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Communication

Comparative Investigation on the Thermophysical Property and System Performance of R1234yf

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Abstract: In this paper, an experimental study of R1234yf replacing R22 in window air conditioning was carried out. The optimum types of capillary tubes and the charge amount were obtained, and the system performance of the window air conditioning charged with R1234yf was tested in an air conditioner performance teat facility under nominal and high-temperature conditions. The results revealed that the cooling capacity and coefficient of performance (COP) of the air conditioner charged with R1234yf were 28.5% and 11.1%, respectively, under nominal conditions, which were lower than that of R22. Under high-temperature conditions, the cooling capacity of R1234yf was still lower than that of R22, but the COP was slightly higher. This suggests that R1234yf may be a suitable substitution for R22 in high-temperature environment.

Keywords: R1234yf; replace; air conditioner; cooling capacity; coefficient of performance (COP)

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1. Introduction

Due to the deleterious effects on the environment, the saturated halohydrocarbon refrigerants that were widely used in refrigeration and heat pump systems have been scheduled to be phased out [1]. According to the Montreal Protocol and the Kigali agreement, developing countries (including China) should cut 97.5% production and consumption of HCFCs by 2030 and 80% production and consumption of HFCs by 2045. Therefore, as for China, there are two challenges posed by the reduction of HCFCs (hydrochlorofluoroolefins) and HFCs (hydrofluorocarbons), and seeking the new environmentally friendly substitutions becomes an urgent task in the refrigeration and heat pump fields.

R22, which has been predominantly used in room air conditioners for the past few decades, has to be phased out because it has deleterious effects on the ozone layer. Over the last several years, much research and development have been focused on substitute refrigerants with low GWP and low ozone depletion potential (ODP) to replace R22. Among them, the natural refrigerants R290 and R1270 received a lot of attention. Shaik et al. [2] analyzed the performance of an air conditioner that uses natural refrigerant R290 both analytically and experimentally. The study revealed that R290 was a viable option to replace R22 used in air conditioners in terms of performance and environmental aspects. Li and Jin [3] carried out a series of experiments on the cooling performance of residential air conditioners with R1270 and R22, and it was revealed that R1270 was a good alternative to replace R22 in residential air conditioners. In addition, with the zero ODP and low GWP, HFOs (hydrofluoroolefins) was also found to be a good choice for usage in the refrigeration system. Due to the excellent environmental property (GWP < 1), R1234yf was viewed as a viable choice among them, and it was classified as A2L category with a weak flammability.

Several works have focused on R1234yf instead of R134a. The boiling heat transfer coefficients observed for R1234yf were comparable to that of R134a [4]. Sayyab [5] conducted experiments to comprehensively evaluate the use of R1234yf in refrigeration and heat pump systems under different steady-state conditions. Kexin Yi [6] used the CFD numerical method to simulate the centrifugal compressor with R1234yf as a direct replacement of R134a, and it was demonstrated that R1234yf has a higher refrigeration capacity. Shubham Soni [7] conducted a theoretical study of refrigerant substitution based on the first law of thermodynamics and mass balance and found that R1234yf has the lowest pressure ratio and slightly more power consumption. Morales-Fuentes [8], Yıldız [9], M Z Sharif [10] analyzed the performance differences between the two refrigerants in vertical refrigerators, heat pumps, and automotive air conditioners, respectively. Pabon [11] performed experimental and theoretical studies to assess the performance of pure R1234yf in compression systems, such as mobile and residential air conditioning, air and water heat pumps, domestic refrigerator and freezer. Ran and Xu et al. [12] were conducted for the first time to evaluate the feasibility of R1234yf in replacing R134a from the perspective of supercritical heat transfer performance. Belman-Flores [13] applied artificial neural network method to analyze the energy performance of refrigeration system with R1234yf.

