.1/31.5/3.4			50.5/47/1/0.9/0.9			19.5/78.5/1.4/0.6		
Boiling point (°C)	-43.50			-38.70			-32.65		
Critical Pressure (kPa)	3,795			4,040			4,003		
Critical Temperature (°C)	80			89			95		
ODP	0			0			0		
GWP	2,330			2,440			1,805		
Class	A1			A1			A1		
Lubricant type	MO/AB/POE			MO/AB/POE			MO/POE		

Table 4
Properties of R438A and R453A

Condition	LT	MT	HT	LT	MT	HT
Refrigerant	R438A			R453A		
Composition	R125/134A/R32/R600/R601a			R125/R32/R134A/R227ea/R600/R601A		
Mass percentage	45/44.2/8.5/1.7/0.6			20/20/53.8/5/0.6/0.6		
Boiling point (°C)	-42.61			-42.20		
Critical Pressure (kPa)	4,179			4,530		
Critical Temperature (°C)	84			88		
ODP	0			0		
GWP	2,265			1,765		
Class	A0			A1		
Lubricant type	MO/POE			MO/POE		

The mixed-refrigerant design should be comparable to natural refrigerants, in terms of having a strong refrigerant effect and high heat rejection, but certain hydrocarbon refrigerant types (e.g., R290 and R1270) are commonly selected for their refrigerant effect and high heat rejection. However, the high refrigerant work and high operating pressure of such refrigerants affect the power consumption of the compressor. Considering systems that operate with R134A [53], R450A [54], R456A [40], R513A [55], and R515A [40] are all refrigerants that have been developed as an alternative to R134A, which are mixed with HCs, HFCs, and HFOs and operated under low pressure, achieving similar results to R453A operating under high pressure with 20% hydrofluorocarbon (HFCs) R32 content in its composition, as shown in Table 5. The fourth-generation refrigerant R22A was the basis for this research, which is currently the most-used ranked 2nd refrigerant, as shown in Figure 5.

Table 5
Properties of R134A, R450A, R456A, R513A, and R515A

Refrigerant	R134A	R450A	R456A	R513A	R515A
Composition	R134A	R134A/ R12354ze(E)	R134a/R32/R1234ze (E)	R134A/ R1234yf	R227ea/ R1234ze
Mass percentage	100	42/58	45/6/49	44/56	12/88
Boiling point (°C)	–26.07	–23.5	–30.75	–28.3	–18.75
Critical pressure (kPa)	4060	3814	4175	3700	3555
Critical temperature (°C)	101.06	105.87	102.65	97.7	108.65
ODP	0	0	0	0	0
GWP	1430	547	687	570	387
Class	A1	A1	A1	A1	A1
Lubricant type	POE	POE	POE	POE	POE

R404A is an azeotropic blend of 143a/125/134a with zero ODP, which is non-flammable, non-toxic, and operates under low pressure, with a GWP of 3922 [56]. R407A [57], R407F [58], R407H [59], R410A [60], R442A [52], R448A [61], R449A [62], R452A [63], R453A [64], and R463A [65] are all refrigerants developed to be retrofitted to replace R404A, as shown in Table 6–9.

Table 6
Properties of R404A, R407A, and R407F

Refrigerant	R404A	R407A	R407F
Composition	R125/R143/R134A	R125/R32/R134A	R125/R32/R134A
Mass percentage	44/52/4	40/20/40	30/30/40
Boiling point (°C) at 1 kPa	–46.6	–45.28	–46.33
Critical pressure (kPa)	3728	4494	4754
Critical temperature (°C)	72.1	82	82.6
ODP	0	0	0
GWP	3943	2107	1825
Class	A1	A1	A1
Lubricant type	POE	POE	POE

Table 7
Properties of R407H, R410A, and R422A

Refrigerant	R407H	R410A	R442A
Composition	R125/R32/R134A	R125/R32	R125/R32/R1234A /R227ea/R152A
Mass percentage	15/32.5/52.5	50/50	31/31/30/5/3
Boiling point (°C)	–44.6	–51.6	–46.5
Critical pressure (kPa)	4856	4811	4760
Critical temperature (°C)	86.53	70.81	82.4
ODP	0	0	0
GWP	1400	1900	1888
Class	A1	A1	A1
Lubricant type	POE	POE	POE

Table 8
Properties of R448A, R449A, and R452A

Refrigerant	R448A	R449A	R452A
Composition	R125/R32/R134A/ R1234yf/R12354ze(E)	R125/R32/R134A/R1234yf	R125/R32/R1234yf
Mass percentage	26/26/20/21/7	24.7/24.3/25.7/25.3	59/11/30
Boiling point (°C)	–40.1	–45.95	–47.2
Critical pressure (kPa)	4675	4662	4014
Critical temperature (°C)	83.66	83.85	75.05
ODP	0	0	0
GWP	1273	1282	1945
Class	A1	A1	A1
Lubricant type	POE	POE	POE

Table 9
Properties of R453A and R463A

Refrigerant	R453A	R463A
Composition	R125/R32/R134A/R227ea/ R600/R601A	R125/R32/R134A/R1234yf/R744
Mass percentage	20/20/53.8/5/0.6/0.6	30/36/14/14/6
Boiling point (°C)	–42.2	–60.13
Critical pressure (kPa)	4530	5283
Critical temperature (°C)	87.9	73.15
ODP	0	0
GWP	1765	1377
Class	A1	A1
Lubricant type	POE	POE

