ENERGY PERFORMANCE ASSESSMENT OF VIRTUALLY NON-FLAMMABLE MIXTURES FOR R134a APPLICATIONS

by

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In this study, three new mixed refrigerants with low GWP values, R1234yf/R134a, R1234yf/R125, and R1234yf/R13I1, were evaluated as replacements for R134a refrigerant using two vapor compression configurations. The experiment revealed that these mixtures can be used as environmentally friendly alternatives for this configuration.

Key words: *R1234yf, R125, R13I1, R134a, vapor compression system*

Introduction

Global warming has been one of the most important problems facing mankind, and it has caused series energy crisis. Many kinds of energy saving devices were appeared, including the spring-pendulum systems [1, 2], microelectromechanical systems [3-5] and Fangzhu system [6]. Now the energy saving technology became a useful tool in various fields, *e.g.* architectural engineering [7], for control and optimization of energy consumption [8, 9]. This article focuses on low GWP refrigerants [10], because recently R134a refrigerant was identified as one of the controlled GHG. In the near future, it needs to be replaced by more environmentally friendly refrigerants [11]. Low GWP refrigerants, which are considered as R134a alternatives, include HC, R152a, and CO_2. The performance of HC has competitive advantages over R134a [12]. However, HC may lead to unsafe conditions because of their high flammability. The properties of R152a are similar to those of R134a [13]. The COP of R152a is higher than that of R134a, while the cooling capacity is slightly lower than that of R134a. However, R152a is not recommended because of its flammability and high compressor discharge temperature. Meanwhile, CO_2, the natural refrigerant, is non-flammable. The performance of the vapor compression system using CO_2 was competitive [14], however, the system requires major modifications because CO_2 operates on a trans-critical cycle.

Recently, R1234yf refrigerant has been considered as an alternative to R134a. For the thermodynamic properties of R134a and R1234yf, most of the work in the literature focused on flow boiling and condensing heat transfer coefficients inside tubes [15, 16]. The test results showed that the boiling and condensing heat transfer coefficients of R134a and

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R1234yf are quite close. Several studies were carried out to investigate the performance of the two refrigerants. An experimental comparison between R134a and R1234yf in a household refrigerator of the frost-free type was presented, showing that a slight energy saving with R1234yf and an improvement of the cooling capacity have been noticed [17]. A comparative experimental analysis between R134a, R1234yf, and a refrigerant mixture of R134a/R1234yf (10/90% weight) was carried on, showing that the mixture became non-flammable with a GWP value below 150. The refrigerant mixture has a close behavior to that of R134a [18]. In an experimental study on three identical domestic refrigerators using R1234yf as a drop-in replacement for R134a, the optimal charge for R1234yf resulted in 7.8% lower than the one for R134a, representing a small increase of 4% in energy consumption compared to R134a [18]. Some studies [19-22] compared the performance of the two refrigerants in a vapor compression system by controlling the evaporation and condensation temperatures. The experimental results showed that the cooling capacity of R1234yf was about 9% lower than that of R134a, while its volumetric efficiency was lower than that of R134a by approximately 5%. The COP of R1234yf was 5%-30% lower than that obtained with R134a within the test range.

At present, R1234yf is the lowest cost alternative in the manufacturers. The main problem with R1234yf is its mild-flammability [23]. Flammability of R1234yf is relatively low, however, compared with these non-flammable refrigerants, it may bring some insecurity. In Europe, R1234yf was rejected by a major car manufacturer due to the flammable problems in the actual situation. In fact, a European manufacturer has provided the authorities with a survey on the safe use of the R1234yf. This corresponds to a severe head-on collision, in which the refrigerant line could be damaged, releasing R1234yf into the exhaust system, thus causing a fire. Therefore, some companies like to use the safe R134a in their cars, instead of R1234yf.

In this study, three mixtures R1234yf/R134a, R1234yf/R125 and R1234yf/R13I1 (90%/10%, 95%/5% and 90%/10%, by mass) were proposed to replace R134a in various applications, such as automotive air conditioners, beverage coolers and centrifugal coolers. By adding the flame retardants to R1234yf, the mixtures become virtually non-flammable with GWP still less than 150. Therefore, they can successfully solve the main problem of R1234yf's flammability. The aim of this work is to compare theoretically the energy performance of two vapor compression refrigeration configurations and to provide the data with comparison against R134a and the proposed refrigerants.