More studies have been conducted using other air conditioning units. Rajendran Prabakaran [14] studied the condensation of R1234yf in a plate heat exchanger with an offset strip fin flow structure for electric vehicle heat pumps. Umut Gungor [15] studied the cooling capacity of R1234yf compared to R134a in automobile air conditioning systems equipped with a coaxial internal heat exchanger. Thanh Nhan Phan [16] studied the heat transfer characteristics of R1234yf in the convective boiling process in a horizontal tube, comparing the cases where the inner surface is a smooth surface and the micro-fin is different. Isakhani Zakaria [17] and Tohidi Moghadam [18] both studied the boiling and condensation heat transfer coefficients, pressure drop, and flow pattern of R1234yf in an inclined optical tube, respectively. Khairul Bashar [19] experimentally investigated the condensation heat transfer between R1234yf and R134a in smooth and micro-ribbed tubes. All these documents displayed that, while the heat transfer performance of R1234yf is slightly lower than that of R134a, the difference is insubstantial.

There was little study concerning R1234yf as a replacement for R22. Oruç, V [20] compared the thermodynamic behavior of R22 and R1234yf in an experimental study at four different ambient temperatures. The results showed that the evaporation temperatures of the two refrigerants were similar, and that R1234yf had a lower cooling capacity than R22 and 12% lower refrigerant charging amounts than R22.

In this study, the experiments on the optimum types of capillary tubes and the charge of R1234yf were conducted using a room air conditioner, allowing us to verify the possibility of substituting R22 under the high-temperature environment.

2. Thermodynamic Properties

In the selection of a fluid to be used as a refrigerant, first we discuss the thermodynamic properties of R1234yf and R22. Table 1 presents the fundamental properties of R1234yf and R22. The thermodynamic properties of R1234yf and R22 are based on the data from NIST REFPROP V8 (NIST). The saturated vapor pressure of R1234yf and R22 are compared in Figure 1.

Table 1. The fundamental properties of R1234yf and R22.

Properties	R1234yf	R22
Chemical formula	$CF_3CF{=}CH_2$	CHF_2Cl
Relative molecular mass (RMM)	114	86.48
Normal boiling point/°C	−29.4	−40.86
Critical temperature/°C	95	96.13
Density (liquit)/(kg/m^3)	1109.857	1209.907
Density (vapor)/(kg/m^3)	32.796	38.477
Security level	A2L	A1
Latent heat (20 °C)/(kJ/kg)	149.29	187.60
ODP	0	0.04–0.06
GWP	<1	1700

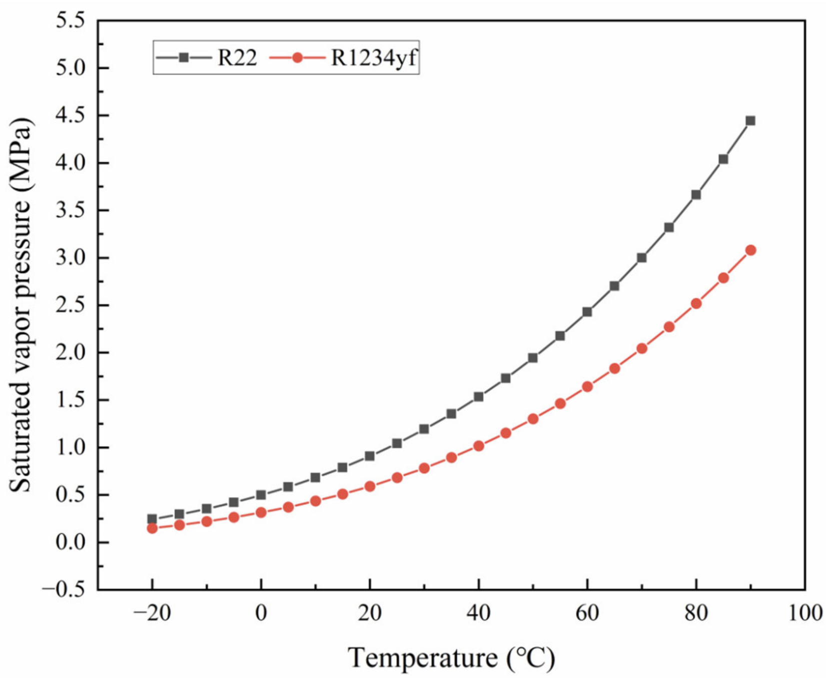

Figure 1. The saturated vapor pressure of HFO-1234yf and R22.

