Thermodynamic Performance Assessment of R32 and R1234yf Mixtures as Alternatives of R410A

Nan Zheng[a], Yunho Hwang[b]*, Li Zhao[a]

[a]Key Laboratory of Efficient Utilization of Low and Medium Grade Energy, MOE,Tianjin University, Tianjin 300350, China
[b]*Center for Environmental Energy Engineering, University of Maryland, 4164 Glenn Martin Hall Bldg., College Park MD 20742, USA*

Abstract

HFC refrigerants with high Global Warming Potential (GWP) including R410A will be phased down to meet the new historic agreement under the Montreal Protocol. To develop a suitable alternative refrigerant for R410A which could meet the requirements of both system performance and environmental performance, the use of refrigerant mixtures of R32 and R1234yf was investigated in the present study. First, a comparison of thermodynamic properties, heat transfer coefficients and GWP values of R410A, R32, R1234yf and R32/R1234yf mixtures was conducted. When the R32 mass fraction is about 0.218, the GWP of the R32/R1234yf mixture reaches to 150. Second, the cycle performance of a single-stage refrigerating/heat pump system operating with different refrigerants was analyzed theoretically. Calculation results of R32/R1234yf mixtures show that both the condensing pressure and discharge temperature increases with an increase in R32 mass fraction while the cooling and heating capacities increase. When the R32 mass fraction is 0.218, the heating and cooling capacities of the mixture are lower than those of R410A by 13.5% and 17.6%, respectively but the heating and cooling COPs of this mixture are comparable to those of R410A, respectively. However, with the R32 fraction higher than 0.45, those of R32/R124yf mixtures can be even higher than R410A.

Selection and/or peer-review under responsibility of the organizers of the 12th IEA Heat Pump Conference 2017.

Keywords: refrigerant mixture; R32/R1234yf; GWP; R410A; COP; air conditioning; heat pump

* Corresponding author. Tel.: +1-301-405-5247; fax: +1-301-405-2025.
E-mail address: yhhwang@umd.edu.

1. Introduction

According to the amendment for Montreal Protocol on Substances that Deplete the Ozone Layer, the use of HFCs will be reduced gradually from as early as 2019 to prevent the global temperature from increasing 0.5 degrees Celsius by the end of the century. HFC-410A (R410A), as one of the most widely used HFCs to replace HCFC-22 (R22) in household air conditioners, is now facing the challenge of being phased down due to its high GWP value (ca. 2,088). Therefore, it requires researchers to search for alternatives of R410A to protect the environment. In recent years, refrigerant HFO-1234yf (R1234yf) with a GWP as low as 4 is considered. However, since R1234yf has much smaller latent heat than R410A, the coefficient of performance (COP) of a heat pump system would be decreased if R1234yf were to be substituted directly. To maintain a R410A system performance, some researchers proposed to use refrigerant mixtures of R1234yf and other fluids with large latent heat, such as HFC32 (R32). Fujitaka et al. [1] conducted experiments to compare the system performances of R32/R1234yf mixtures to that of R410A in a room air-conditioner. Results indicated that the system performance of the mixture improved as the mass fraction of R32 was increased. Okazaki et al. [2] tested R32/R1234yf in a modified room air-conditioner and pointed out that the modified unit with mixture having a 60% R32 mass fraction could reach 93.3% of the annual performance factor (APF) of R410A. In addition, studies were conducted on the vapor-liquid equilibrium [3], dynamic viscosity [4], flow boiling heat transfer coefficient [5] and compressor operating characteristics [6] of the R32/R1234yf mixture with certain mixing ratio. In order to achieve both a low GWP and high system performance, the mixing ratio of the R32/R1234yf mixture should be carefully determined. In this paper, the basic properties and theoretical cycle performance of the mixture with various R32 mass fractions were compared with those of R410A under both heating and cooling conditions. The optimal mixing ratios of the mixture considering the trade-off between GWP and COP based on different working conditions were obtained.

2. Comparison of Properties

2.1 Property comparison of Pure Refrigerants

Table 1 shows the comparison of some selected properties of R410A, R32 and R1234yf. The basic thermodynamic properties of each refrigerant were obtained from REFPEOP [7], and the information about safety class, ODP and GWP was originated from previous publications [5,8]. Table 1 shows that the ODP value of these refrigerants are all zero. R32, showing the largest latent heat, has similar critical temperature and boiling point as those of R410A and its GWP value is reduced by about two third compared to that of R410A. R1234yf has the lowest GWP and latent heat among the three fluids.

