

Performance Evaluation of a Vapor Injection Refrigeration

System Using Mixture Working Fluid R32/R1234ze

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Abstract

This work presents a performance evaluation of a vapor injection refrigeration system using a mixture working fluid R32/R1234ze, through steady-state simulations used to accomplish a parametric analysis considering the influence of the refrigerant composition and vapor injection mass over the following parameters: heating capacity, heating COP; compressor power input, a thermodynamically analytical model on the vapor injection refrigeration system using a mixture working fluid R32/R1234ze was derived. Based on the above research, the prototype was developed and its experimental setup established. A comprehensive experiment for the prototype have been conducted, and the results show that, compared with the single-stage and one working fluid compression system, the vapour injection system using mixture working fluid R32/R1234ze has a better performance for the heating condition not only the heating capacity but also the energy efficiency.

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keywords: vapor injection; R1234ze/R32; heating COP; heat pump

1. Introduction

HFOs are synthetic fluids that contain a carbon-carbon double bond and characterized by very low GWP values, low flammability and non-toxicity and similar properties to HFC. R1234ze is classified as low-flammable refrigerant (A2L) by ASHRAE 34 even though it is slightly less flammable than R1234yf. If the air humidity is equal to or less than 10% and the temperature is 296.15 K, R1234ze is non-flammable [1]. R1234ze is also an alternative to R134a proposed in new systems of medium temperature applications. Recently, many studies have been conducted to characterize the properties and therefore, the thermal and energetic behaviours of this fluid. [2] Presented a density measurement system at pressures of up to 100 MPa and temperature from 283 to 363 K. The maximum expanded uncertainty for R1234ze is 0.23%. [3] Reported viscosity measurements at temperatures between 243 and 373 K and saturated pressures up to 30 MPa, using a vibrating-wire viscometer. The AAD (average absolute deviation) of the experimental results for R1234ze is 0.59%. [4] Measured R1234ze triple point value and obtained results very close that present in open literature. [5] Concluded that R1234ze can be a potential refrigerant in high-temperature heat pump systems for industrial purposes, rather than typical air conditioners or refrigeration systems.

Recently, R32 has also been considered as an important alternative for use in small to medium capacity air conditioners and heat pumps by many countries [6]. Besides the influence of the environmental consideration (ODP and GWP), Which one to use in a air-conditioner will depend on the operating conditions, for example, in a domestic air-conditioner at low ambient temperature, the temperature of the environment (the heat sink) starts at -20 °C and ends far above 35 °C. Running under above condition, all of the working fluids exists the same problems: the discharge temperature is too high, and the heating capacity decrease seriously. Experiment results showed that, the discharge temperature of both R22 and R410A are higher than 120 °C when running under the

condition of lower than $-15\text{ }^{\circ}\text{C}$. The discharge temperature of the R32 compressor is typically approximately $20\text{ }^{\circ}\text{C}$ higher than that with R410A in standard air conditioning condition. The excess may be over $30\text{ }^{\circ}\text{C}$ in severe conditions such as with ambient temperature lower than $-15\text{ }^{\circ}\text{C}$ [7]. The extremely high discharge temperature reduces the reliability of system operation due to the possibility of lubricating oil degradation, and leads to the limited operating envelope of compressors. Various technologies have been found to be conducive to decreasing discharge temperature. Among them, vapor injection is considered to be promising for wide application. In this situation, the discharge temperature would be sharply decreased and its heating performance may be improved [8-10].

If add some of R1234ze to R32, the mixture GWP may vary from around 4 to 150, and the discharge temperature may be sharply decreased. The present study was motivated by a desire to explore vapor injection refrigeration system using mixture working fluid R1234ze/R32 (80%/20% by mass) as working fluid. A scroll compressor with vapor injection for vapor compression heat pump system was designed and a test bench has been built. The performances of heating mode at different temperature was tested and analyzed.

