FEASIBILITY OF R1234yf/R13I1 MIXTURE REFRIGERANT AS REPLACEMENT OF R134a REFRIGERANT IN VAPOR COMPRESSION SYSTEM

by

Weibing YANG[a], Zhaofeng MENG[b*], Ziheng HUO[b], and Chuangchuang DING[b]

[a] Henan University of Technology Luohe Institute of Technology, Luohe, Henan, China
[b] Zhongyuan University of Technology, Zhengzhou, Henan, China

Original scientific paper
https://doi.org/10.2298/TSCI2403083Y

The performance of a new mixed refrigerant R1234yf/R13I1 with a mass ratio of 90/10 under basic refrigeration cycle and refrigeration cycle with internal heat exchanger is calculated in comparison with the performance of R134a under basic refrigeration cycle at different condensation temperature and evaporation temperature. The results show that R1234yf/R13I1 is virtually non-flammable with global warming potential of less than 4. Under basic refrigeration cycle, the compressor power consumption, cooling capacity and COP of R1234yf/R13I1 are lower than these of R134a by about 4.5%, 9.5%, and 7.5%, respectively. Under refrigeration cycle with internal heat exchanger, the compressor power consumption, cooling capacity, and COP of R1234yf/R13I1 are lower than these of R134a by about 2%, 4.5%, and 3%, respectively. The R1234yf/R13I1 is a beneficial refrigerant of replacing R134a in vapor compression system.

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

Introduction

Since the 1930's, chlorofluorocarbon has been widely used in refrigeration and air-conditioning installations. However, it has a high ozone depletion potential (ODP). In order to protect the atmosphere, the Montreal Protocol [1] was proposed to phase out it as a refrigerant in 1987. To fill the void created by the phase-out, much research has been carried out to find alternative refrigerants with zero ODP, among which the R134a refrigerant [2, 3] has been successfully applied to household refrigerators and air-conditioning systems.

Global warming has always been one of the most important issues facing mankind. In 1997, the Kyoto Protocol [4] was proposed to control the emission of GHG, including some hydrochlorofluorocarbons. The R134a refrigerant is identified as one of the controlled greenhouse gases with the 100-year global warming potential (GWP) of 1300 compared to CO_2 [5]. It needs to be replaced by more environmentally friendly refrigerants in the near future according to the *Kigali Programme* [6].

Recently, the R1234yf refrigerant has been considered as a potential refrigerant that can replace the R134a refrigerant. Compared with R134a, R1234yf has zero ODP and excellent life cycle of climate performance. The 100-year GWP of R1234yf is 4 compared to that

* Corresponding author, e-mail: mengzhaofeng325@163.com

of CO_2 [7]. The boiling and condensation heat transfer coefficients of R134a and R1234yf are quite close [8-10]. In addition, Tanaka *et al.* [11] studied the thermodynamic properties data of R1234yf and R134a under saturated conditions, showing that they are also very similar. There are also many comparative studies on the performance of the two refrigerants in air conditioner system. Ankit *et al.* [12] proposed a theoretical comparison of the thermodynamic properties of the two refrigerants under two typical indoor and outdoor ambient temperatures. The results showed that the performance of R1234yf was similar to that of R134a.

Adrian *et al.* [13] and Joaquin *et al.* [14] compared the performance of two refrigerants in a vapor compression system by controlling the evaporation and condensation temperatures. The test results showed that the cooling capacity of R1234yf was about 9% lower than that of R134a. The volumetric efficiency of R1234yf was about 5% lower than that of R134a. The COP of R1234yf was 5-30% lower than that of R134a in the tested range. Cho *et al.* [15] studied the performance of two refrigerants with and without regenerators in automotive air-conditioning systems. The test showed that the cooling capacity and COP of R1234yf were reduced by 7% and 4.5%, respectively, compared with R134a without a regenerator, and the cooling capacity and the COP of R1234yf were reduced by 1.8% and 2.9%, respectively, in the case of a regenerator. Colombo *et al.* [16] studied the running performance of R1234yf and R1234ze(E) in a water-to-water heat pump. Research showed that the heating capacity and the COP of R1234yf was decreased by 9.8% and 7.3%, compared to the R134a, respectively. Lee *et al.* [17] and Li *et al.* [18] paid close attention to the system performance of R1234yf in vehicle air conditioner system. The test mainly changed different compressors and throttling devices, different forms of condensers and evaporators under different conditions. Research showed that the system performance of R1234yf was slightly lower than that of R134a.