Thermodynamic analysis

Fluid properties

The environmental and physical properties of refrigerants are shown in tab. 1. All the thermodynamic properties were obtained from the REFPROP 9.1 [24]. The GWP values of R1234yf, R1234yf/R134a, R1234yf/R125, and R1234yf/R13I1 are, respectively, 4, 147, 143, and 4, much lower than that of R134a. The temperature glide of R1234yf/R134a and R1234yf/R13I1 is near 0 °C, and the temperature glide of R1234yf/R125 is lower than 1.74 °C in the pressure range of 0.1-1.5 MPa. The critical temperature and critical pressure of all compared refrigerants were found to be lower than those of R134a. This indicates that COP may be lower under the same condensation and evaporation temperature condition.

Table 1. Properties of the refrigerants

Refrigerant	R134a	R1234yf	R1234yf/R134a	R1234yf/R125	R1234yf/R13I1
Ozone depression potential	0	0	0	0	0
GWP	1300	4	147	143	4
Normal boiling point [°C]	–26.1	–29.5	–30.7	–32.0	–29.1
Critical temperature [°C]	101.1	94.7	95.4	93.14	96.5
Critical pressure [MPa]	4.05	3.38	3.40	3.42	3.42
Temperature glide [°C; 0.1-1.5 MPa]	0	0	<0.1	<1.74	<0.21
Latent heat [kJkg^{-1}; 5 °C]	194.7	160.1	168.1	159.5	153.9
Liquid density [kJkg^{-1}; 5 °C]	1278.1	1160.4	1172.6	1167.2	1216
Liquid therm. cond. [mWm^{-1}K^{-1}; 5 °C]	89.8	69.9	71.8	65.7	65.4
Liquid viscosity [μPa·s; 5 °C]	250.1	197.1	201.2	195.25	203.1

Refrigerants flammable property was also tested. The results showed that R1234yf/R134a mixture became non-flammable with more than 10% of R134a [23]. The inhibition coefficients of R125 and R13I1 are four times and two times higher than that of R134a, respectively [25]. The mass ratio of R1234yf/R125 was chosen to maximize the mass fraction of R125, in order to ensure the mixture is predicted non-flammable, while the GWP value continues to be less than 150. The mass ratio of R1234yf/R13I1 was chosen to ensure the mixture is non-flammable because the GWP of the mixture is very low.

Table 1 lists the latent heat, liquid density, liquid thermal conductivity and liquid viscosity of the proposed refrigerants at 5 °C. These reflect generally the trend of these refrigerants within a broader temperature range. It was observed that all compared refrigerants had a lower latent heat compared to R134a. The lower latent heat leads to a decrease in the cooling capacity of the system, which increases the running time of the compressor. The liquid density of all compared refrigerants was found to be lower than that of R134a. This indicates that the optimal refrigerant charge requirement can be less than R134a. The liquid thermal conductivity of all compared refrigerants was determined to be lower than that of R134a, which results in lower heat exchanger efficiency. The liquid viscosity of all compared refrigerants was found to be lower than that of R134a, resulting in low friction (low irreversibility).

Configurations selected

In this paper, two vapor compression configurations are considered: basic cycle, and basic cycle with internal heat exchanger. Diagram and *P-h* cycle of configurations is shown in fig. 1. Basic cycle mainly includes compressor, condenser, throttle and evaporator. Basic cycle with internal heat exchanger configuration is achieved by adding a heat exchanger between the suction and the liquid line. Cooling the liquid line, the refrigerant entering in the evaporator has a lower enthalpy, and the refrigerating effect in it is greater. On the other hand, suction gas is heated, this can cause higher gas discharge temperature. The COP variation could be positive or negative, depending on the studied refrigerant.

In order to calculate the thermodynamic cycle of the vapor compression system, some assumptions are made. The compressor isentropic efficiency and volumetric efficiency are 0.75 and 0.8, respectively. The compressor has a constant stroke volume of 33 cc/rev and