2. vapor injection compression system

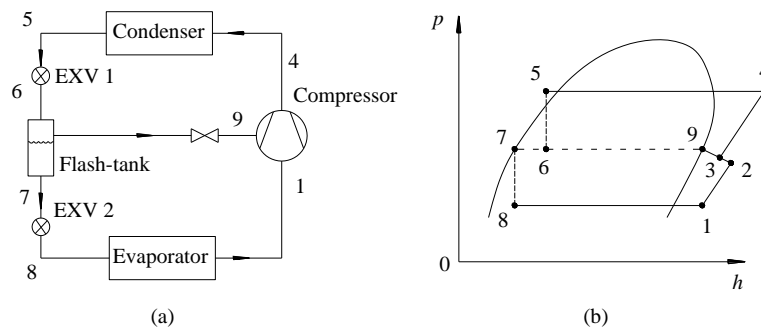


Fig. 1 heat pump with vapor injection

The operating fundamentals of the R1234ze/R32 vapor injection compression refrigeration system are shown in Fig. 1. The system has a flash-tank with the system compressor having supplementary inlets. The high pressure refrigerant from the condenser flows into the expansion valve 1 (EXV1) and its pressure drops to intermediate pressure, and then enters into flash-tank. In the flash-tank, the refrigerant is separated into pure liquid and saturated vapor. On one hand, the liquid refrigerant from the bottom of the flash-tank flows into expansion valve 2 (EXV2) and its pressure drops to the evaporating pressure, and then enters into the evaporator; on the other hand, the saturated vapor leaving from the top of the flash-tank is injected into the compressor with suitable pressure.

To ensure that the heating performance of the system is relatively high under the condition of low temperature, there are two key parameters for the system: the optimal location of the vapor injection inlets and the most suitable vapor injection pressure, both the two parameters were derived from experiment and calculation suggested by Xu et al. [6]. Equation (1) was used to calculate the most suitable vapor injection pressure.

$$p_m = k\sqrt{p_e p_c} \quad (1)$$

Where, p_e is evaporating temperature [MPa], p_c is condensing temperature [MPa], k is factor of vapor injection pressure.

The heating COP almost increase firstly and then decrease with the increasing of the relative vapor injection pressure factor, k . At a certain value of k , heating COP reaches the maximum value, respectively. For example, k is 1.2 when heating COP is the biggest under the condition of $t_o=0\text{ }^{\circ}\text{C}$. The favorable value of k should be between 1.15 and 1.35 when the evaporating temperature is $-10\text{ }^{\circ}\text{C} \sim 0\text{ }^{\circ}\text{C}$. These results are fundamental for adjusting the R1234ze system with vapor injection.

3. Testing procedure

This study analyzes the performance of a prototype air-conditioner using R1234ze/R32 measured using the experimental apparatus described by Fig. 2.

