Analysis the characteristics of R1234yf, R1234ze, R134a on reefer container

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Abstract. In this work, the characteristics of R1234yf, R1234ze, R134a on reefer container were studied. According to pressure enthalpy (p-h) diagram, a computer code developed by Matlab was used to calculate power consumption, coefficient of performance (COP), compression ratio, discharge temperature, etc. The result shows that, at the same degree of subcooling and superheat, the power consumption, discharge temperature and compression ratio of R1234yf is higher than that of R1234ze, R134a. The COP of R1234yf is maximum. R1234yf can be used as an environment-friendly replacement for R134a in reefer container.

1. Introduction

R134a is a widely used refrigerant in refrigerators and freezers, while the Global Warming Potential (GWP) of R134a is 1430. As a consequence of Kyoto protocol, the European Union (EU) has banned the new developed HFC refrigerants with high GWP since the beginning of 2011[1,2]. It is urgent to study the substitution of R134a.

The selection of candidate refrigerants for R134a, some criteria should be taken into account, such as thermo-physical characteristics, technological issues, economic aspects, safety considerations and environmental factors [3]. At the same time, Ozone Depleting Potential (ODP) is another very important parameter for the selection of the refrigerants.

Jaime Sieres et al.[4] presented an experimental study of the R1234yf drop-in performance in an R134a small power vapor-compression refrigeration system. Results showed that R1234yf may be an adequate drop-in refrigerant for R134a as it closely matches its cooling capacity at the expense of lower EER values.

Adrian Mota-Babiloni et al.[5] presented an experimental analysis of a non-flammable R1234ze/R134a mixture as R134a drop-in replacement. Results showed that R1234ze/R134a mixture can be considered as a good candidate to replace R134a.

Even though many researchers have already carried out experimental and theoretical comparisons among R1234yf, R1234ze and R134a, drop-in analysis at reefer container system is quite scarce. In this paper, R1234yf and R1234ze drop-in analysis performed in an R134a reefer container system is investigated.
2. Qualitative evaluation of the refrigerants

The properties of five main refrigerating fluids used on marine reefer container are given in Table 1. Some properties are determined by Refprop 9.1. As shown in the table, ODP of R22, which is in HCFC group, is 0.055. At the same time, since GWP is higher than 150, the usage of R134a, R32 and R22 will be forbidden according to EU F-gas regulation [6]. HFO-1234yf and HFO-1234ze are classified as A2 and have a GWP of 4, 7 respectively. In this study, R1234yf and R1234ze were preferred as R134a's alternatives because these refrigerants have zero ODP and low GWP.

Table 1 Properties of selected refrigerants

| Refrigerant | R1234yf | R1234ze | R134a | R32 | R22 |
|-------------|---------|---------|-------|-----|-----|
| Composition | R1234yf | R1234ze | R134a | R32 | R22 |
| Mass%       | 100     | 100     | 100   | 100 | 100 |
| ASHRAE Safety Group | A2    | A2    | A1    | A2  | A1  |
| Global Warming Potential | 4     | 7     | 1430  | 675 | 1810 |
| Ozone Depletion Potential | 0     | 0     | 0     | 0.055 |
| Critical Pressure (MPa) | 3.4   | 3.6   | 4.1   | 5.8  | 5.0 |
| Critical Temperature (℃) | 95    | 109   | 101   | 78   | 96  |
| ASHRAE Toxicity | No   | No    | No    | No   | No  |

3. Reefer container system and data reduction

Fig.1 Pressure enthalpy (p-h) diagram of reefer container

The pressure enthalpy (p-h) diagram of reefer container is shown in the Fig.1. The figure depicts the cycle of vapor compression refrigeration. The suction line connects the evaporator outlet (point 0) and the compressor suction (point 1). After being compressed by the compressor, the refrigerant changes into a high pressure vapor and discharges from the compressor outlet (point 3) at constant entropy. However, the compression process at constant entropy only happened in theoretical cycle. In the actual cycle, the entropy of refrigerant will increase during the compression process, resulting in higher discharge temperatures and adding the amount of heat to the refrigerant. Thus, the compressor outlet is represented by point 2. The discharge line connects the compressor outlet (point 2) and the condenser suction (point 4). In the condenser, the high pressure refrigerant will be changed from high temperature vapor to low temperature and high pressure liquid refrigerant. The liquid line connects the condenser outlet (point 5) and the expansion valve inlet (point 6). Then the high pressure refrigerant flows through a throttle valve. After being throttled, the high pressure liquid changes to a low pressure, low temperature, and saturated liquid/vapor (point 7). The saturated liquid/vapor enters the evaporator absorbs heat, then changes to a low pressure and dry vapor (point 0). After that, the low pressure, dry vapor returns to the compressor. Thus, the cycle then starts again.

The evaporation pressure is given by Eq. (1).

\[ p_e = p_0 \]  (1)
Here \( p_0 \) is the saturation pressure of a refrigerant at the evaporation temperature, MPa.
The condensation temperature is given by Eq. (2).

\[
p_c = p_5
\]

Here \( p_5 \) is the corresponding saturation pressure of the refrigerant at the condensation temperature, MPa.
The discharge temperature is defined as Eq. (3).

\[
t = t_2
\]

Here \( t_2 \) is the discharge temperature of compressor, ℃.
The compression ratio is defined as Eq. (4).

\[
\pi = \frac{p_c}{p_c}
\]

Unit mass refrigerating capacity \( q_0 \) is calculated by Eq. (5).

\[
q_0 = h_1 - h_7
\]

Here \( h_1 \), \( h_7 \) is the enthalpy of the evaporator outlet and the enthalpy of the evaporator inlet respectively, kJ/kg.