The cited research shows that R1234yf can be used as a replacement for R134a, which means that it does not have to make major modifications in the assembly line or system design to adapt the product. Currently, R1234yf is the lowest-cost alternative, but the initial cost of the product is much higher than that of R134a. The main problem with R1234yf is its mild flammability. The R1234yf is classified as A2L safety level [19]. The flammability of R1234yf is relatively low, however, compared with these non-flammable refrigerants, it may also bring some unsafe factors. In Europe, R1234yf was rejected by a major car manufacturer due to practical flammability concerns. In fact, a European car manufacturer has provided the authorities with an investigation on the safe use of R1234yf. In some realistically simulated frontal crash scenarios, the refrigerant lines of the air-conditioning system could become damaged and release R1234yf onto the exhaust system, causing a fire. However, current R134a did not cause an open flame in a similar test. Therefore, some companies seem to be willing to use the safe R134a in their cars instead of R1234yf in situations of high safety requirements.

In this study, an azeotropic mixture of R1234yf/R13I1 was proposed to replace R134a in various applications, such as automotive air conditioners, beverage coolers, and centrifugal coolers. By adding 10% flame retardant R13I1 to R1234yf, the flammability of the mixture is greatly reduced and the mixture is basically non-flammable. The GWP value of the mixture is still less than 150. Therefore, it can successfully solve the main problem of flammability of R1234yf. The purpose of this article is to theoretically calculate the performance of this mixture at different ambient evaporation and condensation temperatures, and provide data for comparison with R134a.

The basic thermal properties of R1234yf/R13I1

Table 1 lists the basic thermophysical properties and environmental performance of R1234yf, R134a, R13I1, and R1234yf/R13I1. The main parameters were calculated by using NISTRefprop9.1 [20]. It can be seen from the table that the ODP of R1234yf, R13I1, and R1234yf/R13I1 are all 0, and their GWP values are all small, which is lower than 4. The environmentally friendly performance of these refrigerants are very good. The temperature glide of R1234yf/R13I1 at 0.1-2MPa is less than 0.21 °C, which can be regarded as an azeotropic mixture. This is because the standard boiling points of R13I1 and R1234yf are similar, which helps to form an azeotropic mixture. Azeotropic mixtures do not easily occur component separation as non-azeotropic mixtures making the working pressure in the evaporator and condenser change frequently, resulting in system instability. Therefore, when R1234yf/R13I1 replaces R134a, the operation of the R1234yf/R13I1 system will be relatively stable.

Table 1. Basic thermophysical properties of R1234yf, R13I1, R1234yf/R13I1, and R134a

Refrigerant	R1234yf	R13I1	R1234yf/R13I1	R134a
Molecular weight	114.04	195.91	119.02	102.03
Normal boiling point [℃]	–29.45	–21.85	–	–26.07
Temperature glide [℃] (0.1-2 MPa)	–	–	< 0.21	–
Critical temperature[℃]	94.7	123.29	96.44	101.06
Critical pressure [MPa]	3.38	3.953	3.41	4.05
ODP	0	0	0	0
GWP	4	< 1	< 4	1300

Thermodynamic cycle characteristics

In this paper, two kinds of refrigeration cycles are simulated. One is the basic refrigeration cycle, which mainly includes compressor, condenser, throttle valve, and evaporator. The cycle diagram and pressure-enthalpy diagram are shown in fig. 1. The second is a refrigeration cycle with an internal heat exchanger. The cycle diagram and pressure-enthalpy diagram are shown in fig. 2. The cycle with an internal heat exchanger is achieved by adding a heat exchanger between the evaporator and condenser. The refrigerant liquid passing through the internal heat exchanger will be further cooled, making it enter the evaporator with a lower specific enthalpy and increasing the cooling effect. On the other hand, the suction gas is overheated, leading to higher compressor discharge temperature and a corresponding increase in compressor consumption. Finally, depending on the refrigerant studied, the COP change may be positive or negative. According to the applicable occasions of R134a, the thermodynamic calculation program of the refrigeration cycle is compiled, and the calculation is obtained. The thermodynamic performance parameters for the basic refrigeration cycle and the refrigeration cycle with the internal heat exchanger of the R13I1/R134a and the basic refrigeration cycle of the R134a are calculated. The condensation temperature is selected as 40 °C, 50 °C, and 60 °C, and the evaporation temperature is –20 °C to 10 °C. The calculation formula comes from [21, 22]. The assumptions used in the calculation are:

– The isentropic efficiency and volumetric efficiency of the compressor are 0.75 and 0.82, respectively.

– The rotational speed and displacement of the compressor are 2000 rpm and 33 cm^3/rev, respectively.
– There is no pressure drop in the condenser, evaporator, or each refrigeration pipeline.
– There is no heat exchange loss with the outside world in the system.
– The specific enthalpy of the refrigerant before and after the throttle valve remains unchanged.
– The efficiency of the regenerator is 0.3.
– Both the basic refrigeration cycle and the refrigeration cycle with regenerator have a degree of superheat and subcooling of 2 °C.

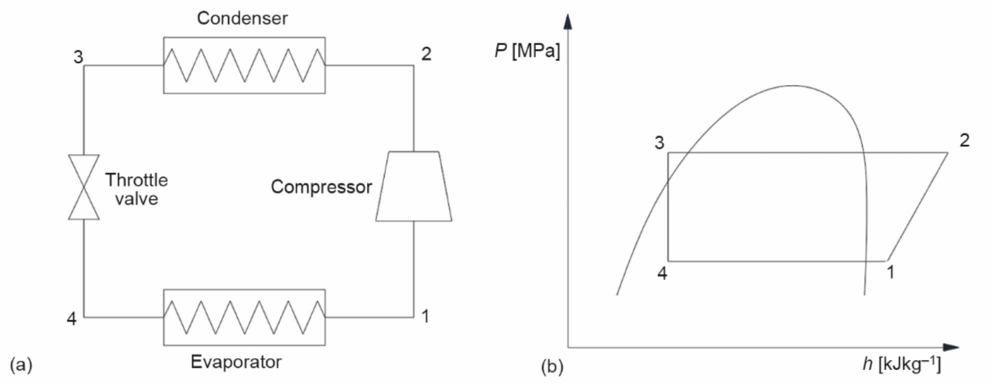

Figure 1. Basic refrigeration cycle and *P-h* diagram

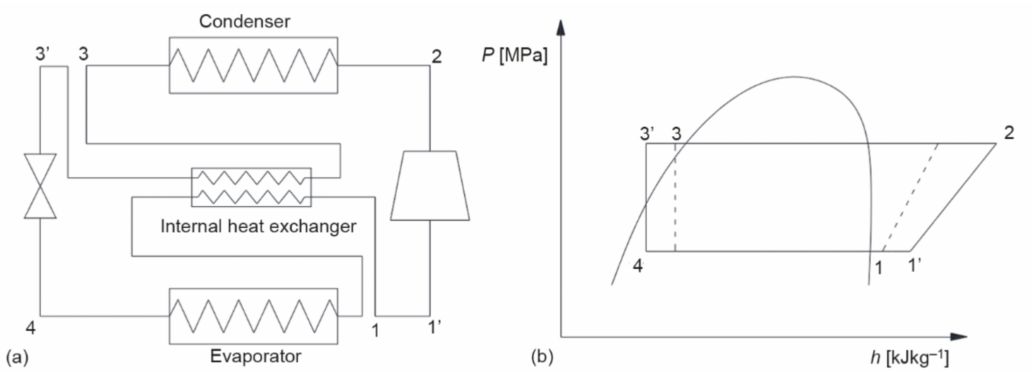

Figure 2. Refrigeration cycle with internal heat exchanger and *P-h* diagram

Results and discussion

Cycle performance analysis

The comparison of mass-flow rate of R1234yf/R13I1 and R134a *vs.* the evaporation temperature is shown in fig. 3. It can be seen from the figure that the mass-flow rate of R1234yf/R13I1 is about higher than that of R134a by 26% and 18%, respectively, under the basic refrigeration cycle and the refrigeration cycle with internal heat exchanger (IHX). This is because the suction density of R1234yf/R13I1 is relatively large. The mass-flow rate basically unchanged with the increase of the condensation temperature. This is because at different condensation temperature, when the evaporation temperature is constant, the corresponding suction density is equal. Therefore, the change in mass-flow rate caused by the condensation temperature can be ignored.