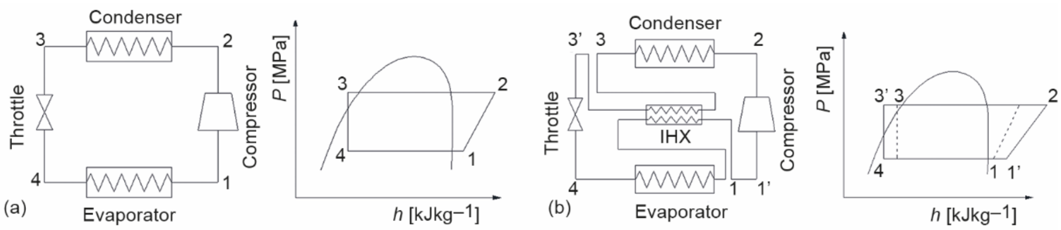

Figure 1. Diagram and *P-h* cycle of configurations; (a) basic cycle and (b) basic cycle with internal heat exchanger

a constant speed of 3000 rpm. There is no pressure drop in condenser, evaporator, and connection pipelines tubes. The system does not have the loss of heat exchange with the outside. Heat exchange efficiency in internal heat exchanger is 0.3 (in order to avoid high discharge temperatures).

Some important performance characteristics such as volumetric cooling capacity, *VCC*, cooling capacity, Q_c, compressor power consumption, *P*, COP, mass-flow rate, $\dot{m}_r$, pressure ratio, *PR*, and heat exchange efficiency in internal heat exchanger, ε_{IHX}, were estimated:

$$VCC = \frac{(h_{e.o} - h_{e.i})\eta_{vol}}{v_1} \tag{1}$$

$$Q_c = \dot{m}_r (h_{e.o} - h_{e.i}) \tag{2}$$

$$P = \frac{\dot{m}_r (h_{com.o} - h_{com.i})}{\eta_{is}} \tag{3}$$

$$COP = \frac{Q_c}{P} \tag{4}$$

$$PR = \frac{p_c}{p_e} \tag{5}$$

$$\dot{m}_r = \frac{RPM}{60} V_{dis} \rho_1 \eta_{vol} \tag{6}$$

$$\varepsilon_{IHX} = \frac{T_{suc} - T_{e.out}}{T_{c.out} - T_{e.out}} \tag{7}$$

where *h* is the enthalpy, η_{vol} – the volumetric efficiency, η_{is} – the isentropic efficiency, v_1 – the specific volume at compressor inlet, *RPM* – the compressor speed, p_c and p_e – the condensation pressure and evaporation pressure, respectively.

Relative deviations from baselines R134a are given in:

$$\%P = \frac{P_{alternative} - P_{baseline}}{P_{baseline}} 100 \tag{8}$$

$$\%VCC = \frac{VCC_{\text{alternative}} - VCC_{\text{baseline}}}{VCC_{\text{baseline}}}100 \tag{9}$$

$$\%COP = \frac{COP_{\text{alternative}} - COP_{\text{baseline}}}{COP_{\text{baseline}}}100 \tag{10}$$

$$\Delta T_{\text{dis}} = T_{\text{dis.alternative}} - T_{\text{dis.baseline}} \tag{11}$$

Simulation conditions

Standard working conditions and variable working conditions are combined to simulate the performance for the vapor compression cycle. Standard working condition is as follows: the evaporation temperature and condensation temperature are 7.2 and 54.4 °C, respectively, the super-cooling and super-heating temperature are both 2 °C. Variable working conditions are shown in tab. 2. The evaporation temperature and the condensation temperature are –20/10 °C and 30/60 °C, respectively, the super-cooling and the super-heating temperature are both 2 °C. The evaporation temperature and condensation temperature are selected as the maximum and minimum possible temperatures. This represents the maximum and minimum performance difference between alternative refrigerants and R134a, and then the average performance difference can be obtained.

Table 2. Variable working conditions

Condition	Evaporation temperature	Condensation temperature
1	–20 °C	30 °C
2	10 °C	
3	–20 °C	60 °C
4	10 °C	

Analysis of standard working conditions

Table 3 lists the performance of the refrigerants under standard working conditions. The performance of alternative refrigerants is compared with R134a basic cycle. It can be seen from the table that the pressure ratio of all compared refrigerants is found be lower. While the mass-flow rate of all compared refrigerants is found to be higher. Volumetric cooling capacity is a major factor affecting the size of the compressor. Alternative refrigerant does not need to change the original compressor when it has the similar volumetric cooling capacity with the substituted refrigerant. For basic cycle, the volumetric cooling capacity of R1234yf and R1234yf/R13I1 is slightly insufficient. In terms of system performance, COP of R134a is better than that of all compared refrigerants. The COP of R1234yf is slightly larger than that of R1234yf/R125. While the COP of R1234yf/R134a and R1234yf/R13I1 is larger than that of R1234yf. Compressor discharge temperature of all compared refrigerants is lower. For the basic cycle with internal heat exchanger, the volumetric cooling capacity of R1234yf and R1234yf/R13I1 is increased compared to it in basic cycle, while the volumetric cooling capacity of R1234yf/R134a and R1234yf/R125 is almost the same as that of R134a. The COP of all compared refrigerants has improved compared with these in basic cycle, however, it is still less than that of R134a. Compressor discharge temperature of all compared refrigerants is slightly higher than that of R134a.