Table 1. Comparison of properties of three refrigerants

Properties	R410A	R32	R1234yf
M (g/mol)	72.585	50.024	114.04
T_{nb} (ºC)	-51.40	-51.651	-29.45
T_{crit} (ºC)	71.35	78.105	94.700
P_{crit} (bar)	49.019	57.82	33.822
ΔH_{lv} @ -15 ºC (kJ/kg)	238.54	337.28	172.37
ΔH_{lv} @ 45 ºC (kJ/kg)	148.27	223.99	127.37
Safety Class	A1	A2L	A2L
ODP	0	0	0
GWP	2,088	675	4

Fig. 1 shows the comparison of the three refrigerants on a temperature-entropy (T-s) diagram. It can be seen clearly from the figure that the difference in latent heat between R1234yf and other two refrigerants increases gradually as the saturation temperature decreases. As shown in the figure, the saturation vapour curve of R1234yf exhibits a negative slope, while R410A and R32 have positive saturation vapour curve slope. According to the previous study [9], R1234yf is regarded as wet refrigerant, and the other two refrigerants are as dry refrigerants. Mixing of R32 and R1234yf could lead to isentropic mixtures.

Fig. 2 shows the comparison of the flow boiling heat transfer coefficients of R410A, R32 and R1234yf based on the experimental results published by Longo et al. [10] and Li et al. [5]. All of the experimental data were obtained under same mass velocity (400 $kg/m^2 \cdot s$) and heat flux (12 kW/m^2) conditions. As shown in Fig. 2, R32 exhibits slightly higher heat transfer coefficient than that of R410A under the same conditions, and the difference in the heat transfer coefficient becomes larger as the vapour quality increases. When the tube diameter is 2 mm and saturation temperature is 15°C, R1234yf shows much lower heat transfer coefficient than that of R32 within the entire variation range of vapor quality.

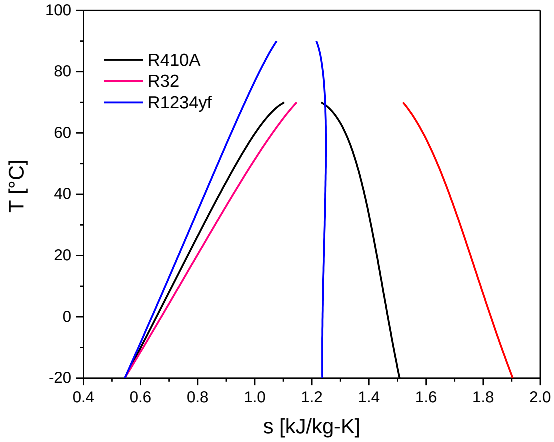


Fig.1. T-s diagram of three refrigerants

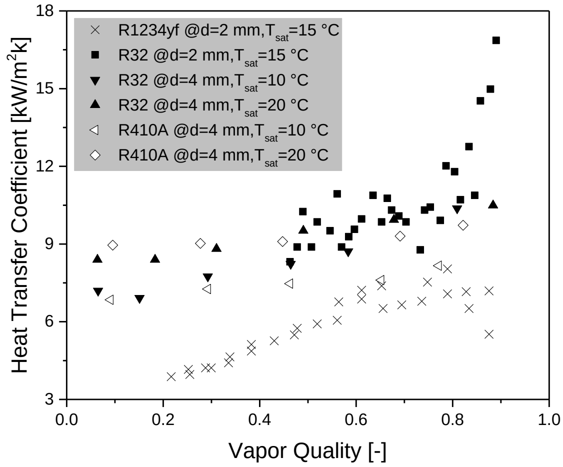


Fig. 2. Flow boiling heat transfer coefficients of R410A, R32 and R1234yf (G=400 $kg/m^2 \cdot s$ and q=12 kW/m^2)