As seen in Figure 1, the saturated vapor pressure of R1234yf was lower than that of R22. The compressor with R1234yf has lower discharge temperature and pressure, both of which confer R1234yf an advantage in the system.

The specific heat capacity and thermal conductivity of R1234yf and R22 are compared in Figures 2 and 3.

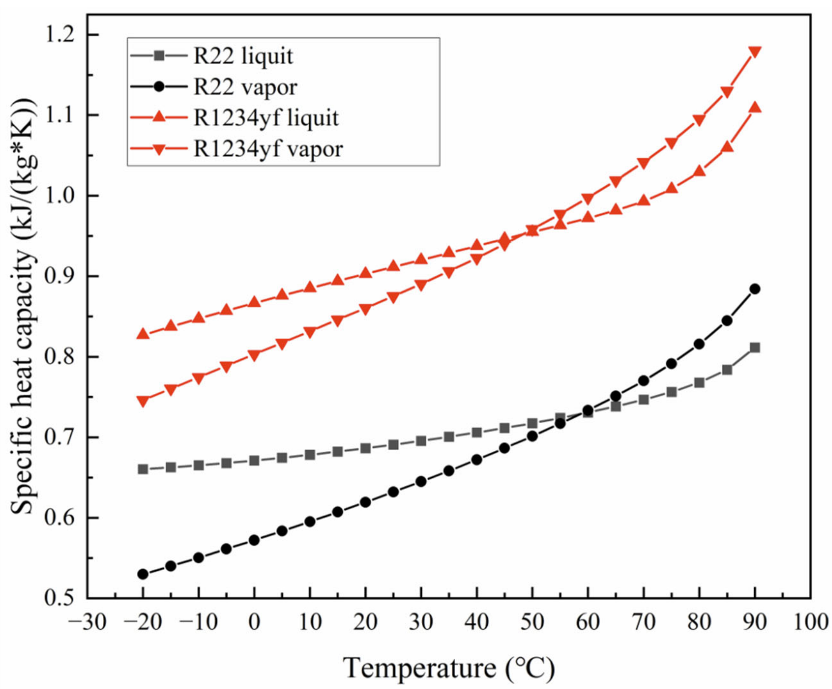

Figure 2. Specific heat capacity of HFO-1234yf and R22.

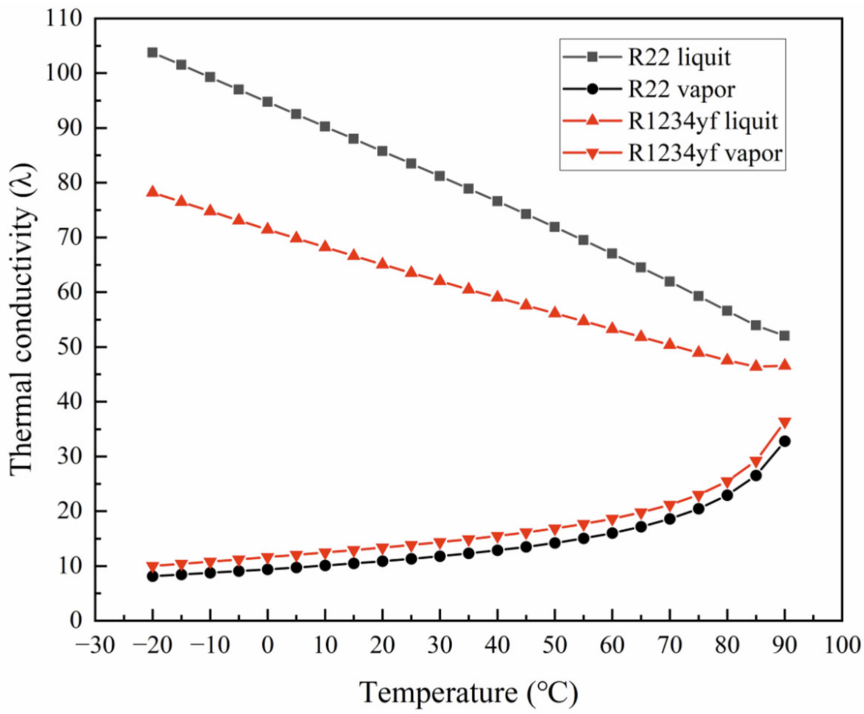

Figure 3. Thermal conductivity of HFO-1234yf and R22.