The comparison of pressure ratio of R1234yf/R13I1 and R134a *vs.* the evaporation temperature is shown in fig. 4. It can be seen from the figure that when the condensation temperature is 40 °C, 50 °C, or 60 °C, the pressure ratio of the R1234yf/R13I1 under basic refrigeration cycle and the refrigeration cycle with internal heat exchanger is smaller than that of R134a by 5-12%, 7-13%, and 8-14%, respectively. The pressure ratio difference between the two refrigerants decreases with the increase of the evaporation temperature and increases with the increase of the condensation temperature. The pressure ratio mainly affects the volumetric efficiency of the compressor, therefore, the R1234yf/R13I1 can operate with a higher volumetric efficiency of the compressor.

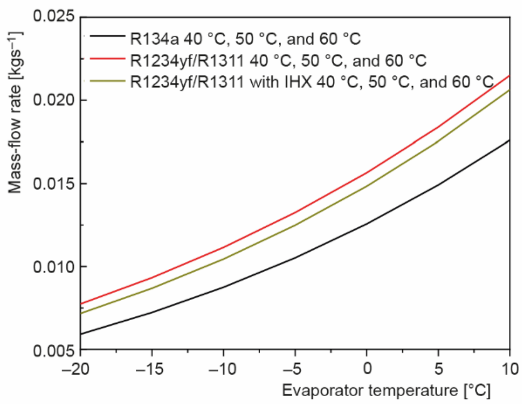

Figure 3. Variation of mass-flow rate *vs.* evaporator temperature

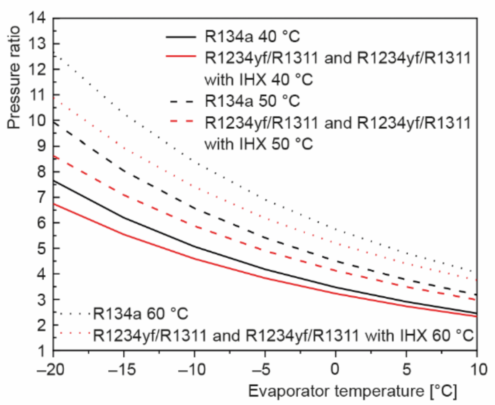

Figure 4. Variation of pressure ratio *vs.* evaporator temperature

The comparison of compressor power consumption of R1234yf/R13I1 and R134a *vs.* the evaporation temperature is shown in fig. 5. It can be seen from the figure that when the condensation temperature is 40 °C, 50 °C, and 60 °C, the compressor power consumption of R1234yf/R13I1 under the basic refrigeration cycle is about 2.2%, 2.8%, and 3.4% less than that of R134a, respectively. The compressor power consumption of R1234yf/R13I1 under the refrigeration cycle with internal exchanger is about 1.5%, 1.9%, and 2.2% less than that of R134a, respectively. This is mainly because the isentropic compression ratio of R134a is higher. It can also be seen from the figure that the compressor power consumption of the R1234yf/R13I1 under the refrigeration cycle with internal exchanger is greater than that of the R1234yf/R13I1 under basic refrigeration cycle. This is mainly because the specific enthalpy of the suction point under the refrigeration cycle with internal exchanger is higher than that of the basic refrigeration cycle, resulting in an increase in the compression specific work, thereby increasing the compressor power consumption accordingly.