The lowest normal boiling point of R463A is –60.13 °C, which is lower than that of R404A by 23%. This is due to hydrofluorocarbon (HFCs) R32 (36%) and carbon dioxide (CO_2) R744 (7%) being in its composition, consistent with R445A [64] and R455A [65]. R445A and R455A both have low boiling points (–49.15 °C and –52.0 °C, respectively) and are attractive as alternative refrigerants with lower GWP than R134A and R404A, due to the CO_2 R744 content of 6% and 3%, respectively, in their compositions. R448A and R449A displayed the lowest GWP values of 1273 and 1282, respectively, due to the HFOs R1234yf and R1234ze in their compositions. The GWP of R463A has been found to be 1377, with a lower boiling point than that of R404A by 23%; even though the ratio of R1234yf in R463A is less than that in both R448A and R449A. However, the GWP of R463A has been found to be slightly higher than those of R448A and R449A. The cost of R463A is also lower than R448A and R449A. Hydrofluorocarbons can also be combined with carbon dioxide (CO_2), which has a lower GWP and boiling point. The lower boiling point and GWP are consistent with the evolution of the fourth-generation refrigerants that contain a mixture of HFCs, HFOs, HCs, and natural refrigerants, which are required to produce a low-GWP, zero ODP, high-capacity, low-operating pressure, and non-toxic refrigerant. The refrigerant effect and heat rejection of R463A have been found to be higher than those of R404A, due to the presence of hydrofluorocarbon (HFCs) R32 (36%) and carbon dioxide (CO_2) R744 (7%) in its composition, consistent with R424A and R453A, which are composed of hydrocarbons (HCs) at contents of 1.8% and 1.2%, respectively. The mixed-refrigerant design should be comparable to natural refrigerants, in terms of having a strong refrigerant effect and high heat rejection. Refrigerants operated under low pressure display low refrigerant work value; in this case, the lowest refrigerant work is observed in R452A. This refrigerant possesses HFOs R1234yf and R1234ze (E) in its composition. The highest refrigerant work value is observed for R463A, which contains hydrofluorocarbon (HFCs) R32 (36%) and carbon dioxide (CO_2) R744 (7%), and operates at the highest evaporator pressure. This means that a refrigerant system which is operated at low pressure should use a mix of refrigerants that can operate under low pressure, such as R1234yf, R1234ze, and R134A. R450A [49], R456A [50], R513A [51], and R515A [50], which are mixed with hydrofluoroolefins (HFOs) and can operate under low pressure, have achieved similar results. R453A had the highest COPc, as R453A does not have the highest refrigerant effect and heat rejection, nor the lowest boiling point, but can be operated under low pressure, which has an impact on low refrigerant work. The COPc level of R463A was recorded at 1.34, which is 10% higher than that of R404A under low-temperature conditions only. The promising results for COPc obtained by R407F, R448A, and R449A are due to the refrigerants being operated under low pressure, which has an impact on low refrigerant work. The same effect has been observed for R453A; however, these four refrigerants do not have a low normal boiling point or high Cp liquid/vapor or liquid/vapor conductivity. This shows that a mixed-refrigerant design should consider all parameters, such as the GWP, boiling point, Cp liquid/vapor and liquid/vapor conductivity, refrigerant effect, heat rejection, refrigerant work, evaporator pressure, high pressure, and COPc.

Due to the costs shown in Figure 6 [43], refrigerants should be mixed with HFOs. The figure shows that the HFOs had the highest refrigerant cost, but does not include HCs refrigerant costs compared with HFO refrigerant costs, and is presented for comparative purposes in this research (as it is generally composed of HCs).

The class properties of hydrocarbon refrigerants are shown in Figure 7 below. Some zero ODP and near-zero GWP Class A3 refrigerants, as shown in Table 10 and 11, are R170 [66], R290 [67], R600 [68], R600a [69] and Table 2 for R601 [70], R601a [71], R1150 [72], and R1270 [73]. The lowest boiling points were found to be -88.70 °C and -103.8 °C, respectively, for R170 and R1270; however, their critical temperatures were found to be 32.17 °C and 9.5 °C. This means that these cannot be operated as refrigerants in accordance with the CAN/ANSI/AHRI540 Air-Conditioning, Heating, and Refrigeration Institute (AHRI) standards considered in this research [74-76]. R290 and R1270 were found to have boiling points near that of with R22 (-42.1 °C and -47.7 °C, respectively), but operate at high condenser pressures, which affect the evaporator pressure, condenser pressure, and cooling coefficient of performance. Therefore, in this research, we used R1270 for the base line for new refrigerant mixes, as R1270 has a low boiling point and high refrigerant effect.

