Investigation and analysis of green refrigerant zero ODP as an alternative refrigerant lower cost and GWP

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Abstract:

This research presents the development of hydrocarbon refrigerant mixture in hydrofluorocarbon blend, a non-flammable refrigerant that was retrofitted to replace R22. The properties of all refrigerant, as analyzed using national institute of standards and technology (NIST) reference fluid thermodynamic and transport properties database (REFPROP) software and NIST vapor compression cycle model accounting for refrigerant thermodynamic and transport properties (CYCLE_D-HX) software, are in accordance with the CAN/ANSI/AHRI540 standards of the Air-Conditioning, Heating, and Refrigeration Institute (AHRI). The results of this research showed. The cooling coefficient of performance (COPc) of R453A was nearly R22 at all condition with zero ODP. The R453A can be retrofitted to replace R22A due to its composition of POE, Class A1 incombustibility, and lower toxicity. R453A is another alternate refrigerant option that is composed of 1.2% hydrocarbon (HCs) R600 (0.6%) and R601a (0.6%), and is consistent with the evolution of fourth-generation refrigerants that contain a mixture of HFCs, HFOs, HCs, and natural refrigerants, which are required to produce a low-GWP, zero-ozone-depletion-potential (ODP), high-capacity, low-operating-pressure, and nontoxic refrigerant.

Keywords: hydrocarbon refrigerant, refrigeration system, energy technology; environmentally friendly
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 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.

Refrigerant trends in Thailand have shown improvements in increasing energy efficiency and decreasing global-warming potential (GWP), as shown in Figure 3 [8,9], which is related to the hydrofluorocarbon (HFC) phase-down schedule, as shown in Figure 4 [10]. First- and second-generation refrigerants were composed of natural refrigerants and hydrocarbons (HCs), both of which do not impact the environment, have low GWP, and zero ozone-depletion potential (ODP) [11–13]. R744 operates under high pressure, and is highly toxic and flammable (Figure 5) [14–16]. Following the second generation, third-generation refrigerants were composed of chlorofluorocarbons (CFCs) [17–19] and hydrochlorofluorocarbon (HCFCs) [20–22], which are easy to use, can operate under low pressure, and are nontoxic. However, they have high GWP and ODP, contributing to ozone depletion and global warming. Therefore, the development of refrigerants has significantly decreased ODP and GWP. Moreover, third-generation refrigerants, CFCs and HCHCs, were further developed into hydrofluorocarbon (HFC) refrigerants that still possessed low GWP and zero-ODP [23–25]. Fourth-generation refrigerants are mainly hydrofluoroolefins (HFOs) with low GWP and low capacity [26–28]. Therefore, they are refrigerants that are mixed with HFCs [29–31], HFOs [32–34], and HCs [35–37]. Natural refrigerants are low-GWP, zero-ODP, high-capacity, low-pressure, and nontoxic [38–40].

For the refrigerant used in food industry as shown in Figure 5 below, that show the first refrigerants was R404A of 40%, that have refrigerants develop for R404A [41], R407A [42], R407F [43], R407H [44], R410A [45], R442A [46], R448A [47], R449A [48], R452A [49], R453A [50], and R463A [51] were developed to be retrofitted to replace R404A, and are mixed with HCs, HFOs, R134A, R32 and R744. These conform to the refrigerant-development trend and are an alternate option that can be mixed with HFC. The refrigerant proportion that was mixed with R125 was more or less similar to that of the R32 mixture, and it also possesses Class A1 nonflammability property [42-51]. Moreover, the second rank of
refrigerant used in food industry was R22 of 25% and the refrigerant was the basis for this research, and it is currently the most used refrigerant, that mean R22 still used in present and need to retrofit to refrigerants are low-GWP, zero-ODP, high-capacity, low-pressure, and nontoxic [9]. For the cost of refrigerant as shown in Figure 6 below [43], the refrigerant should be mixed with HFOs [52-54]. It also highest refrigerant cost but does not include HCs refrigerant cost compare with HFOs refrigerant cost, which is being presented as a refrigerant for comparative purposes in this research as it is composed of HCs [55-57] as showed on table 1-2.

The properties of hydrocarbon refrigerant that class A3 high flammability as shown in Figure 7 below but zero ODP and GWP nearly zero, shown in Table 1 for R170 [58], R290 [59], R600 [60], R600a [61] and Table 2 for R601 [62], R601a [63], R1150 [64], R1270 [65]. The highest boiling of R170 and R1270 were found to be -88.70 °C and -103.8 °C respectively but the critical temperature was found to be 32.17 °C and 9.5 °C. This means those are refrigerant that cannot operated in refrigerant in accordance with the CAN/ANSI/AHRI540 Air-Conditioning, Heating, and Refrigeration Institute (AHRI) standards that standard for this research [66-68]. The R290 and R1270 were found to be nearly boiling point with R22 at -42.1. °C and -47.7 °C respectively but operate at high condenser pressure that will affect to refrigerant work and cooling coefficient of performance. as a result, Therefore, the R600, R600a, R601, R601a should be mix with HFC for alternative refrigerant.

**Material and Methods**

The properties of all refrigerants, summarized in Tables 4–7, conform to the use of REFPROP [69-71] and CYCLE_D-HX [72–74] software, as stipulated by the National Institute of Standards and Technology (NIST) [75–77], and are in accordance with the CAN/ANSI/AHRI540 Air-Conditioning, Heating, and Refrigeration Institute (AHRI) standards, as shown in Table 3 [66-68]. Both software programs can redefine 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. Results illustrated the relationship of all parameters for R417A [78], R417B [79], R422A [80], R422B [81], R422C [82], R422D [83], R424A [84], R437A [85], R438A [86] and R453A [50], such as GWP, boiling point, refrigerant effect, heat rejection, refrigerant work, evaporator pressure, high pressure, and cooling coefficient of performance (COPc), as shown in Tables 4–7 [88-91].
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, which 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.