The comparison of cooling capacity of R1234yf/R13I1 and R134a *vs.* the evaporation temperature is shown in fig. 6. It can be seen from the figure that when the condensation temperature is 40 °C, 50 °C, and 60 °C, the cooling capacity of the R1234yf/R13I1 under the basic refrigeration cycle is about 6.5%, 9% and 12.5% smaller than that of R134a, respectively. The cooling capacity of R1234yf/R13I1 under the refrigeration cycle with internal exchanger is about 3%, 4.5%, and 6.5% smaller than that of R134a, respectively. The difference in cooling capacity increases with the increase of evaporation temperature and increases with the decrease of condensation temperature. It can be seen from the figure that the cooling capacity of R1234yf/R13I1 under the refrigeration cycle with internal exchanger is greatly improved compared with the cooling capacity of R1234yf/R13I1 under the basic refrigeration cycle. This is because under the refrigeration cycle with internal exchanger, the R1234yf/R13I1 is subcooled again at the outlet of the condenser, and the specific enthalpy value is further reduced. Due to the large mass-flow rate of the R1234yf/R13I1, a small change in the specific enthalpy value will cause correspondingly large cooling capacity changes.

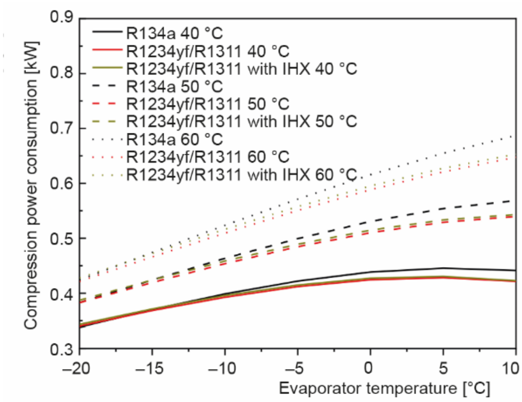

Figure 5. Variation of compressor power consumption *vs.* evaporator temperature

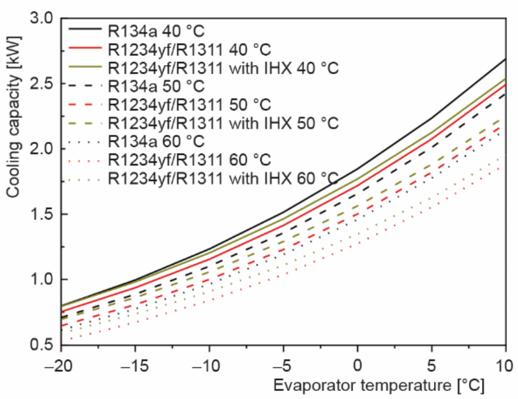

Figure 6. Variation of cooling capacity *vs.* evaporator temperature

The comparison of COP of R1234yf/R13I1 and R134a *vs.* the evaporation temperature is shown in fig. 7. It can be seen from the figure that when the condensation temperature is 40 °C, 50 °C, and 60 °C, the COP of R1234yf/R13I1 under the basic refrigeration cycle is about 4.5%, 6.5%, and 9.5% lower than that of R134a, respectively. The COP of the R1234yf/R13I1 under the refrigeration cycle with internal exchanger is approximately 1.5%, 2.5%, and 4.5% lower than that of R134a. The COP difference decreases with the increase evaporation temperature and decreases with increase condensation temperature. The COP of the R1234yf/R13I1 under the refrigeration cycle with internal exchanger is improved obviously compared with the COP of R1234yf/R13I1 under the basic refrigeration cycle.

The comparison of compressor discharge temperature of R1234yf/R13I1 and R134a *vs.* the evaporation temperature is shown in fig. 8. The compressor discharge temperature is the main factor affecting the service life of the compressor. Higher compressor discharge temperatures will affect lubricant performance, thus reducing the service life of the compressor. It can be seen from the figure that when the condensation temperature is 40 °C, 50 °C, and 60 °C, the compressor discharge temperature of the R1234yf/R13I1 under basic refrigeration cycle is about 6-14 °C, 8-15 °C, and 9-16 °C lower than that of R134a, respectively, while the compressor discharge temperature of the R1234yf/R13I1 under the refrigeration cycle with internal heat exchanger is basically the same as that of R134a. It can be concluded that when R1234yf/R13I1 replaces R134a, the compressor will have a relatively longer life under basic refrigeration cycle, while the life will not be affected much under the refrigeration cycle with internal heat exchanger. The compressor discharge temperature of the R1234yf/R13I1 under the basic refrigeration cycle is higher than that of the R1234yf/R13I1 under the refrigeration cycle with internal heat exchanger, this is because the refrigerant gas passing through the internal heat exchanger is further overheated, the specific enthalpy of refrigerant at the suction point increases, and the compressor compresses to the same exhaust pressure, the specific enthalpy of the exhaust gas increases, thereby increasing the compressor discharge temperature.