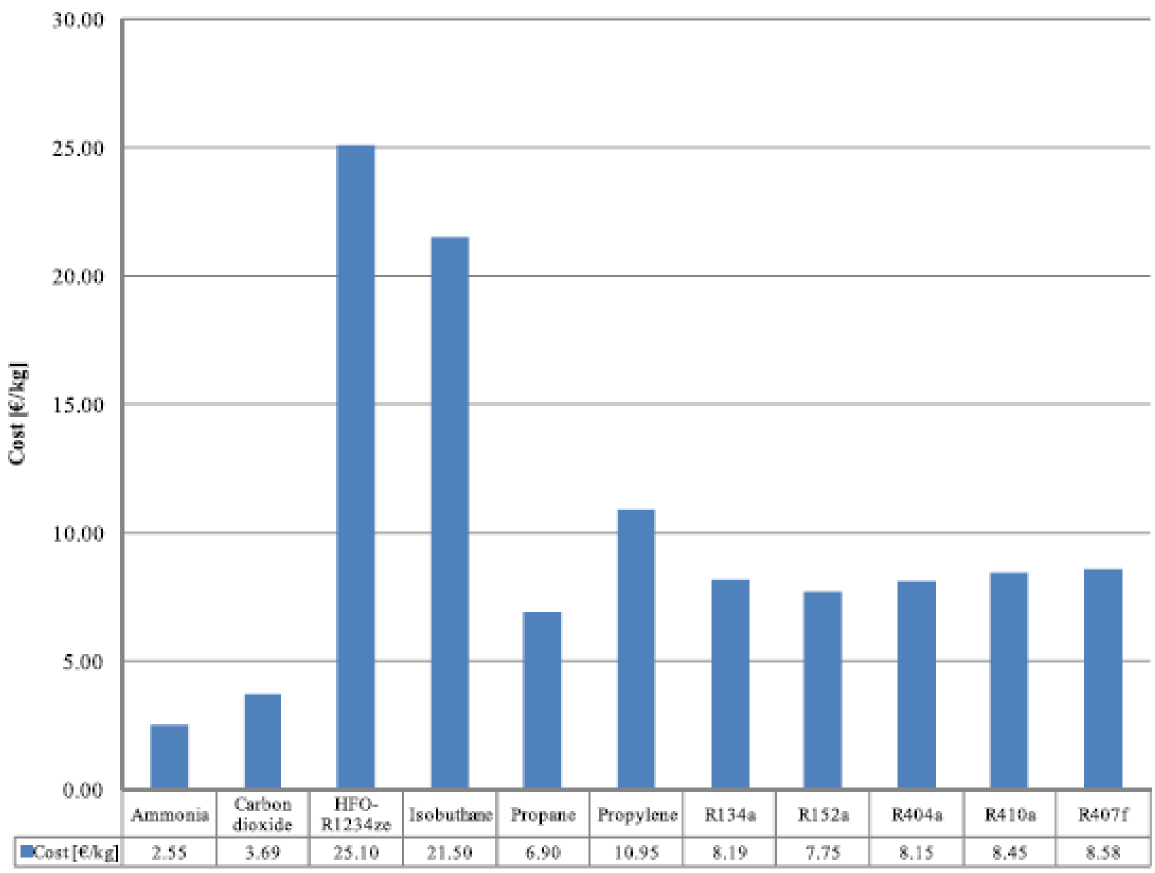


Fig. 6. Cost of refrigerants

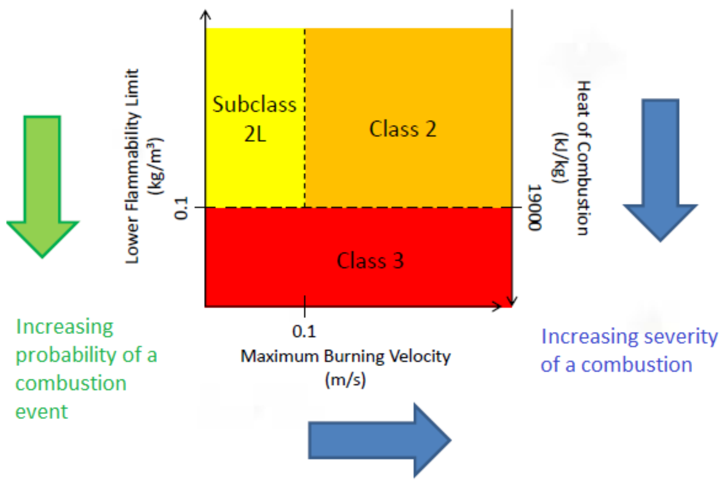


Fig. 7. Class properties of hydrocarbon refrigerants

Table 10
Properties of R170, R290, R600, and R600a

Condition	LT	MT	HT	LT	MT	HT	LT	MT	HT	LT	MT	HT
Refrigerant	R170			R290			R600			R600a		
Formula	C_2H_6			C_3H_8			C_4H_{10}			C_4H_{10}		
Chemical name	Ethane			Propane			Butane			Isobutane		
Boiling point (°C)	-88.7			-42.1			-0.5			-11.73		
Critical Pressure (kPa)	4872			4251			3796			3629		
Critical Temperature (°C)	32.17			96.74			151.98			134.66		
ODP	0			0			0			0		
GWP	3			3			3			3		
Class	A3			A3			A3			A3		
Lubricant type	MO/POE			MO/POE			MO/POE			MO/POE		
Q_{evap} (kJ/kg)	N/A	N/A	N/A	388.96	240.37	223.89	235.72	261.99	255.88	207.03	231.52	223.97
Q_{cond} (kJ/kg)	N/A	N/A	N/A	221.85	349.48	314.59	400.21	371.49	348.29	358.39	332.01	308.46
Work (kJ/kg)	N/A	N/A	N/A	221.85	109.11	90.70	164.50	109.51	92.41	151.35	100.49	84.49
COPc	N/A	N/A	N/A	1.33	2.20	2.47	1.43	2.39	2.77	1.37	2.30	2.65
Evaporator Pressure (kPa)	N/A	N/A	N/A	157.70	385.90	623.90	26.20	80.20	145.60	43.30	123.50	216.00
Condenser Pressure (kPa)	N/A	N/A	N/A	1653.10	1803.10	2269.40	484.30	535.40	705.00	670.60	736.80	955.00

Table 11
Properties of R601, R601a, R1150, and R1270

Condition	LT	MT	HT	LT	MT	HT	LT	MT	HT	LT	MT	HT
Refrigerant	R601			R601a			R1150			R1270		
Formula	C_5H_{12}			C_5H_{12}			C_2H_4			C_3H_6		
Chemical name	Pentane			Isopentane			Ethylene			Propylene		
Boiling point (°C)	36.1			27.7			-103.8			-47.7		
Critical Pressure (kPa)	3370			3378			5042			4660		
Critical Temperature (°C)	196.55			187.2			9.5			92.4		
ODP	0			0			0			0		
GWP	4			4			3			2		
Class	A3			A3			A3			A3		
Lubricant type	MO/POE			MO/POE			MO/POE			MO/POE		
Q_{evap} (kJ/kg)	239.30	267.22	264.13	221.18	248.05	244.65	N/A	N/A	N/A	232.45	247.13	228.13
Q_{cond} (kJ/kg)	402.16	376.31	356.72	374.81	350.99	331.95	N/A	N/A	N/A	404.89	358.77	320.62
Work (kJ/kg)	162.86	109.09	92.59	153.63	102.94	87.30	N/A	N/A	N/A	172.44	111.64	92.48
COPc	1.47	2.45	2.85	1.44	2.41	2.80	N/A	N/A	N/A	1.35	2.21	2.47
Evaporator Pressure (kPa)	4.70	18.10	37.00	7.20	25.90	51.20	N/A	N/A	N/A	199.70	478.10	764.40
Condenser Pressure (kPa)	155.80	175.10	242.20	201.70	225.40	307.00	N/A	N/A	N/A	1964.90	2143.80	2686.70

2. Materials and Methods

For the properties of refrigerants and the refrigeration simulation system, we used the REFPROP database and CYCLE_D-HX software from the National Institute of Standards and Technology [78-80], respectively, as shown in Figure 9 below. The properties of all refrigerants, conformed to the use of REFPROP and the CYCLE_D-HX software, as stipulated by the National Institute of Standards and Technology (NIST) [78-80], in accordance with the CAN/ANSI/AHRI540 Air-Conditioning, Heating, and Refrigeration Institute (AHRI) standards, as shown in Table 12 [74-76].