The greater the specific heat capacity, the lower the suction temperature and irreversible system loss. As shown in Figure 2, compared with R22, R1234yf has both higher saturated vapor and higher saturated liquid specific heat capacity, which improved the efficiency of the system.

Figure 3 shows the thermal conductivity of R1234yf and R22. The larger the thermal conductivity, the more heat will be exchanged in the unit area heat exchanger. R1234yf has lower saturated liquid thermal conductivity than R22 and the same saturated vapor thermal conductivity, with the difference decreasing as temperature increasing.

R1234yf has lower suction, discharge temperature, and pressure, thus contributing to the operation of the compressor, and is more suitable for high-temperature environment than R22.

3. Experimental Setup

3.1. Experimental Facility

Performance tests to evaluate usage of R1234yf as a replacement of R22 were conducted in an enthalpy lab with a window-type air conditioner inclusive of a compressor, condenser, capillary, and evaporator, as shown in Figure 4. The cooling capacity of the air conditioner with R1234yf was lower than that of R22—when the cooling capacity of the air conditioner is larger, use of R1234yf to replace R22 will need more charge. The photo of the air conditioner is shown in Figure 5. The temperature and humidity in the outdoor and indoor chambers could be measured by the sampling unit and controlled by the evaporator or the heater and humidifier. The air flowing through the test sample was provided by a blower and was measured by the nozzles in the wind tunnel. The capacity of the system was measured by the flow rate and the enthalpy of the air at the inlet and outlet in the indoor chamber.

The refrigerants used during the tests were R22 and R1234yf. The temperature and pressure of air and refrigerant were recorded by temperature sensor and pressure transducers, respectively. The precision and uncertainties of the measured parameters are shown in Table 2. The tests were conducted under normal conditions and high-temperature conditions, as shown in Table 3.

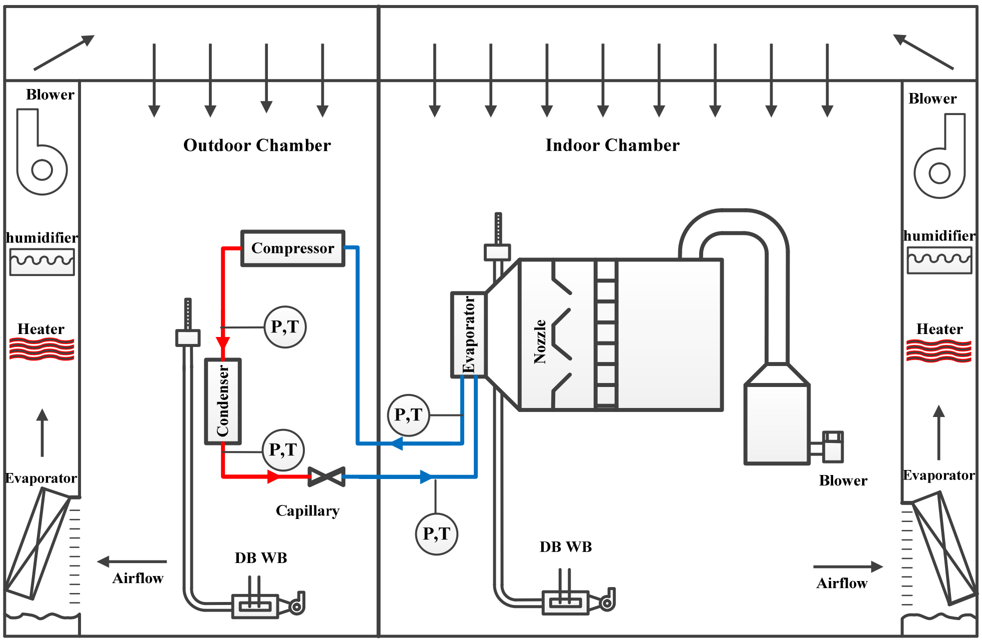

Figure 4. Schematic of air conditioner performance test facility.