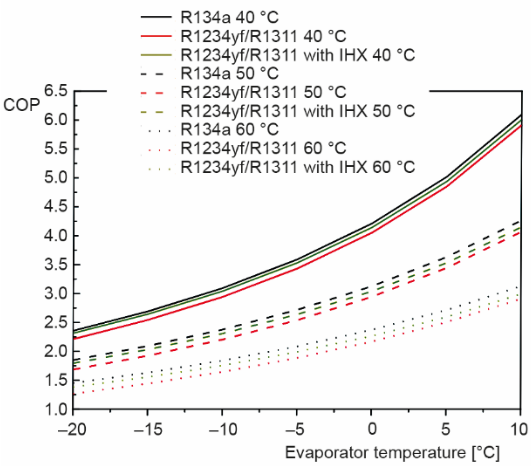

Figure 7. Variation of COP *vs.* evaporator temperature

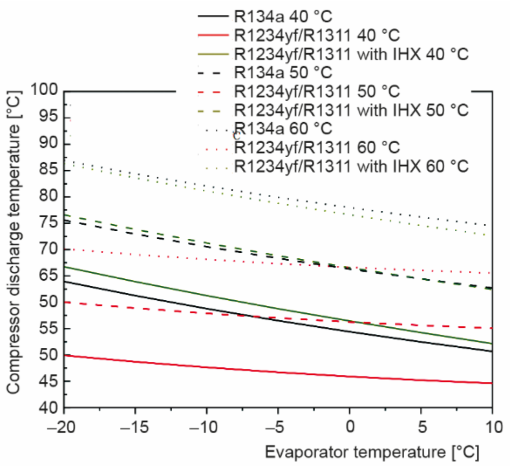

Figure 8. Variation of compressor discharge temperature *vs.* evaporator temperature

Safety performance analysis

The R1234yf has a self-ignition point of 405 °C. It is weakly flammable. The flammability of R1234yf is much lower than that of several known flammable refrigerants. The R1234yf is a low-toxic chemical substance. The R13I1 is a new type of fire extinguishing agent developed as a substitute for halon. It has excellent environmental performance, with no ozone layer depletion and greenhouse effects, and it is non-combustible. The research results on its toxicity are encouraging. Lee *et al.* [23] has tested that adding 10% R134a to R1234yf can make the mixture non-flammable. The flame retardancy coefficient of R13I1 is much greater than that of R134a [24], so it can be inferred that R1234yf/R13I1 is non-flammable, and the safety performance of R1234yf/R13I1 is high.

Compatibility of materials

The R1234yf is inactive and corrosive to all metal materials, including carbon steel, stainless steel, copper, brass, *etc*, which is commonly used in refrigeration equipment. However, it can react with aluminum, magnesium, and zinc, especially aluminum, magnesium, and zinc that remove the surface oxide layer. It should be banned in this equipment. The R1234yf is less corrosive to plastics and rubber. The R1311 will not react with or show corrosion to the sealing materials (such as neoprene, polybutadiene, *etc*.) and metal materials (such as copper, stainless steel, *etc*.). The R1311 do not react with aluminum, magnesium, zinc and other metals, so there will be no problem in the selection of materials.

Lubricating oil

The R134a is compatible with ester oil but has a low affinity for mineral oil or alkylbenzene oil, making it incompatible with all mineral oils. The R1234yf is compatible with most lubricants. The R13I1 has good oil solubility and thermal stability. From this, it can be inferred that R1234yf/R13I1 does not need to replace the lubricating oil of the original compressor when replacing R134a.