Table 12
Standard testing for refrigeration systems [74-76]

Temperature Point	Air Conditioning and Heat Pump		Refrigeration		
	Heating	Cooling	Low	Medium	High
Suction dew point (°C)	–15.0	10.0	–31.5	–6.5	7.0
Discharge dew point (°C)	35.0	46.0	40.5	43.5	54.5
Suction return gas temperature (°C)	–4.0	21.0	4.5	18.5	18.5
Superheat (K)	11.0	11.0	11.0	11.0	11.0
Subcooling (K)	0.0	0.0	0.0	0.0	0.0

Both software programs can pre-define mixtures and create new refrigerant mixtures. REFPROP can display results related to refrigerant properties under various conditions, and the CYCLE_D-HX software can also display results related to refrigerant cycles under various conditions. The results illustrated the relationships of all parameters, such as GWP, boiling point, refrigerant effect, heat rejection, refrigerant work, evaporator pressure, high pressure, and cooling coefficient of performance (COPc), Results illustrated the relationship of all parameters for R22 [41], R417A [42], R417B [43], R422A [44], R422B [45], R422C [46], R422D [47], R424A [48], R433A [49], R437A [50], R438A [51], and R453A [52], such as GWP, boiling point, refrigerant effect, heat rejection, refrigerant work, evaporator pressure, high pressure, and cooling coefficient of performance (COPc), as shown in Table 13–16 [81-84].

Table 13
Properties of R22, R417A and R417B

Condition	LT	MT	HT	LT	MT	HT	LT	MT	HT
Refrigerant	R22			R417A			R417B		
Composition	R22			R125/R134a/R600			R125/134a/600		
Mass percentage	100			46.6/60/3.4			79/18.3/2.7		
Boiling point (°C)	-40.80			-39.10			-45.20		
Critical Pressure (kPa)	4,990			4,036			3,737		
Critical Temperature (°C)	96			87			74		
ODP	0.055			0			0		
GWP	1,600			1,950			3,027		
Class	A1			A1			A1		
Lubricant type	MO			MO/AB/POE			MO/POE		
Qevap (kJ/kg)	138.71	144.16	134.47	92.27	101.79	92.37	71.27	79.91	59.79
Qcond (kJ/kg)	235.21	205.79	185.35	170.66	152.59	134.11	139.29	123.85	97.99
Work (kJ/kg)	96.50	61.63	50.88	78.39	50.79	41.74	68.02	43.93	38.21
COPc	1.44	2.34	2.64	1.18	2.00	2.21	1.05	1.82	1.57
Evaporator Pressure (kPa)	155.00	402.80	671.70	115.50	324.70	559.10	160.50	429.50	714.90
Condenser Pressure (kPa)	1,831.90	2,017.60	2,572.70	1,720.60	1,889.90	2,424.60	2,114.90	2,312.60	3,209.40
Evaporator Temp glide (°C)	0.00	0.00	0.00	-2.00	-2.10	-1.80	-1.50	-1.50	-1.00
Condenser Temp glide (°C)	0.00	0.00	0.00	2.60	2.50	2.10	1.60	1.50	0.90

Table 14
Properties of R422A, R422B and R422C

Condition	LT	MT	HT	LT	MT	HT	LT	MT	HT
Refrigerant	R422A			R422B			R422C		
Composition	R125/R134a/R600a			R125/R134a/R600a			R125/R134a/R600a		
Mass percentage	85.1/11.5/3.4			55/42/3			82/15/3		
Boiling point (°C)	-46.80			-41.59			-46.20		
Critical Pressure (kPa)	3,665			3,857			3,696		
Critical Temperature (°C)	72			82			72		
ODP	0			0			0		
GWP	2,530			2,526			3,085		
Class	A1			A1			A0		
Lubricant type	MO/AB/POE			MO/POE			MO/POE		
Qevap (kJ/kg)	65.84	88.62	N/A	86.33	95.54	85.69	68.21	76.65	N/A
Qcond (kJ/kg)	131.32	135.61	N/A	162.26	144.62	125.93	134.89	119.66	N/A
Work (kJ/kg)	65.48	46.99	N/A	75.92	49.09	40.23	66.68	43.00	N/A
COPc	1.01	-2.10	N/A	1.14	1.95	2.13	1.02	1.78	N/A
Evaporator Pressure (kPa)	178.40	385.30	N/A	125.80	351.00	601.20	170.30	451.30	N/A
Condenser Pressure (kPa)	2,233.50	2,149.10	N/A	1,835.80	2,014.30	2,575.90	2,184.90	2,387.30	N/A
Evaporator Temp glide (°C)	-1.10	-2.10	N/A	-2.30	-2.30	-1.90	-1.40	-1.30	N/A
Condenser Temp glide (°C)	1.00	2.00	N/A	2.50	2.40	1.90	1.20	1.10	N/A