The refrigerating capacity per unit volume is calculated by Eq. (6).

\[
q_v = \frac{q_0}{\nu_1}
\]

Here \( \nu_1 \) is the specific volume of the compressor suction.
The unit power consumption of compressor \( P_m \) is calculated by Eq. (7).
Here $h_2$ is specific enthalpy of refrigerant at the compressor discharge; $h_1$ is the specific enthalpy of refrigerant at the compressor suction; $\eta_m$ is mechanical efficiency of compressor (0.95); $\eta_{m0}$ is the transmission efficiency of motor (0.85).

Based on GB/T 21145-2007 (Mechanical transport refrigeration units), the nominal refrigeration testing working condition of marine reefer container is evaporating temperature: -5 ℃, condensing temperature: 45 ℃.

The analysis procedure follows the flowchart shown in Fig. 2. All refrigerant properties were obtained by using the Refprop 9.1 database. Matlab was used in the calculation step of thermodynamic properties of refrigerants.

4. Results and discussions

From the Fig.3, the compressor power consumption of the three refrigerants decrease linearly as subcooling increases. Among these refrigerants, the R1234ze consumes the most power, the R1234yf consumes the least power. When the subcooling degree is 1 ℃, the power consumption of R1234yf is 2401 W, which is 33.3 % lower than R134a. The power consumption of R1234ze is the most sensitive to subcooling, as the subcooling increases from 1 ℃ to 10 ℃, the power consumption decreases by 330 W.

Fig.3 Effect of subcooling in power consumption of compressor.

Fig.4 depicts the variation trend of discharge temperature of compressor with subcooling degree. As shown in the figure, subcooling degree has little effect on exhaust temperature. Among these refrigerants, R134a has the highest discharge temperature, while the R1234yf is minimum. The discharge temperature of R1234ze stays at 57.6 ℃ basically.

Fig.5 depicts the influence of subcooling degree on the system’s compression ratio. As shown in the figure, the compression ratio does not change with subcooling degree basically. R1234ze has the highest compression ratio 8.3, while R1234yf has the lowest compression ratio 4.3. Low compression ratio is good for system operation.

The change trend of COP (coefficient of performance) with subcooling degree is shown in the Fig.6. From the figure, COP of the three refrigerants increases with the increase of subcooling degree. R1234yf has the maximum COP, R1234ze has the minimum COP. When the subcooling degree is 5 ℃, the COP of R134a stables around 2.64, which is 0.7, 0.68 higher than R1234ze, R134a respectively.
Fig. 5 Effect of subcooling on compression ratio. Fig. 6 Effect of subcooling on COP.

Fig. 7 Power consumption of compressor changes with the superheat. Fig. 8 Effect of superheat on discharge temperature.

Fig. 9 Effect of superheat on compression ratio. Fig. 10 Effect of superheat on COP.

The relationship between the power consumption of compressor and superheat is shown in the Fig. 7. As shown in the figure, power consumption decreases with the increase of superheat. R1234ze consumes the maximum power, while R1234yf consumes the minimum. When the superheat is 5 °C, the power consumption of R134a is 3060 W, which is 789 W higher than R1234yf and 38 W lower than R1234ze.

Fig. 8 depicts the variation of discharge temperature as a function of degree of superheat. As shown in the figure, the discharge temperature increases with the increases of superheat. When the superheat
is 5 °C, the discharge temperature of R1234yf is 52.1 °C, which is 5.5 °C, 16.3 °C lower than R1234ze, R134a respectively.

Fig. 9 depicts the variation of compression ratio as a function of degree of superheat. As shown in the figure, superheat does not change the compression ratio basically. The compression ratio of R1234ze almost stays at 8.3, which is 4, 0.3 higher than R1234yf, R134a respectively.

Fig. 10 depicts the variation of COP as a function of degree of superheat. As shown in the figure, the COP does not change with superheat degree basically, R1234ze has the lowest COP. When superheat is 5 °C, the COP of R1234yf is about 2.64, which is 34.7% higher than that of R134a.

5. Summary
This paper covered pressure enthalpy (P-h) analysis of low GWP refrigerants as drop-in replacement for R134a in reefer container. During the analysis, the evaporation temperature and condensation temperature were set -5 °C and 45 °C respectively. Calculations with each refrigerant were performed for subcooling degree from 1 to 10 °C, superheat degree from 1 to 10 °C. The following major conclusions are drawn from the calculations:

(1) At the same degree of subcooling, the average power consumption of R1234yf is up to 823 W, 786 W lower than that of R1234ze, R134a, the average discharge temperature of R1234yf is around 5.5 °C, 16.3 °C lower than that of R1234ze, R134a.

(2) At the same degree of superheat, the average power consumption of R1234yf is up to 826 W, 790 W lower than that of R1234ze, R134a. The average discharge temperature of R1234yf is around 5.6 °C, 10.8 °C lower than that of R1234ze, R134a.

(3) In the process of changing superheat and subcooling degree, the COP of R1234yf is higher than that of R1234ze, R134a.

R1234yf can be used as an environment-friendly replacement for R134a in reefer container.

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