Conclusions

This paper proposes a new type of mixed refrigerant R1234yf/R13I1 (90/10 by mass). It theoretically calculates the basic refrigeration cycle and the refrigeration cycle with internal heat exchanger at different condensation and evaporation temperatures. The thermodynamic performance are compared with the basic refrigeration cycle of R134a. The feasibility of replacing R134a in vapor compression system is discussed. The conclusions are as follows.

- The temperature glide of R1234yf/R13I1 is relatively small, which can be approximated as an azeotropic mixture. The R1234yf/R13I1 is very friendly to the environment, with zero ODP and GWP of less than 4. The R1234yf/R13I1 is essentially non-flammable and safe.
- Under the basic refrigeration cycle, the compressor power consumption, cooling capacity, COP and compressor discharge temperature of R1234yf/R13I1 are about 4.5%, 9.5%, 7.5%, and 11°C lower than those of R134a, respectively. Under the refrigeration cycle with internal heat exchanger, the compressor power consumption, cooling capacity and COP of R1234yf/R13I1 are about 2%, 4.5% and 3% smaller than those of R134a, respectively. The compressor discharge temperature of R1234yf/R13I1 is basically equal to that of R134a. The R1234yf/R13I1 is an ideal refrigerant for replacing the R134a in vapor compression system. If nanoparticles are added in the refrigerants as that discussed in [2], the thermal transfer will be greatly enhanced, and the nanofluid mechanics [25-28] can be used for analysis of the refrigerator systems.

Acknowledgment

This work is supported by Science and technology project of Henan Province (232102320220) Ministry of Housing and Urban-Rural Development of the people's Republic of China the Research Program of Science and Technology (No.2020-K-031), Henan Province Major Program of Science and Technology (No.221100320100), Henan Institute of Civil Architecture the program of Scientific and technological guidance (No.202120).

References

[1] Dasilva, D. H., *et al.*, Montreal and Kyoto Protocols: Common Points and Essential Differences [J]. *Revista Brasileira de Politica Internacional*, *52* (2009), 2A, pp. 155-172
[2] Govindasamy, S., *et al.*, Experimental Analysis of Domestic Refrigerator System Using Nanorefrigerant [CeO2 ZnO+R134a], *Thermal Science*, *26* (2022), 2, pp. 969-974
[3] Asim, M., *et al.*, Flow Boiling Heat Transfer Characteristics of Low Global Warming Potential Refrigerants in a Vertical Min-Channel, *Thermal Science*, *26* (2022), 1A, pp. 63-76