Table 15
Properties of R422D, R424A and R437A

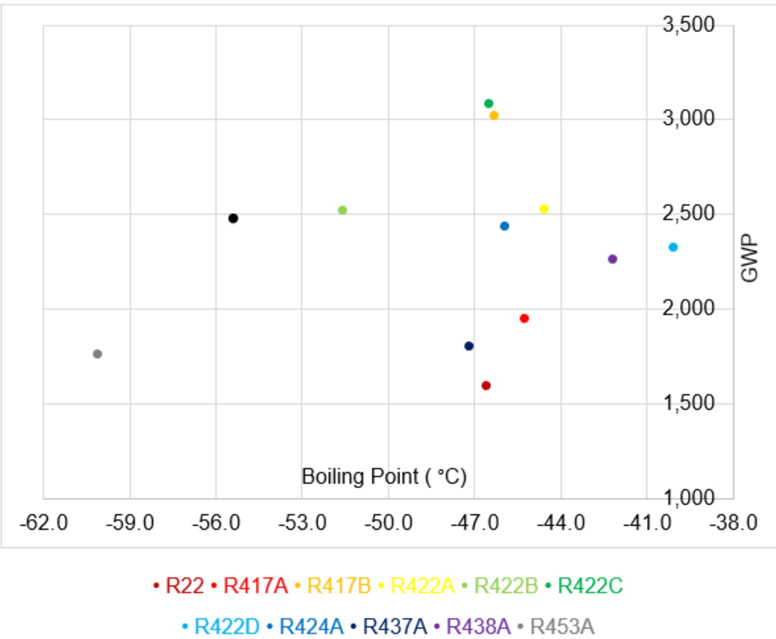
Condition	LT	MT	HT	LT	MT	HT	LT	MT	HT
Refrigerant	R422D			R424A			R437A		
Composition	R125/R134a/R600a			R125/R134a/R600/R600a/R601a			R125/134A/R600/R601		
Mass percentage	62.1/31.5/3.4			50.5/47/1/0.9/0.9			19.5/78.5/1.4/0.6		
Boiling point (°C)	-43.50			-38.70			-32.65		
Critical Pressure (kPa)	3,795			4,040			4,003		
Critical Temperature (°C)	80			89			95		
ODP	0			0			0		
GWP	2,330			2,440			1,805		
Class	A1			A1			A1		
Lubricant type	MO/AB/POE			MO/AB/POE			MO/POE		
Qevap (kJ/kg)	79.66	88.62	N/A	90.78	99.74	90.03	109.16	119.17	110.77
Qcond (kJ/kg)	152.44	135.61	N/A	167.43	149.68	131.16	194.69	174.79	156.70
Work (kJ/kg)	72.79	46.99	N/A	77.09	49.95	41.13	85.53	55.62	45.93
COPc	1.09	1.89	N/A	1.17	2.00	2.19	1.28	2.14	2.41
Evaporator Pressure (kPa)	140.50	385.30	N/A	117.00	329.10	566.50	87.60	254.80	448.00
Condenser Pressure (kPa)	1,961.70	2,149.10	N/A	1,743.60	1,915.10	2,465.80	1,422.10	1,568.30	2,031.60
Evaporator Temp glide (°C)	-2.10	-2.10	N/A	-2.20	-2.40	-2.00	-1.80	-2.00	-1.90
Condenser Temp glide (°C)	2.10	2.00	N/A	2.90	2.80	2.30	2.60	2.50	2.20

Table 16
Properties of R438A and R453A

Condition	LT	MT	HT	LT	MT	HT
Refrigerant	R438A			R453A		
Composition	R125/134A/R32/R600/R601a			R125/R32/R134A/R227ea/R600/R601A		
Mass percentage	45/44.2/8.5/1.7/0.6			20/20/53.8/5/0.6/0.6		
Boiling point (°C)	-42.61			-42.20		
Critical Pressure (kPa)	4,179			4,530		
Critical Temperature (°C)	84			88		
ODP	0			0		
GWP	2,265			1,765		
Class	A1			A1		
Lubricant type	MO/POE			MO/POE		
Qevap (kJ/kg)	103.36	112.02	101.50	184.91	178.36	165.49
Qcond (kJ/kg)	188.79	167.29	146.94	312.00	255.92	228.96
Work (kJ/kg)	85.43	55.28	45.44	127.56	77.56	63.47
COPc	1.21	2.03	2.23	1.45	2.30	2.61
Evaporator Pressure (kPa)	128.70	359.00	616.00	121.00	342.10	595.70
Condenser Pressure (kPa)	1,901.30	2,089.90	2,675.80	1,808.70	2,002.50	2,584.30
Evaporator Temp glide (°C)	-2.80	-3.00	-2.70	-5.20	-5.10	-4.70
Condenser Temp glide (°C)	3.90	3.70	3.10	5.00	4.80	4.20

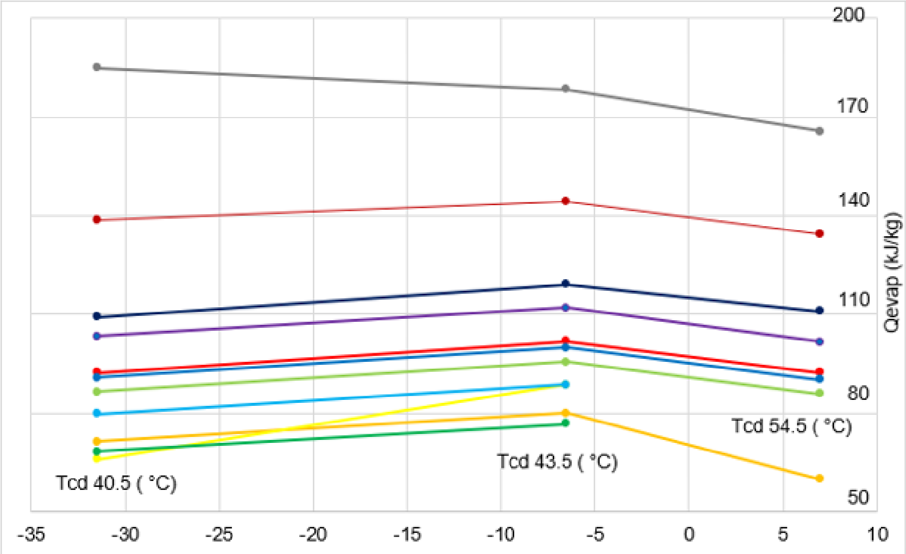
3. Results and Discussion

The results of the boiling point in Figure 8, shown in Figure 8 below, indicate that the lowest normal boiling point of R422A and R422C were -46.80 °C and R422C were -46.80 and -46.20, respectively, which was lower than that of R22 by 12.82% and 11.69%. This was due to hydrofluorocarbons (HFCs) R125 (85.1% and 82.0%) in its composition, which were consistent with those of R410A and R507. R410A and R507 displayed low boiling points of -51.6 and -46.74 °C, respectively, and are attractive as an alternative refrigerant to R134A and R404A, due to HFCs R125 contents of 50%, respectively, The Boiling point of R125 was -48.1 °C, witch high GWP values at 3,450 that effect to GWP of R422A and R422C displayed the highest GWP values at 3,143 and 3,185, respectively, The R422A and R422C have hydrocarbon (HCs) R601a (3%) in its composition. The boiling point and GWP of R601a was 0 and -11.73°C and, respectively, that effect to reduce GWP and add more boiling point. The Lower GWP compare with R22 in Figure 9 that R453A and R437A were 1,765 and 1,805, respectively, this was due to hydrofluorocarbons (HFCs) R134a (53.8% and 78.5%) in its composition and hydrofluorocarbons (HFCs) R32 (20%) in its composition for R453A, which consistent with the R407A, R407H and R407F that combine with R134a and R32 in R744 contents of 6% and 3%, respectively, in their compositions. The Boiling point and GWP will Inverse by adjusting the composition of the refrigerant that low-high GWP and boiling point. For refrigerant The R438A does not have the lowest GWP, it has a lower boiling point than R22. 4%, which can be substituted for R22 as it is a refrigerant with zero ODP.