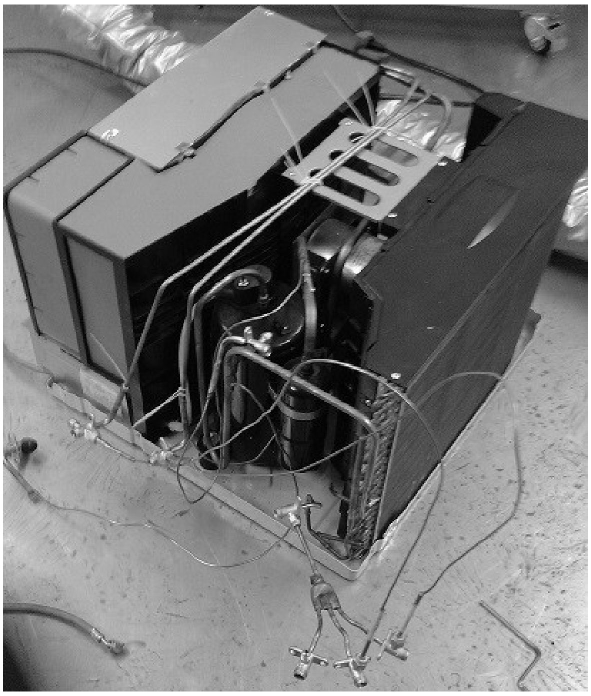

Figure 5. Window-type air conditioning system: black and white versions.

Table 2. Main instruments and measurement precision.

Name of Instrument	Specifications and Range	Accuracy
Thermocouples (K-type)	−55 °C–125 °C	±0.15 °C
Pressure transducers	0 to 3.5 MPa	±0.25% FS
Mass flow meter	0.003 to 0.09 kg s^{-1}	±0.2%
Power transducer	0–5 kW	±10 W

Table 3. Test conditions in the experimental tests.

Conditions		Normal Conditions (T1)	High Temperature Conditions (T3)
The indoor air condition/°C	dry-bulb temperature	27	29
	wet-bulb temperature	19	19
The outdoor air condition/°C	dry-bulb temperature	35	46
	wet-bulb temperature	24	24

3.2. Performance Test

The system was vacuumed before the experiment was conducted to prevent the refrigerant R1234yf from mixing with the original R22 refrigerant. In order to ensure the accuracy of experimental data, the system was allowed to run for thirty minutes after operation became stable and the data were successively measured and recorded.

First, performance of the air conditioner with R22 under normal and high-temperature conditions was tested. The charge of R22 was 790 g, using $\varphi 1.6 \times 1000$ mm capillary.

Second, the same test was conducted with R1234yf. In this test, the best match with respect to capillary and charge had been identified in advance to make the cooling capacity of the system reach the maximum.

4. Results and Discussion

4.1. Capillary and Charge Optimization Results

Table 4 shows the capillary and charge optimization results. From Table 4 it is evinced that when the cooling capacity reaches its maximum, the optimization capillary is $\varphi 1.4 \times 1000$ mm and the charge is 1275 g. Compared with R22, the capillary of R1234yf was thinner, and the R1234yf refrigerant required greater charge, a phenomenon which can be attributed to its smaller volumetric cooling capacity.

Table 4. Capillary and charge optimization of the system with R1234yf.