[4] Duic, N., *et al.*, Croatia Energy Planning and Kyoto Protocol, *Energy Policy, 33* (2005), 8, pp. 1003-1010
[5] Liu, B., *et al.*, Evaluation of a Low-GWP and Nonflammable Blend as a New Alternative for R134a in the Heat Pump System, *International Journal of Refrigeration*, *143* (2022), Nov., pp. 1-10
[6] Birmpili, T., *et al.*, Montreal Protocol at 30: The Governance Structure, the Evolution, and the Kigali Amendment, *Comptes Rendus Geoscience*, *350* (2018), 7, pp. 425-431
[7] Lee t, *et al.*, Design Optimization of External Variable Displacement Compressor with R1234yf for Vehicle Air Conditioning System, *Applied Thermal Engineering, 198* (2021), 117493
[8] Wang, D., *et al.*, Experimental Study of the Heat Transfer of Supercritical R1234yf as a Substitute for R134a in a Horizontal Micro-Fin Tube, *International Journal of Refrigeration*, *144* (2022), Dec., pp. 1-13
[9] Prabakaran R, *et al.*, Heat Transfer and Pressure Drop Characteristics of R1234yf During Evaporation in a Plate Heat Exchanger with Offset Strip Fins: An Experimental Study, *International Journal of Heat and Mass Transfer*, *194* (2022), 123091
[10] Jige, D., *et al.*, Condensation Heat Transfer of Pure Refrigerants R1234yf and R32 Inside Multiple Circular Minichannels, *International Journal of Heat and Mass Transfer*, *195* (2022), 123146
[11] Tanaka, K., *et al.* Thermodynamic Properties of HFO-1234yf(2,3,3,3-tetrafluoropropene), *International Journal of Refrigeration*, *33* (2010), 3, pp. 474-479
[12] Ankit, S., *et al.*, Low GWP R134a Replacements for Small Refrigeration (Plug-in) Applications, *International Journal of Refrigeration*, *66* (2016), June, pp. 64-72
[13] Adrian, M. B., *et al.*, Drop-in Energy Performance Evaluation of R1234yf and R1234ze(E) in a Vapor Compression System as R134a Replacements, *Applied Thermal Engineering*, *2014* (2014), 71, pp. 259-265
[14] Joaquin, N. E., *et al.*, Experimental Analysis of the Internal Heat Exchanger Influence on a Vapour Compression System Performance working with R1234yf as a Drop-in Replacement for R134a, *Applied Thermal Engineering*, *59* (2013), 1-2, pp. 153-161
[15] Cho, H., *et al.*, Performance Characteristics of an Automobile Air Conditioning System with Internal Heat Exchanger Using Refrigerant R1234yf, *Applied Thermal Engineering, 61* (2013), 2, pp. 563-569
[16] Colombo, L., *et al.,* Experimental Analysis of the Use of R1234yf and R1234ze(E) as Drop-in Alternatives of R134a in a Water-to-Water Heat Pump, *International Journal of Refrigeration*, *115* (2020), July, pp. 18-27
[17] Lee, T., *et al.*, Design Optimization of External Variable Displacement Compressor with R1234yf for Vehicle Air Conditioning System, *Applied Thermal Engineering*, *198* (2021), 117493
[18] Li, W., *et al.*, Performance Evaluation of R1234yf Heat Pump System for an Electric Vehicle in Cold Climate, *International Journal of Refrigeration*, *115* (2020), July, pp. 117-125
[19] Zhao, Z., *et al.*, Experimental Study on the Influence of Flame Retardants on the Flammability of R1234y [J], *Journal of Loss Prevention in the Process Industries*, *81* (2023), 104945
[20] Lemmon, E. W., *et al.*, NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties-REFPROP, Version 9.1. National Institute of Standards and Technology, Gaithersburg, Md., USA, 2013
[21] Fatouh, M., *et al.*, Assessment of Propane/Commercial Butane Mixtures as Possible Alternatives to R134a in Domestic Refrigerators, *Energy Conversion and Management*, *47* (2006), 15-16, pp. 2644-2658
[22] Mota-Babiloni, A., *et al.*, Theoretical Comparison of low GWP Alternatives for Different Refrigeration Configurations Taking R404A as Baseline, *International Journal of Refrigeration*, *44* (2014), Aug., pp. 81-90
[23] Lee, Y., *et al.*, Performance of Virtually Non-Flammable Azeotropic HFO1234yf/HFC134a Mixture for HFC134a Applications, *International Journal of Refrigeration*, *36* (2013), 4, pp. 1203-1207
[24] Zhong, Q., *et al.*, Experimental Study on the Influence of Trifluoroiodomethane on the Flammability of Difluoromethane and Propane, *International Journal of Refrigeration*, *135* (2022), Mar., pp. 14-19
[25] Kumar, K., *et al.*, Irreversibility Analysis in Al_2O_3-Water Nanofluid Flow with Variable Property, *Facta Universitatis Series: Mechanical Engineering, 20* (2022), 3, pp. 503-518
[26] He, J. H., Abd-Elazem, N. Y., The Carbon Nanotube-Embedded Boundary Layer Theory for Energy Harvesting, *Facta Universitatis Series: Mechanical Engineering*, *20* (2022), 2, pp. 211-235

[27] He, J., *et al.*, Efficacy of a Modulated Viscosity-dependent Temperature/Nanoparticles Concentration Parameter on a Non-linear Radiative Electromagneto-Nanofluid Flow along an Elongated Stretching Sheet. *Journal of Applied and Computational Mechanics, 9* (2023), 3, pp. 848-860
[28] He, J. H., Abd-Elazem, N. Y., Insights into Partial Slips and Temperature Jumps of a Nanofluid Flow over a Stretched or Shrinking Surface, *Energies*, *14* (2021), 20, 6691

Paper submitted: April 7, 2023
Paper revised: August 1, 2023
Paper accepted: August 7, 2023