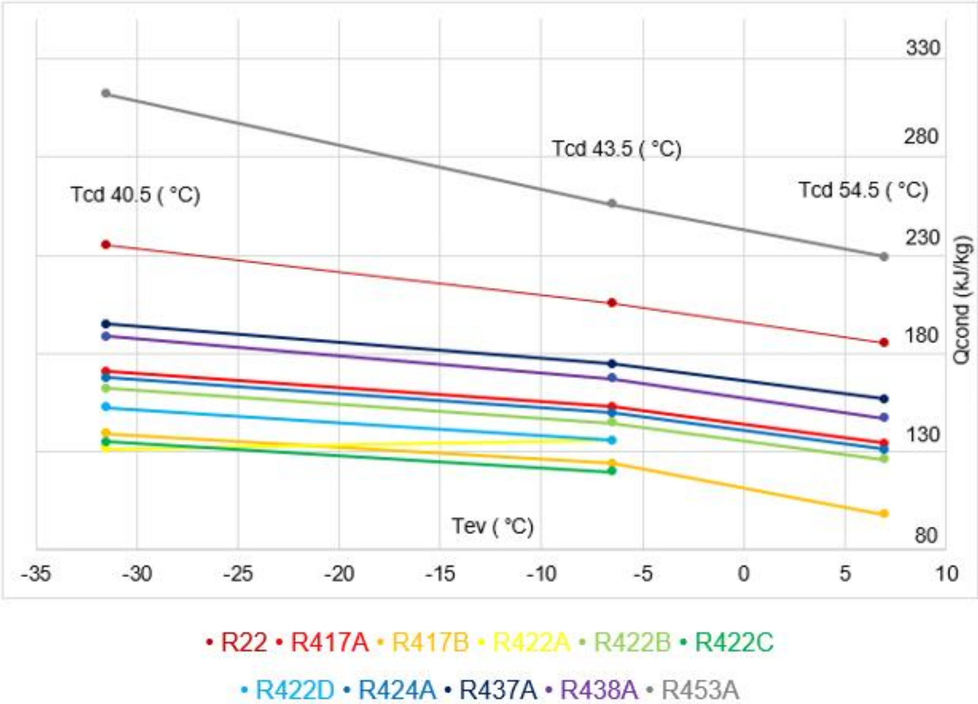
X axis is boiling point (°C)
Y axis is global warming potential
Fig. 8. GWP and Normal boiling point of all refrigerants

The result of the refrigerant effect in Figure 9 shows that R453A has the highest refrigerant effect, at 184.91, 178.36, and 165.49 kJ/kg for low, medium, and high conditions, respectively. This is 24.99%, 19.17% and 18.74 higher for low medium and high conditions, respectively, compared to R22.



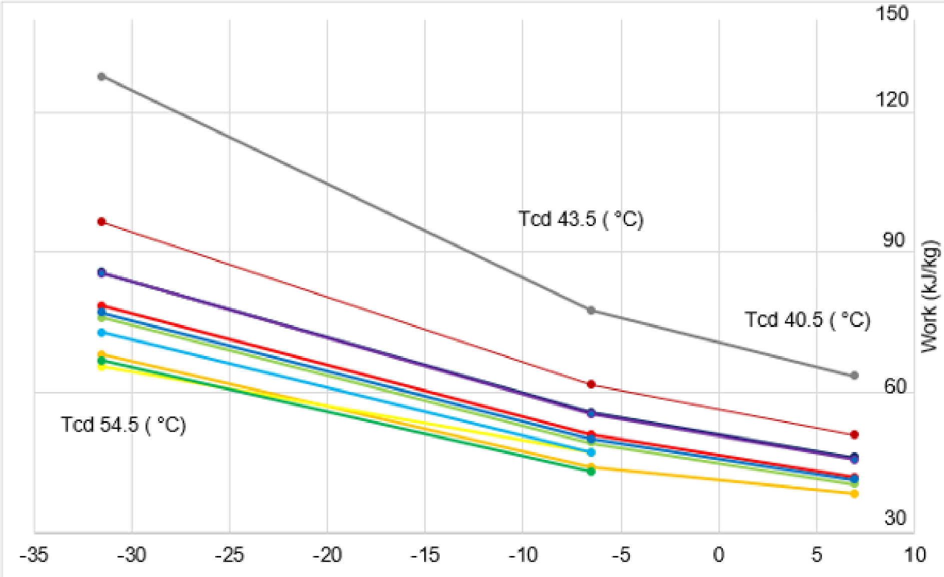
• R22 • R417A • R417B • R422A • R422B • R422C
• R422D • R424A • R437A • R438A • R453A
X axis is evaporator temperature (T_{ev})
Y axis is refrigerant effect Qevap (kJkg)
Fig. 9. Refrigerant effects of all refrigerants