2.2 Properties of R32/R1234yf mixtures

The mixing of R32 and R1234yf results in zeotropic mixtures since each component fluid has a different boiling point. For zeotropic mixtures, the saturation temperature changes during the phase change process. The temperature difference between the saturated liquid and vapor points at a constant pressure is defined as the temperature glide. Fig. 3 shows the variation of the temperature glides of R32/R1234yf mixture with R32 mass fraction under two pressures at which the average saturation temperatures are -15°C and 45°C. According to the calculation results, when the R32 mass fraction is about 0.15, the maximum temperature glides of the mixture is 9.8°C for lower pressure and 7.9°C for higher pressure. The variation of GWP value versus R32 mass fraction in mixture is also illustrated in Fig. 3. For simplicity, the GWP of the mixture is estimated based on the linear weighted sum method, hence, a higher R32 mass fraction will lead to a larger GWP value for the mixture. In this paper, the upper limit of the GWP value is set to 150 as an example, since refrigerants with GWP above that value are banned from use in mobile air-conditioners in EU market from 2011. As shown in Fig. 3, the GWP of the mixture reaches to the upper limit as R32 mass fraction increases to about 0.218.

According to the test data [5], the variation of boiling heat transfer coefficient by the R32 mass fraction change is not linear for the R32/R1234yf mixture. As shown in Fig. 4, the boiling heat transfer coefficient first decreases and then increases as the mixture becomes rich in R32 component, and reaches to the minimum value around R32 mass fraction of 0.2. The decrease in heat transfer coefficient could be related to the non-linear variation in the thermophysical properties of the zeotropic mixture caused by the interactions between blend components.

Fig. 5 shows the variation of the liquid viscosity and latent heat versus R32 mass fraction for R32/R1234yf mixtures at two different saturation temperatures. The latent heat of the mixture increases gradually with an increasing R32 mass fraction. The dynamic viscosity of the saturated liquid of R1234yf is higher than that of R32. For R32/R1234yf mixtures, the saturated liquid viscosity decreases obviously with an increasing R32 mass fraction, but the variation curve begins to be flat as the R32 mass fraction approaching to unit value. Lower viscosity of the liquid corresponds to smaller friction in liquid pipelines, contributing to a smaller pressure drop.

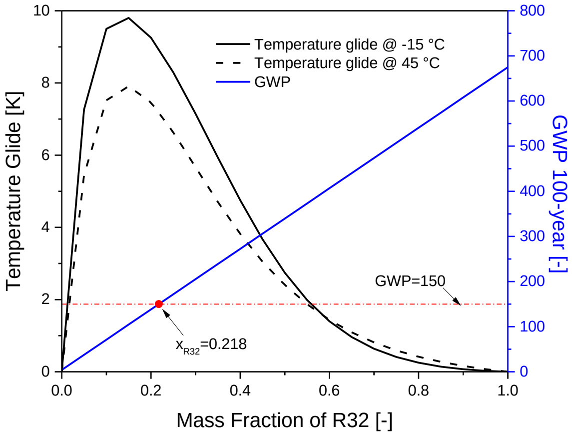


Fig. 3. Temperature glide and GWP of R32/R1234yf mixtures

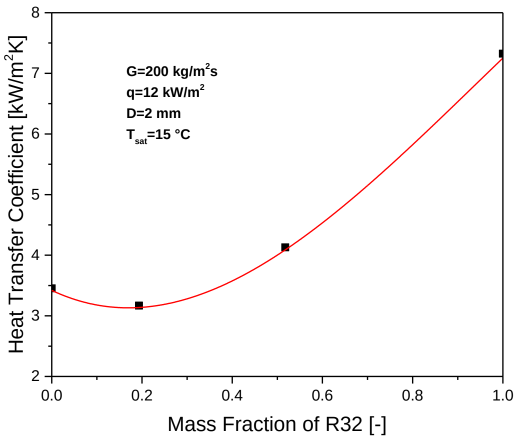


Fig. 4. Boiling Heat transfer coefficient of mixture R32/R1234yf at different R32 mass fractions

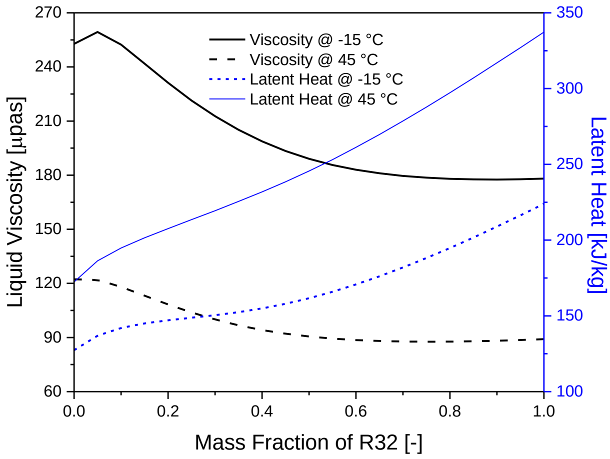


Fig.5. Saturated liquid viscosity and latent heat of R32/R1234yf mixtures.