The result of the refrigerant effect in Figure 10 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. The result of heat rejection, shown in Figure 11, 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.
The results of the refrigerant work, shown in Figure 12, demonstrate a relationship between evaporator pressure, shown in Figure 13, and condenser pressure, shown in Figure 14. 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.

The COPc results in Figure 15 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.
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 R453A zero ODP, 1765 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. R453A is another alternate refrigerant option that is composed of 1.2% 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 COP of the refrigerant.

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Conflict of Interest

"The authors declare no conflict of interest".

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List of Tables

Table 1. Properties of R170, R290, R600, R600a.

| Condition     | LT       | MT       | HT       | LT       | MT       | HT       | LT       | MT       | HT       |
|---------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| Refrigerant   | R170 [58]| R290 [59]| R600 [60]|          |          |          |          |          |          |
| Formula       | C2H6     | C3H8     | C4H10    |          |          |          |          |          |          |
| Chemical name | Ethane   | Propane  | Butane   |          |          |          |          |          |          |
| Boiling point (°C) | -88.7  | -42.1    | -0.5     |          |          |          |          |          |          |
| Critical Pressure (kPa) | 4872   | 4251     | 3796     |          |          |          |          |          |          |
| Critical Temperature (°C) | 32.17  | 96.74    | 151.98   |          |          |          |          |          |          |
| ODP           | 0        | 0        | 0        |          |          |          |          |          |          |
| GWP           | 3        | 3        | 3        |          |          |          |          |          |          |
| Class         | A3       | A3       | A3       |          |          |          |          |          |          |
| Lubricant type | MO/POE  | MO/POE   | MO/POE   |          |          |          |          |          |          |
| Qevap (kJ/kg) | N/A      | N/A      | N/A      | 388.96   | 240.37   | 223.89   | 235.72   | 261.99   | 255.88   |
| Qcond (kJ/kg) | N/A      | N/A      | N/A      | 221.85   | 349.48   | 314.59   | 400.21   | 371.49   | 348.29   |
| Work (kJ/kg)  | N/A      | N/A      | N/A      | 221.85   | 109.11   | 90.70    | 164.50   | 109.51   | 92.41    |
| COPc          | N/A      | N/A      | N/A      | 1.33     | 2.20     | 2.47     | 1.43     | 2.39     | 2.77     |
| Evaporator Pressure (kPa) | N/A  | N/A      | N/A      | 157.70   | 385.90   | 623.90   | 26.20    | 80.20    | 145.60   |
| Condenser Pressure (kPa)  | N/A   | N/A      | N/A      | 1653.10  | 1803.10  | 2269.40  | 484.30   | 535.40   | 705.00   |
|                 |          |          |          |          |          |          |          |          |          |
| 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 |
Table 4. Properties of R22, R417A and R417B

| Condition          | LT  | MT  | HT  | LT  | MT  | HT  | LT  | MT  | HT  |
|--------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Refrigerant        | R22 [87] | R417A [78] | R417B [79] |
| Composition 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)      | 138.7 | 144.1 | 134.4 | 101.7 |
| Qcond (kJ/kg)      | 235.2 | 205.7 | 185.3 | 170.6 | 152.5 | 134.1 | 139.2 | 123.8 |
| 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) | 1,831 | 2,017 | 2,572 | 1,720 | 1,889 | 2,424 | 2,114 | 2,312 | 3,209 |
| Condenser Pressure (kPa) | 90 | 60 | 70 | 60 | 90 | 60 | 90 | 60 | 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 5. Properties of R422A, R422B and R422C

| Condition          | LT  | MT  | HT  | LT  | MT  | HT  | LT  | MT  | HT  |
|--------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Refrigerant        | R422A [92] | R422B [93] | R422C [94] |
| Composition        | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| Refrigerant | R422A [80] | R422B [81] | R422C [82] |
|-------------|------------|------------|------------|
| 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 \(^\circ\text{C}\) | -46.80 | -41.59 | -46.20 |
| Critical Pressure (kPa) | 3,665 | 3,857 | 3,696 |
| Critical Temperature \(^\circ\text{C}\) | 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 |
| Qcond (kJ/kg) | 131.32 | 135.61 | N/A |
| Work (kJ/kg) | 65.48 | 46.99 | N/A |
| COPc | 1.01 | -2.10 | N/A |
| Evaporator Pressure (kPa) | 178.40 | 385.30 | N/A |
| Evaporator Condenser Pressure (kPa) | 2,233. | 2,149. | N/A |
| Evaporator Temp glide \(^\circ\text{C}\) | -1.10 | -2.10 | N/A |
| Condenser Temp glide \(^\circ\text{C}\) | 1.00 | 2.00 | N/A |

Table 6. Properties of R422D, R424A and R437A
| Condition | LT | MT | HT | LT | MT | HT |
|-----------|----|----|----|----|----|----|
| Refrigerant | R438A [86] | | | R453A [50] | | |
| Composition | R125/134A/R32/R600/R601a | | | A | | |
| 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 | | |
| Qe vap (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) | 1,901.3 | 2,089.9 | 2,675.8 | | | |
| Evaporator Temp glide (°C) | -2.80 | -3.00 | -2.70 | -5.20 | -5.10 | -4.70 |
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