The result of heat rejection, shown in Figure 10, indicates that the maximal heat-rejection values for R453A were 312.00, 255.92, and 228.96 kJ/kg for the low, medium, and high conditions, respectively, which were 24.61% ,19.59% and 19.05% higher for the low, medium and high conditions, respectively, compared to those of R22. The refrigerant effect and heat rejection of R453A were found to be higher than those of R22 due to the presence of 20% hydrofluorocarbons (HFCs) R32. The R453A combined with hydrocarbons (HCs) R600 (0.6%) due to the high Qevap (kJ/kg) and high Qcond (kJ/kg) at 235.72 , 261.99 and 255.88 kJ/kg for low, medium, and high conditions, respectively for Qevap and 400.21 , 371.49 and 348.29 for low medium and high conditions, respectively for Qcond, and combined with R601a due to the high Qevap (kJ/kg) and high Qcond (kJ/kg) at 221.18 , 248.05 and 244.65 kJ/kg for low, medium, and high conditions, respectively for Qevap and 374.81 , 350.99 and 331.95 kJ/kg for low medium and high conditions, respectively for Qcond. The mixed-refrigerant design should be comparable to natural refrigerants in terms of having a strong refrigerant effect and high heat rejection but for select hydrocarbons refrigerant type, such as R290 and R1270 refrigerant effect and high heat rejection. The Qevap for R290 were 221.85, 240.37 and 223.89 kJ/kg for low, medium, and high conditions, respectively and The Qcond for R290 were 338.96, 349.48 and 314.59 kJ/kg for low, medium, and high conditions, respectively. The Qevap for R1270 were 232.45, 247.13 and 228.13 kJ/kg for low, medium, and high conditions, respectively and The Qcond for R1270 were 404.89, 358.77 and 320.62 kJ/kg for low, medium, and high conditions, respectively. But. The R290 and R1270 high refrigerant work and high operating pressure that will affect to power consumptions of compressor.



X axis is evaporator temperature (Tev)
Y axis is heat rejection Qcond (kJkg
Fig. 10. Heat rejection of all refrigerants

The results of the refrigerant work, shown in Figure 11, demonstrate a relationship between evaporator pressure, shown in Figure 12, and condenser pressure, shown in Figure 13. Refrigerants operated under low pressure display low refrigerant work value; in this case, the lowest refrigerant work of R422A was found to be 65.48 and 46.99 kJ/kg for low and medium conditions, respectively. This refrigerant possesses HCs from R600a (3%) in its composition. R422A also demonstrated the low evaporator pressure at 178.40 and 385.30 kPa for low and medium conditions, respectively, and operated at the low evaporator pressure of 2,233.50 and 2,149.10 kPa for low and medium conditions, respectively. The R453. The highest refrigerant work values for R453A were 127.56, 77.56, and 63.47 kJ/kg, which contained operated at the high evaporator pressure of 121.00, 342.10, and 595.70 kPa for low, medium and high conditions, respectively, and operated at the highest evaporator pressure of 1808.70, 2002.50, and 2584.30 kPa for low, medium and high conditions, respectively. This means that a refrigerant system that is operated at low pressure should be mixed with refrigerants that can operate under low pressure, such as R1234yf, R1234ze, and R134A. R450A, R456A, R513A and R515A, which were mixed with hydrofluoroolefins (HFOs) and operated under low pressure, achieving similar results to R453A operating under high pressure with 20% hydrofluorocarbons (HFCs) R32 contents in its composition. Same as R438A, it has a lower refrigerant work than R22 due to low evaporator pressure and condenser pressure.



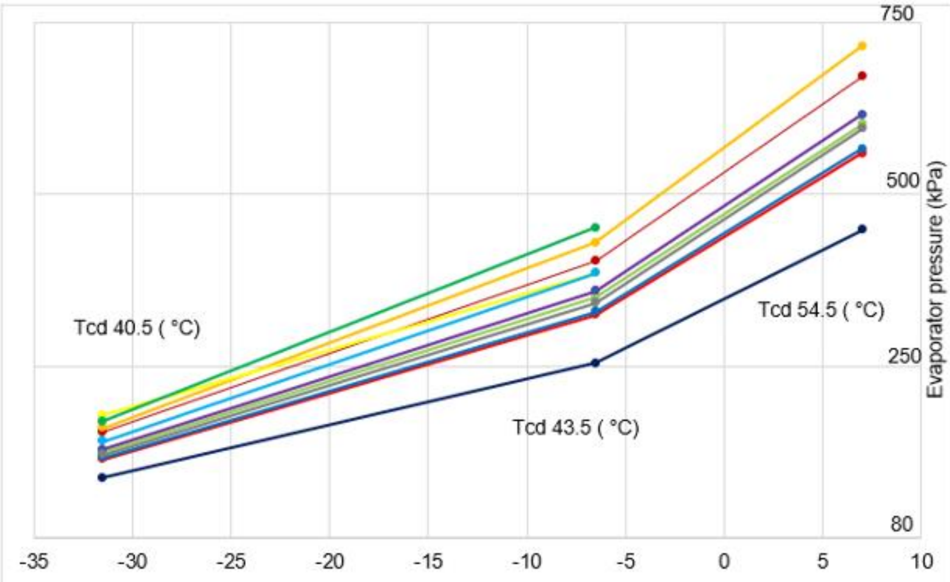
• R22 • R417A • R417B • R422A • R422B • R422C

• R422D • R424A • R437A • R438A • R453A

X axis is evaporator temperature (Tev)

Y axis is refrigerant work (kJkg)

Fig. 11. Refrigerant work of all refrigerants



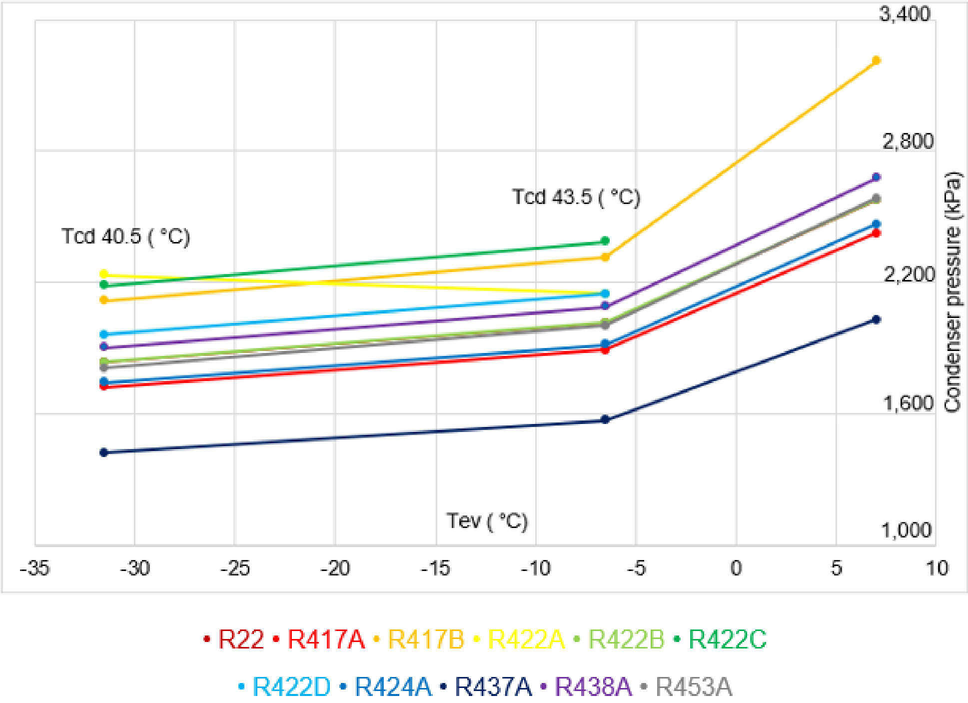
• R22 • R417A • R417B • R422A • R422B • R422C