Item	Charge/g	Capillary/mm	Cooling Capacity/w	COP
1	790	$\varphi 1.6 \times 1000$	3408	2.10
2	790	$\varphi 1.6 \times 1100$	3108	1.91
3	920	$\varphi 1.6 \times 800$	3309	2.07
4	920	$\varphi 1.8 \times 800$	3011	1.90
5	920	$\varphi 1.6 \times 1000$	3268	2.04
6	1070	$\varphi 1.6 \times 1000$	3416	2.11
7	1275	$\varphi 1.6 \times 1000$	2914	1.85
8	1275	$\varphi 1.8 \times 1000$	2671	1.72
9	1275	$\varphi 1.6 \times 800$	2790	1.79
10	1275	$\varphi 1.6 \times 1100$	3224	1.97
11	1275	$\varphi 1.4 \times 1000$	3503	1.98
12	1475	$\varphi 1.4 \times 1200$	3291	1.77
13	1475	$\varphi 1.2 \times 1000$	3365	1.66
14	1475	$\varphi 1.4 \times 1000$	3279	1.82
15	1550	$\varphi 1.2 \times 700$	3240	1.71
16	1550	$\varphi 1.2 \times 800$	3260	1.70

4.2. Comparative Performance Results

This section describes the experimental results obtained from a room air conditioner using R1234yf and R22 in T1 and T3 condition.

Table 5 presents the obtained results under T1 conditions. Table 4 shows that the cooling capacity of the room air condition system using R1234yf is about 28.5% lower than that of R22, and the COP is 0.62 lower. At the same time, the discharge temperature of R1234yf is 6.4 °C lower than that of R22. The lower discharge temperature makes R1234yf more advantageous with respect to the operation of the compressor.

Table 5. Performance of R1234yf and R22 under T1 condition.

	R1234yf	**R22**
Cooling capacity/W	3624	5069
COP	2.08	2.34
Discharge temperature/°C	73.5	79.9
Compressor power/W	1742.5	2165.5

Table 6 presents the obtained results under T3 conditions. It can be observed that the cooling capacity and COP of R1234yf as well as R22 all have decreased as the conditioner worked under the high-temperature conditions. The cooling capacity of R1234yf is also lower than that of R22, though its COP is higher. Additionally, the discharge temperature of R1234yf is lower than that of R22 at almost 12.7 °C. The compressor power of R1234yf under T3 conditions is closer to the rated condition.

Table 6. Performance of R1234yf and R22 under T3 condition.

	R1234yf	**R22**
Cooling capacity/W	3224	4270
COP	1.68	1.66
Discharge temperature/°C	82.5	95.2
Compressor power /W	1922.4	2567

Table 7 presents the decay rate of R1234yf and R22 from T1 to T3 conditions. From Table 7 it is evinced that the decay rate of R1234yf from T1 conditions to T3 conditions is lower than that R22. The cooling capacity decay rate difference between R1234yf and R22 is 4.8% and the COP is 10%. Compared to R22, R1234yf is more suitable to use under high-temperature conditions.

Table 7. The decay rate of R22 and R1234yf.

Decay Rate	**R1234yf**	**R22**
Cooling capacity	11.0%	15.8%
COP	19%	29%

5. Conclusions

In this paper, a series of experimental tests were carried out to evaluate the suitability of R1234yf as a replacement of R22 in a window-type air conditioner. The system performance for the two refrigerants were compared and discussed under normal and high-temperature conditions. The results can be summarized as follows:

(1) As to the window-type air conditioner, the optimal charge amount of R1234yf in the window-type air conditioning system was about 1275 g and 1500 g under the normal and high-temperature conditions, respectively. The charge amount of R1234yf was 60% greater than that of R22. The optimal capillary specification of R1234yf was $\varphi 1.4 \times 1000$ mm. Compared with the capillary size of the original R22 system, which was $\varphi 1.6 \times 1000$ mm, the capillary diameter of R1234yf was smaller.

(2) Under normal conditions, both the cooling capacity and COP for the conditioner charged with R1234yf were lower than those exhibited by the R22 system, although the R1234yf system had a lower discharge temperature.

(3) Under high-temperature conditions, the cooling capacity of the R1234yf system was lower than that of the R22 system. However, the COP of the R1234yf system was a little higher than that of R22. Thus, it can be concluded that the refrigerant R1234yf is more suitable for usage under high-temperature conditions.

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