Table 3. The refrigerants performance under standard working conditions

Refrigerating cycle	Refrigerant	Mass-flow rate [kgh^{-1}]	Volumetric cooling capacity [kJm^{-3}]	Compressor power consumption [W]	COP	Pressure ratio	Compressor discharge temperature [°C]
Basic cycle	R125	164.89	2653.72	1128.61	2.59	3.35	64.51
	R13I1	83.19	1502.17	454.75	3.63	3.60	77.46
	R1234yf	69.68	1695.45	589.73	3.16	3.61	59.34
	R1234yf/R134a	72.59	1775.09	618.94	3.15	3.60	60.27
	R1234yf/R125	69.60	1652.14	577.43	3.15	3.57	59.47
	R1234yf/R13I1	70.94	1685.03	579.35	3.20	3.61	59.95
Basic cycle with internal heat exchanger	R125	151.82	2894.61	1153.29	2.76	3.35	75.60
	R13I1	78.44	1511.55	456.11	3.65	3.60	91.65
	R1234yf	65.22	1791.73	597.12	3.30	3.61	71.42
	R1234yf/R134a	67.88	1873.23	626.51	3.29	3.60	72.34
	R1234yf/R125	69.72	1873.50	626.92	3.29	3.57	71.46
	R1234yf/R13I1	66.44	1773.90	586.14	3.33	3.61	72.14
Basic cycle	R134a	57.80	1886.82	610.76	3.40	3.90	68.88

Analysis of variable working conditions

The compressor power consumption of the refrigerants is shown in fig. 2. For the basic cycle, the average compressor power consumption of R1234yf and R1234yf/R13I1 is about 0.5% and 2.3% lower than that of R134a, respectively. While the R1234yf/R134a and R1234yf/R125 is 0.9% and 2.8% higher than that of R134a, respectively. When the evaporation temperature is low, the compressor power consumption of R1234yf, R1234yf/R134a, R1234yf/R125 exhibits a tendency that is higher than that of R134a as the condensation temperature increases. When the condensation temperature is constant, with the increase of evap-

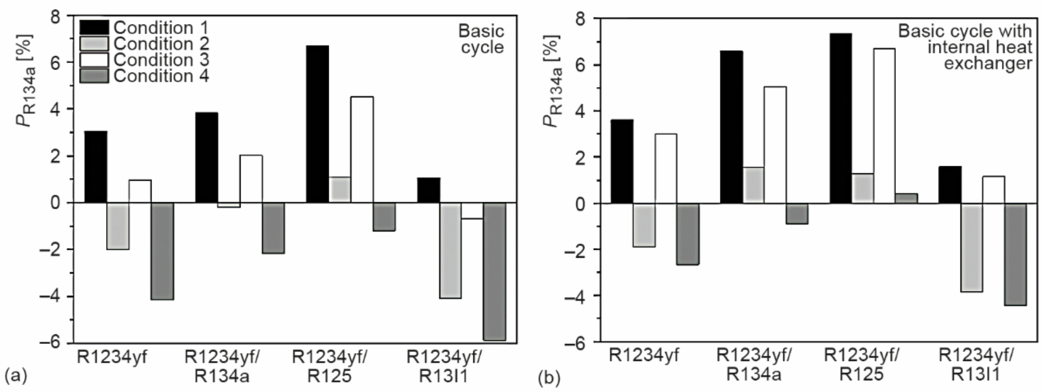

Figure 2. Compressor power consumption compared with R134a (without internal heat exchanger); (a) for basic cycle and (b) for basic cycle with internal heat exchanger

oration temperature, the compressor power consumption of R1234yf, R1234yf/R134a, and R1234yf/R125 exhibits a trend that is firstly more than and then less than that of R134a. However, the compressor power consumption of R1234yf/R13I1 only larger than that of R134a under the low condensation and evaporation temperature. For the basic cycle with internal heat exchanger, the average compressor power consumption of R1234yf, R1234yf/R134a, and R1234yf/R125 is 0.5%, 3%, and 4% higher than that of R134a, respectively. While the R1234yf/R13I1 is 1.3% lower than that of R134a.