• R422D • R424A • R437A • R438A • R453A

X axis is evaporator temperature (Tev)

Y axis is evaporator pressure (kPa)

Fig. 12. Evaporator pressure of all refrigerants



X axis is evaporator temperature (Tev)
Y axis is condensing pressure (kPa)
Fig. 13. Condenser pressure of all refrigerants

The COPc results in Figure 14 show that R453A had the highest COPc at 1.45, 2.3, and 2.607 for low, medium and high conditions, respectively, as R453A did not have the highest refrigerant effect and heat rejection, nor the lowest boiling point, but could be operated under low pressure, which has an impact on low refrigerant work. In this case, that show the hydrocarbon refrigerant mixture in hydrofluorocarbon blend as an alternative Refrigerant to R22 and COPc was nearly. This was due to hydrofluorocarbons (HCs) R600 (0.6%) and R601a (0.6%) that operated under low pressure, which has an impact on low refrigerant work and having a strong refrigerant effect and high heat rejection that affect COPc of R453A was nearly to R22. Hydrofluorocarbons can also be combined with hydrofluorocarbons (HCs), which has a lower GWP, boiling point and high COPc. The lower GWP, boiling point and high COPc are consistent with the evolution of the fourth-generation refrigerants that contain a mixture of HFCs, HFOs, HCs, and natural refrigerants, which are required to produce a low-GWP, zero-ODP, high-capacity, low-operating-pressure, and nontoxic refrigerant. This shows that a mixed-refrigerant design should consider all parameters, such as the GWP, boiling point, Cp liquid/vapor and liquid/vapor conductivity, refrigerant effect, heat rejection, refrigerant work, evaporator pressure, high pressure, and COPc. Although R438A does not have the highest COPc, it still has a higher and closer COPc than R22.

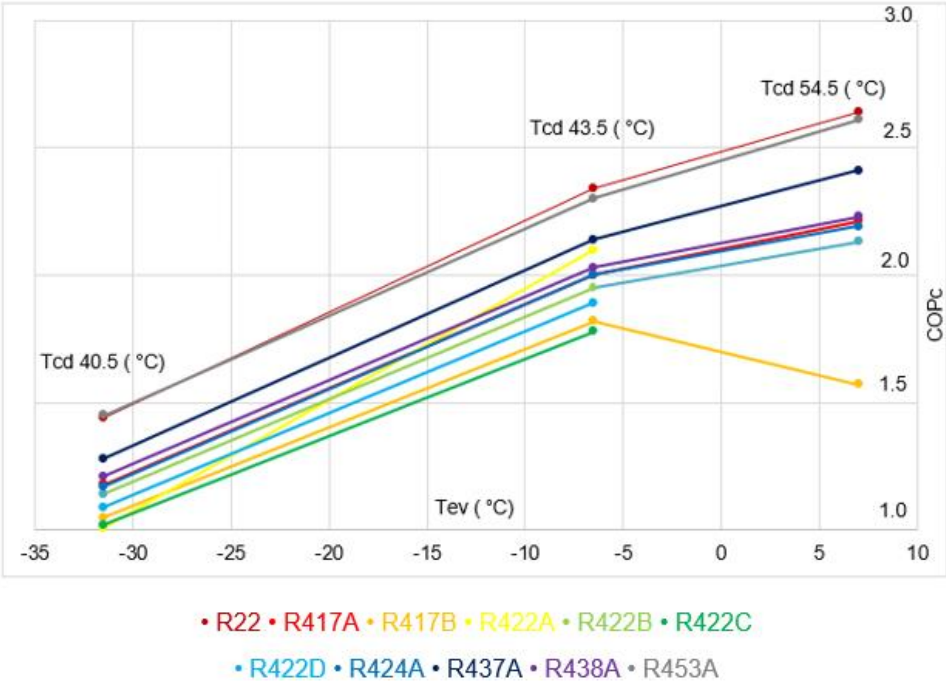


Fig. 14. Cooling coefficient of performance (COPc) for all refrigerants

4. Conclusions

The results for hydrocarbon refrigerant mixture in hydrofluorocarbon blend as an Alternative Refrigerant to R22 using REFPROP and CYCLE_D-HX software, and following the CAN/ANSI/AHRI540 AHRI standards, indicate that COPc of R438A zero ODP, 2,265 GWP nearby R22 0.055 ODP, 1600 GWP. This means that the mixed-refrigerant design should consider all of the parameters, such as the GWP, boiling point, Cp liquid/vapor and liquid/vapor conductivity, refrigerant effect, heat rejection, refrigerant work, evaporator pressure, high pressure, and COPc. R438A is another alternate refrigerant option that is composed of 2.3% hydrocarbon (HCs), and is consistent with the evolution of the fourth-generation refrigerants that contain a mixture of HFCs, HFOs, HCs, and natural refrigerants, which are required to produce a low-GWP, zero-ODP, high-capacity, low-operating-pressure, and nontoxic refrigerant. In the future, researchers should incorporate HCs at contents above 3.4% (R422A and R422D) in order to use natural refrigerants that are low-cost. The problems of high evaporator pressure and high condenser pressure that impact high refrigerant work can be solved by adjusting the composition of the refrigerant or mix using a refrigerant that operates at low pressure, thereby improving the COPc of the refrigerant.

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