3. Thermodynamic cycle model

A steady state thermodynamic model of a single-stage refrigeration cycle was established to evaluate the cycle performance of different refrigerants, based on the following assumptions:

- Constant pressure during phase change process
- Constant compressor isentropic efficiency of 0.75
- Isenthalpic throttling process
- No superheating at evaporator outlet and no subcooling at condenser outlet
- Fixed mass flow rate with unit value

The evaporating and condensing temperatures are fixed values for pure fluid and azeotropic mixture R410A. For R32/R1234yf mixtures, the condensing and evaporating temperatures were set to be the average values of bubble point and dew point under condensing and evaporating pressures. The calculation of the cycle performance for each refrigerant was carried out by a Matlab program, and the required refrigerant properties were determined using REFPROP 9.0 [7].

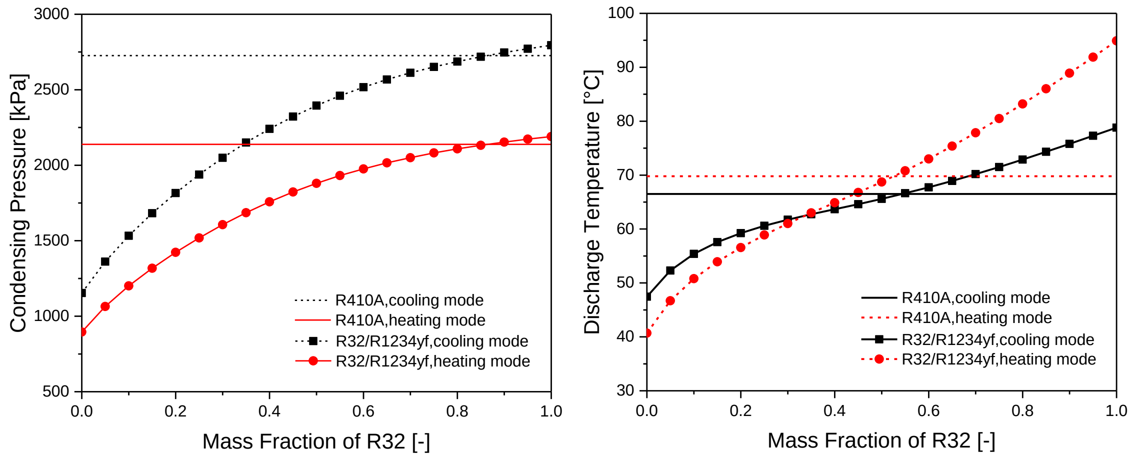
4. Results and Discussion

In this section, the cycle performance of an air conditioning/heat pump system operating with R32/R1234yf mixture is compared with that of R410A under both cooling mode and heating mode conditions. For cooling mode, the evaporating and condensing temperatures were fixed at 10°C and 45°C, respectively; and for heat pumping mode, the evaporating and condensing temperatures were set as -15°C and 35 C, respectively, as shown in Table 2.

Table 2. Temperature conditions

	Evaporation T (°C)	Condensation T (°C)
Cooling Mode	10	45
Heating Mode	-15	35

Fig. 6(a) shows the variation trend of condensing pressure versus R32 mass fraction for the R32/R1234yf mixtures. Since R32 has a much lower boiling point than R1234yf, the condensing pressure is expected to increase with an increasing R32 mass fraction. The condensing pressure of R410A under each mode is also illustrated in the diagram for comparison. It can be seen that the condensing pressure of R32/R1234yf mixture begin to surpass that of R410A, as the R32 mass fraction reaches to about 0.9 for the two modes. When the R32 mass fraction is 0.218, the condensing pressures of the mixture in cooling and heating modes are reduced by 910.3 kPa and 715.6 kPa, respectively as compared to those of R410A.