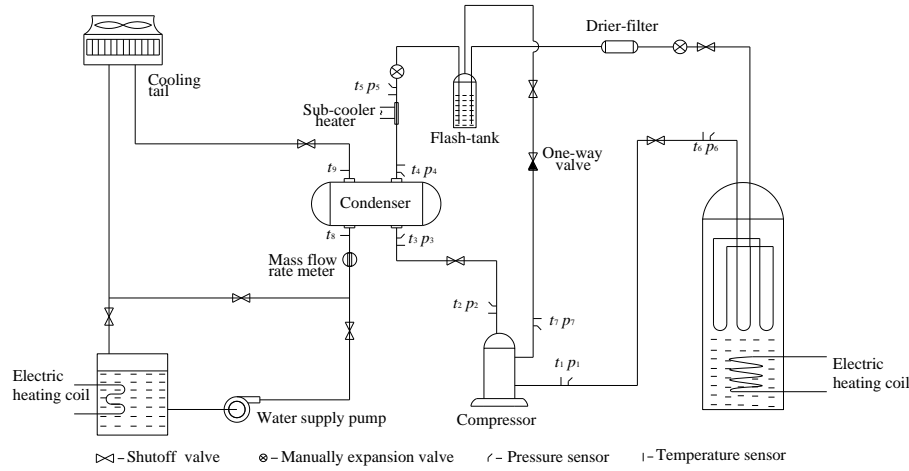


Fig. 2 R1234ze/R32 heat pump with vapor injection

As seen in Fig. 2, the system has a second-refrigerant calorimeter and water-cooled condenser. An electric vehicles scroll compressor originally designed for R22 with two manually controlled expansion valves used to regulate the mass flow rate and vapor injection pressure. In order to use it in R1234ze, we clean out all the mineral oil in the compressor and POE oil suitable for R1234ze was charge into the system. The evaporating temperature (pressure) is adjusted by the manually expansion valves, the vapor suction temperature is adjusted by the electric power input of second-refrigerant calorimeter. The calorimeter use R123 as second-refrigerant and it also contains an electric heaters coil located downstream of the calorimeter, the electric heaters could be controlled between 0~12 kW respectively, to provide the required vapor suction temperatures at the inlets of the compressor. The heating capacity is enthalpy difference multiplying the mass flow rate of the liquid refrigerant through them, respectively. The temperatures and pressures of the fluids at the inlet and outlet of the condenser or evaporator were measured by the sensors or transducers, and the enthalpy can be obtained from the measured data. Table 1 shows the specifications of the compressor. When the prototype was steadily running more than 1 hour under the selected operating mode, the all measured data were recorded only if their fluctuation was within 2 %.

Table 1. Specifications of the compressor

Item	Name
Refrigerant	R1234ze
Normal power input/HP	5
Vapor discharge mass /m ³ /h	8.61
Cooling capacity/kW	8.9
Power input/kW	2.68
Voltage	380VAC

$$q_{mf} = \frac{cm(t_9 - t_8)}{h_3 - h_4} \quad (2)$$

Where, q_{mf} is mass flow rate of liquid refrigerant throw condenser [kg/s], m is water flow rate throw condenser [kg/s], c is the specific heat of water [kJ/(kg. °C)], t_8 , t_9 are the inlet and outlet water temperature of condenser in Fig. 2, respectively.

Heating capacity Q_c :

$$Q_c = q_{mf} (h_3 - h_5) \quad (3)$$

Heating COP:

$$COP = \frac{Q_c}{P} \quad (4)$$

The test conditions were condensing temperatures, t_k , of 45 °C and a suction superheat of 10 °C, a degree of liquid sub cooling of 5 °C. The evaporating temperature, t_o was set to -20~0 °C.

4. Testing procedure

Experimental results are shown in the follow Figures, in the Figures, the symbol of “SS” indicates the single stage system and the “VI” indicates the vapor injection system.

The comparison of different refrigerant, including R1234ze and R1234ze/R32 of the single stage compression system and vapor injection system are shown in Fig. 3 to Fig. 6. From Fig. 3 we can see that, R1234ze system owns the lowest discharge temperature. For example, the discharge temperature was only 82 °C and the highest of R1234ze/R32 SS system was 126 °C when evaporating temperature is -20 °C, respectively. The discharge of R1234ze/R32 is 30 °C~40 °C higher than R1234ze under the evaporating temperature of -20 °C~0 °C. Vapor injection can decrease the discharge temperature of R1234ze/R32 system by about 4 °C.

From Fig. 4 we can see that R1234ze/R32 VI system owns the highest heating capacity value among the three refrigerants while R1234ze owns the lowest. The R1234ze/R32 VI system was higher by 32 %~37 % relative to those of the R1234ze/R32 SS system. But for heating COP, the highest value is R1234ze, the reason is that the power input of R1234ze owns the lowest value. Vapor injection can increase the value of R1234ze/R32 COP by 26 %~33 %.