The volumetric cooling capacity of the refrigerants is shown in fig. 3. For the basic cycle, the average volumetric cooling capacity of R1234yf, R1234yf/R134a, R1234yf/R125, and R1234yf/R13I1 is 8.2%, 5.5%, 5%, and 8.6% less than that of R134a, respectively. Volumetric cooling capacity of alternative refrigerants should be controlled in the range of –8-8% compared to that of original refrigerant. The volumetric cooling capacity of R1234yf and R1234yf/R134a is slightly insufficient, so the original compressor needs to be increased when replacing. While R1234yf/R134a and R1234yf/R125 can be directly charged. For these refrigerants, the deviation is higher at high condensation temperature. For the basic cycle with internal heat exchanger, the volumetric cooling capacity of the alternative refrigerants are greatly improved. The average volumetric cooling capacity of R1234yf, R1234yf/R134a, R1234yf/R125, and R1234yf/R13I1 is 2%, 1.5%, 1%, and 3% less than that of R134a, respectively. These refrigerants are very beneficial to direct charging. Volumetric cooling capacity of the alternative refrigerants shows a trend that is larger than that of R134a at the low evaporation temperature and the condensation temperature range. At lower evaporation temperature, the volumetric cooling capacity of alternative refrigerants increases substantially as compared to it in the basic cycle.

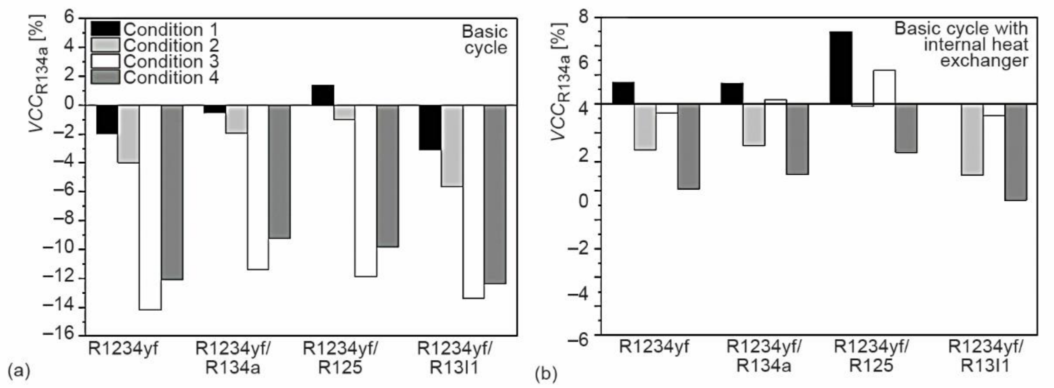

Figure 3. Volumetric cooling capacity compared with R134a (without internal heat exchanger); (a) for basic cycle and (b) for basic cycle with internal heat exchanger

The COP of the refrigerants is shown in fig. 4. For the basic cycle, the average COP of R1234yf, R1234yf/R134a, R1234yf/R125, and R1234yf/R13I1 is 7.5%, 6.5%, 8%, and 6% lower than that of R134a, respectively. The deviation is larger at high condensation temperature, and it decreases with the increase of evaporation temperature and increases with the increase of condensation temperature. For the basic cycle with internal heat exchanger, the COP of alternative refrigerants has improved considerably. The average COP of R1234yf, R1234yf/R134a, R1234yf/R125, and R1234yf/R13I1 are 2.5%, 2%, 3%, and 1.7% lower than that of R134a, respectively.

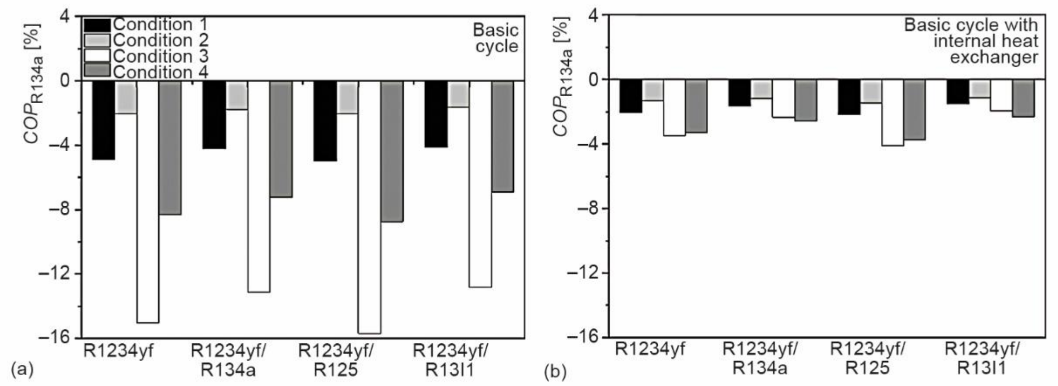

Figure 4. The COP compared with R134a (without internal heat exchanger); (a) for basic cycle and (b) for basic cycle with internal heat exchanger