(a) (b)

Fig. 6. Variation of condensing pressure (a) and discharge temperature (b) for R32/R1234yf mixture

Fig. 6(b) shows the effect of R32 mass fraction on the discharge temperature. Overall, the discharge temperature increases with an increasing R32 mass fraction. When the R32 mass fraction is less than 0.35, the discharge temperature of cooling mode is higher than that of heating mode, though the cooling mode shows smaller cycle temperature lift (35 K) than heating mode (50 K). The variation of the slope of the saturated vapor curve may lead to this phenomenon. Figure 6(b) also indicates that the R32/R1234yf mixture will show higher discharge temperature than R410A as the R32 mass fraction reaches to about 0.55 for both heating and cooling modes. For R32/R1234yf mixture with a 0.218 R32 mass fraction, the discharge temperature is reduced by 7.3°C in cooling mode and 13.2°C in heating mode as compared to that of R410A.

Fig. 7 shows the changes of cooling and heating capacities versus R32 mass fraction for cooling mode and heating mode, respectively. As expected, both the heating and cooling capacities increase with an increasing R32 mass fraction. For cooling mode, the cooling capacity of R32/R1234yf mixture becomes larger than that of R410A as the R32 mass fraction reaches to 0.45. For heating mode, the heating capacity of the zeotropic mixture becomes superior to that of R410A as the R32 mass fraction increases to about 0.5. For R32/R1234yf mixture with an R32 mass fraction of 0.218, the cooling capacity and heating capacity is reduced by 13.5% and 17.6%, respectively as compared to that of R410A under the same condition.

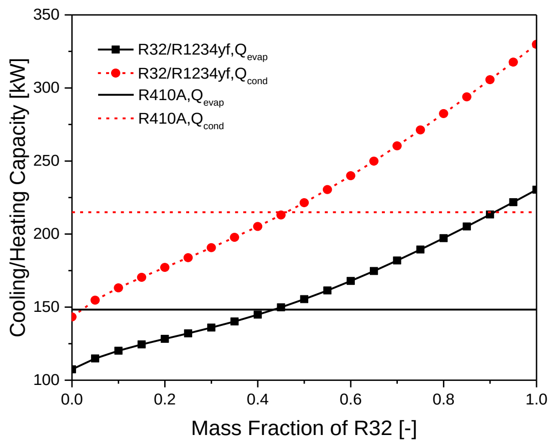
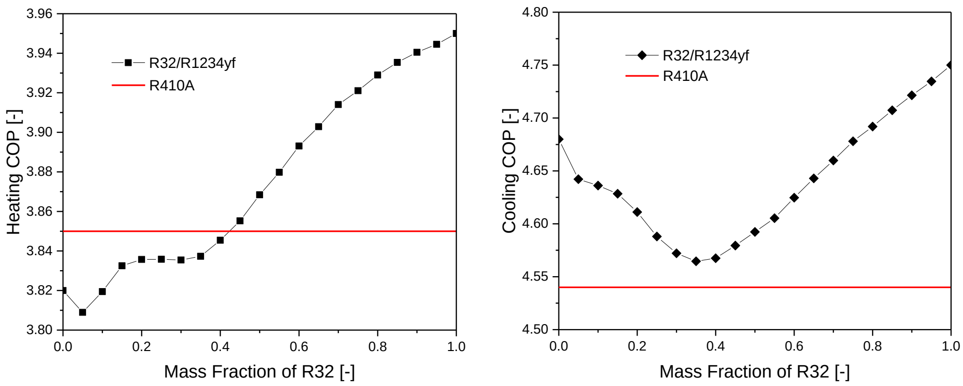


Fig. 7. Variation of cooling and heating capacities of R32/R1234yf



(a) (b)

Fig. 8. Variations of heating and cooling COPs of R32/R1234yf

Fig. 8(a) shows the variation of heating COP versus R32 mass fraction for R32/R1234yf mixture under heating mode. The heating COPs of R1234yf and R32 are 3.82 and 3.95, respectively. The heating COP of the R32/R1234yf shows an increase tendency with R32 mass fraction in general. The heating COP of the mixtures is less than that of R410A (3.85) before the R32 mass fraction reaching to 0.45. Fig. 8(b) shows the comparison of cooling COP between R410A and R32/R1234yf mixture with varying mixing ratio. As shown in the figure, the cooling COP of the mixture first decreases and then increases with an increasing R32 mass fraction. The minimum COP value of 4.56 is reached when the R32 mass fraction increases to 0.35. Fig. 8(b) also shows that when the evaporating and condensing temperatures are 10 °C and 45 °C, respectively, both R32 and R1234yf show higher cooling COP than R410A. When mixture R32/R1234yf with an R32 mass fraction of 0.218 is applied, the heating COP is reduced by 0.4% but the cooling COP is increased by 1.5% as compared to that of R410A.