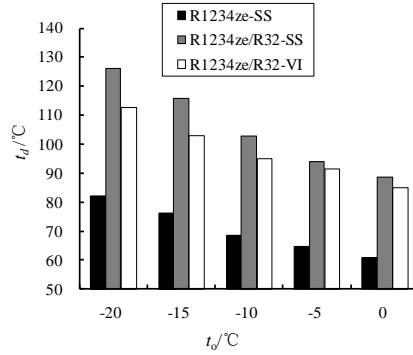


Fig. 3 The variation of discharge temperature with t_o

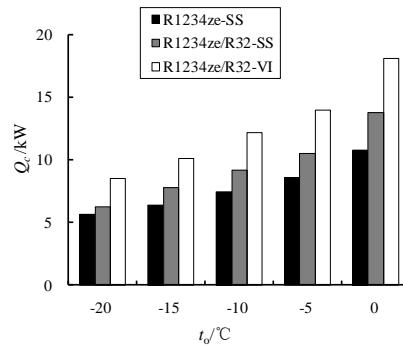


Fig. 4 The variation of Q_c with t_o

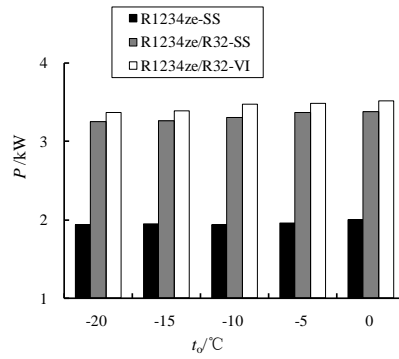


Fig. 5 Comparison of power input with t_o

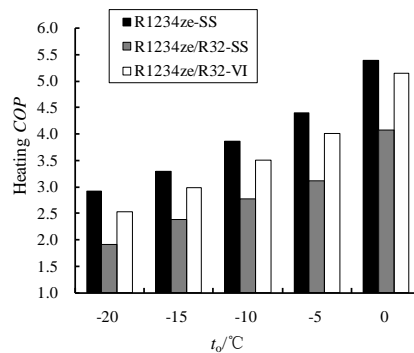


Fig. 6 The variation of heating COP with t_o

5. Conclusions

In this research, vapor injection refrigeration system using mixture working fluid R1234ze/R32 (80%/20% by mass) as working fluid is designed, constructed and tested, and it is also compared with vapour injection system. Based on the experimental results, the following conclusions were drawn:

- 1) R1234ze system owns the lowest discharge temperature and of R1234ze/R32 SS system owns the highest. Vapor injection can decrease the discharge temperature of R1234ze/R32 system by about 4 °C.
- 2) R1234ze/R32 VI system owns the highest heating capacity value and for heating COP, the highest value is R1234ze. Vapor injection can increase the value of R1234ze/R32 COP by 26 % ~ 33 %.

Acknowledgements

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Reviewers' comments:

1. Bibliographical information on fluid could be completed to explain the mixture composition choice.

Answer: we have changed the description in the revised paper (can be seen in 1. Introduction).

“If add some of R1234ze to R32, the mixture GWP may vary from around 4 to 150, and the discharge temperature may be sharply decreased. The present study was motivated by a desire to explore vapor injection refrigeration system using mixture working fluid R1234ze/R32 (80%/20% by mass) as working fluid. A scroll compressor with vapor injection for vapor compression heat pump system was designed and a test bench has been built. The performances of heating mode at different temperature was tested and analyzed.”

2. Introduction Please rephrase as it is not clear in which humidity and temperature conditions, flammability disappears : “If the air humidity is equal to or less than 10% corrected for 296.15 K , R1234ze is non-flammable”.

Answer: we have changed the “Introduction” according to the above comments.

“If the air humidity is equal to or less than 10% and the temperature is 296.15 K, R1234ze is non-flammable [1]”

3. What is the interest of detailing precision information regarding R1234ze modeling data ?

Answer: The most reason of selecting R1234ze as working fluid are the low discharge temperature and low GWP value.

4. Why using the composition 80/20 1234ze/32?

Answer: through calculation, the GWP value of composition R1234ze/R32 (80/20) is only 138, refrigerant with a GWP above 150 is prohibited for domestic refrigerators and freezers in EU (The limitations imposed by EU Regulation No517/2014).

5. Part 3 Table 1 why giving R22 compressor characteristics while it is mentioned before in the text it has been designed for R1234ze.

Answer: in the revised paper, the follow sentence (in section 3 Testing procedure),

“An electric vehicles scroll compressor originally designed for R1234ze with two manually controlled expansion valves used to regulate the mass flow rate and vapor injection pressure”

has been changed as:

“An electric vehicles scroll compressor originally designed for R22 with two manually controlled expansion valves used to regulate the mass flow rate and vapor injection pressure. In order to use it in R1234ze, we clean out all the mineral oil in the compressor and POE oil suitable for R1234ze was charge into the system.”