The compressor discharge temperature of the refrigerants is shown in fig. 5. For the basic cycle, the average compressor discharge temperature of R1234yf, R1234yf/R134a, R1234yf/R125, and R1234yf/R13I1 is about 11 °C, 10 °C, 11 °C, and 10.5 °C lower than that of R134a, respectively. The compressor discharge temperature difference between the alternatives and R134a is greater at the low evaporation temperature range. For the basic cycle with internal heat exchanger, the average compressor discharge temperature of R1234yf, R1234yf/R134a, R1234yf/R125, and R1234yf/R13I1 is about 2 °C, 3 °C, 2 °C, and 3 °C higher than that of R134a, respectively. The compressor discharge temperature difference between the alternatives and R134a is larger at high condensation temperature. It indicates that the life of the compressor can be potentially enhanced for the basic cycle, while the life has little influence for the basic cycle with internal heat exchanger by using these alternatives.

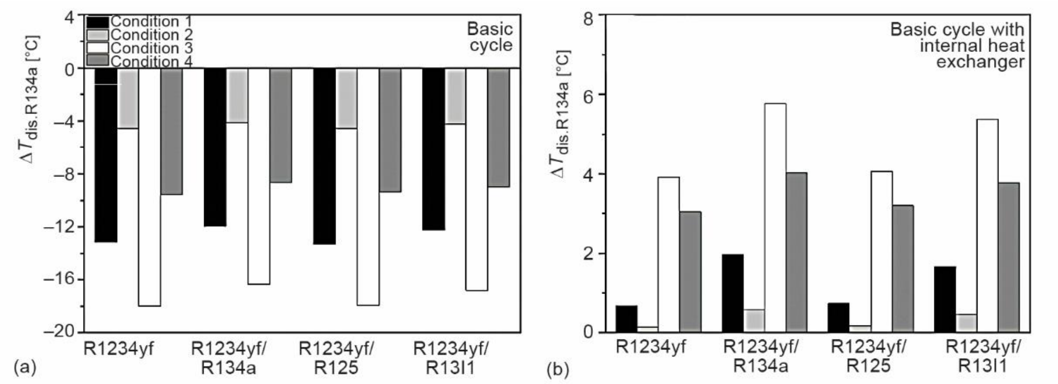

Figure 5.compressor discharge temperature compared with R134a (without internal heat exchanger); (a) for basic cycle and (b) for basic cycle with internal heat exchanger

Conclusions

In this study, the *drop-in* performance of three new mixed refrigerants R1234yf/R134a, R1234yf/R125, and R1234yf/R13I1 (90%/10%, 95%/5%, and 90%/10%, by mass) and R1234yf are theoretically analyzed as alternative to R134a using two vapor compression configurations. The experimental results are helpful for mathematical optimization of mixed refrigerants using two-fractal thermodynamics [26-29]. Based upon the results, following conclusion can be drawn.

The R1234yf/R134a, R1234yf/R125, and R1234yf/R13I1 are virtually non-flammable and have low GWP value of less than 150, which are potential environmentally friendly refrigerants.

For basic cycle, the volumetric cooling capacity of R1234yf and R1234yf/R13I1 is slightly insufficient, so the original compressor needs to be increased. However, R1234yf/R134a and R1234yf/R125 can be directly charged. The average *COP* of R1234yf, R1234yf/R134a, R1234yf/R125, and R1234yf/R13I1 is 7.5, 6.5, 8, and 6% lower that of R134a, respectively. The average compressor discharge temperature of these alternative refrigerants has a decrease about 10 °C.

For the basic cycle with internal heat exchanger, the *COP*, volumetric cooling capacity, compressor discharge temperature of the alternative refrigerants are similar to those of R134a. For configuration, these alternative refrigerants are very beneficial to be directly charged.

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