5. Conclusions

The following conclusions can be drawn from this work:

• Lower R32 mass fraction in the R32/R1234yf mixture leads to the decrease in condensing pressure and discharge temperature but the reduction in cooling/heating capacity so that the compressor displacement volume should be increased.

• When R32 mass fraction is 0.218, the GWP of the mixture R32/R1234yf reaches to 150, which is reduced by 92.8% compared to that of R410A. While the cooling and heating capacities of mixture are reduced by 13.5% and 17.6, respectively as compared to that of R410A under the same conditions, the heating and cooling COPs of the mixture R32/R1234yf with an R32 mass fraction of 0.218 is comparable to that of R410A, respectively.

• Either higher R32 mass fraction in R32/R1234yf or pure R32 would be the choice while considering the heat transfer and COP perspectives but it requires relaxing of GWP value.

• Therefore, the life cycle climate performance evaluation would help in determining the proper GWP value without compromising the environmental impact.

Acknowledgements

This work is sponsored by the National Nature Science Foundation of China (51476110). The support of the Center for Environmental Energy Engineering (CEEE) at the University of Maryland and the China Scholarship Council (CSC) are gratefully acknowledged.

References

[1] Fujitaka, A., Shimizu, T., Sato, S., Kawabe, Y., 2010. “Application of low global warming potential refrigerants for room air conditioner,” 2010 International Symposium on Next-generation Air Conditioning and Refrigeration Technology. Tokyo, Japan, NS 25.

[2] Okazaki, T., Maeyama, H., Saito, M., Yamamoto, T., 2010. “Performance and reliability evaluation of a room air conditioner with low GWP refrigerant,” 2010 International Symposium on Next-generation Air Conditioning and Refrigeration Technology. Tokyo, Japan, NS 27.

[3] Arakawa, Y., Kim, S., Kamiaka, T., Dang, C., Hihara, E., 2010. “Thermophysical properties measurement of HFO-1234yf+R32 mixture,” 2010 International Symposium on Next-generation Air Conditioning and Refrigeration Technology. Tokyo, Japan, NS 22.

[4] Dang Y, Kim HS, Dang C, Hihara E. Measurement of vapor viscosity of R1234yf and its binary mixtures with R32, R125. *Int J Refrig* 2015; 58:131-6.

[5] Li M, Dang C, Hihara E. Flow boiling heat transfer of HFO1234yf and R32 refrigerant mixtures in a smooth horizontal tube: Part I. Experimental investigation. *Int J Heat Mass Tran* 2012;55:3437-46.

[6] Cremaschi, L., Wu, X., Biswas, A., Deokar, P., 2013. “Experimental study of compressor operating characteristics and performance when using refrigerants R-32, R1234yf, and two new low GWP developmental refrigerants as drop-in replacements for R-410A,” 2013 International Conference On Compressors And Their Systems. London, UK.

[7] Lemmon, E., Huber, M., McLinden, M. NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties – REFPROP. Version 9.0, National Institute of Standards and Technology, Standard Reference Data Program; 2010.

[8] Tian Q, Cai D, Ren L, Tang W, Xie Y, He G, Liu F. An experimental investigation of refrigerant mixture R32/R290 as drop-in replacement for HFC410A in household air conditioners. *Int J Refrig* 2015; 57:216-28.

[9] Zheng, N., Hwang, Y., Zhao, L., Radermacher, R., 2016. “Isentropic mixture and their application in heat pump in cold climate region,” 16^{th} International Refrigeration and Air Conditionging Conference at Purdue. West Lafayette, USA, 2387.

[10] Longo GA, Mancin S, Righetti G, Zilio C. HFC32 and HFC410A flow boiling inside a 4 mm horizontal smooth tube. *Int J Refrig* 2016; 61:12-22.