Experimental Study on the Characteristics of Scroll Compressor with Vapor Injection for Electric Vehicles Air Conditioning

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Abstract

When the ordinary heat pump air conditioning system of a pure electric vehicle runs under the condition of ultra low temperature, the discharge temperature by compressor will be too high and the heating capacity of the system will decay seriously. In order to solve this problem, a scroll compressor with vapor injection for pure electric vehicle heat pump air conditioning system was designed, a heat pump compressor has been developed for pure electric vehicles and a test bench has been built. The performance of heating mode at different circumstances temperature was tested and analyzed. The results showed that, compared with the conventional compressor, the compressor with vapor injection was feasible and could meet the temperature requirements of the vehicle cabin.

keywords: vapor injection; R1234ze; heating COP; electric vehicle

1. Introduction

Many kinds of refrigerants have been developed to replace HFC. However, it is not yet clear which alternative will impose definitively in market because they have some disadvantages. HFOs are synthetic fluids that contain a carbon–carbon double bond. They are characterized by very low GWP values, low flammability and non-toxicity and similar properties to HFC. There are two kinds of typical HFO refrigerants: R1234yf and R1234ze. 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% corrected for 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] Presents thermodynamic cycle analysis of mobile air conditioning system using R1234yf as alternative replacement for R134a. [6] 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 [7]. 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 ℃ and ends far above 35 ℃. 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 ℃ when running under the condition of lower than -15 ℃. The discharge temperature of the R32 compressor is typically approximately 20 ℃ higher than that with R410A in standard air conditioning condition. The excess may be over 30 ℃ in severe conditions such as with ambient temperature lower than -15 ℃ [8]. 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 [9-11].

The present study was motivated by a desire to explore a low ambient temperature electric vehicles air conditioning using R1234ze and its binary mixture with R32, R1234ze/R32 (80%/20% by mass) as working fluid. A scroll compressor with vapor injection for pure electric vehicle heat pump air conditioning system was designed and a test bench has been built. The performances of heating mode at different circumstances temperature was tested and analyzed.

2. R1234ze vapor injection compression system

The operating fundamentals of the R1234ze 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.

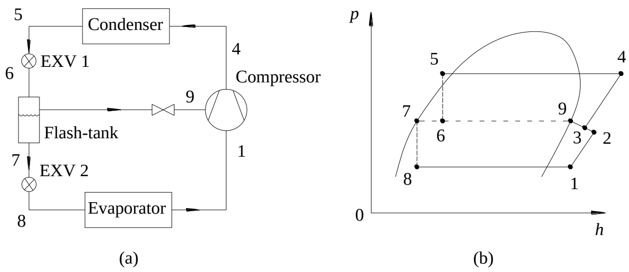

Fig. 1 R1234ze heat pump with vapor injection

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. [7]. Equation (1) was used to calculate the most suitable vapor injection pressure.

$$p_m = k\sqrt{p_e p_c} \tag{1}$$

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 ℃. The favorable value of *k* should be between 1.15 and 1.35 when the evaporating temperature is -10 ℃～0 ℃. 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 measured using the experimental apparatus described by Fig. 2. As seen in Fig. 2, the system has a second-refrigerant calorimeter and water-cooled condenser. 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. 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 been 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 %.

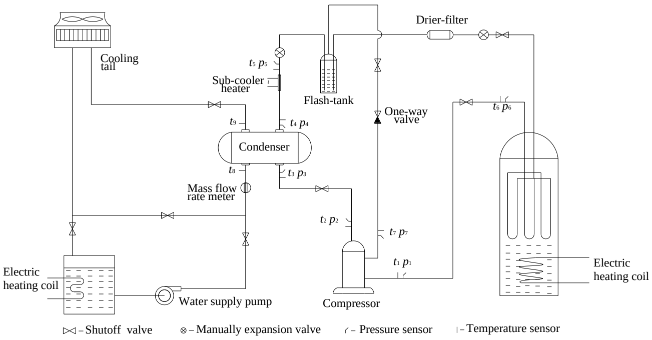

Fig. 2 R1234ze heat pump with vapor injection

Table 1. Specifications of the compressor

Item	Name
Producer	Nanjing Aotecar, China
Brand	ER28300A-0065H
Lubrication oil	RL68H 300mL
Refrigerant	R134a
Speed	1000~6500rpm
Voltage	300VDC

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

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.℃)], t_8, t_9 are the inlet and outlet water temperature of condenser in Fig. 2, respectively.

Heating capacity Q_c:

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

Heating COP：

$$COP = \frac{Q_c}{P} \tag{4}$$

Table 2 Experimental data for prototype (t_o=-5℃)

		p_1(bar)	t_1(℃)	p_2(bar)	t_2(℃)	t_8(℃)	t_9(℃)	m/(m^3/h)	P(kW)	Q_c(kW)
SS	R1234ze	1.77	2.06	8.91	83.63	38.08	41.57	0.74	1.21	3.00
	R32	6.90	2.03	2.79	102.00	38.00	43.00	2.90	5.90	17.06
	R1234ze/R32	2.91	2.12	16.50	114.06	33.64	38.14	0.92	2.51	6.42
VI	R1234ze	1.71	1.94	8.89	83.48	38.12	41.49	1.01	1.40	3.97
	R32	6.90	2.00	2.80	92.00	37.60	41.80	4.00	6.00	19.62
	R1234ze/R32	3.20	1.93	16.50	110.00	33.02	37.53	1.44	3.27	8.80

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

4. Testing procedure

Experimental results are shown in the follow Table 2 and follow Figures, in the Figures, the symbol of "SS" indicates the single stage system and the "VI" indicates the vapor injection system.

4.1. Comparison of different refrigerant

The comparison of different refrigerant, including R32, R1234ze and R1234ze/R32 of the single stage compression system are shown in Fig. 3 to Fig. 6, under the condition of evaporating temperature was set to -15 ℃～0 ℃ and condensing temperatures was set to 45 ℃. From Fig. 3 we can see that, R1234ze owns the lowest discharge temperature. For example, the discharge temperature was about 92 ℃ and the highest of R32 was 125 ℃ under the evaporating temperature of -15 ℃, respectively. For R32, if the discharge temperature continue increase (the evaporating temperature is lower than -10 ℃), the compressor may stop running. The discharge of R1234ze/R32 is 10 ℃～20 ℃higher than both R1234ze and R32 under the evaporating temperature of -5 ℃～0 ℃. From Fig. 4 we can see that R32 owns the highest heating capacity value among the three refrigerants while R1234ze owns the lowest. The R1234ze/R32 was higher by 50 % relative to those of the R1234ze system. For heating COP, R1234ze/R32 is about 2 %～10 % larger than R1234ze with evaporating -5 ℃～0 ℃.

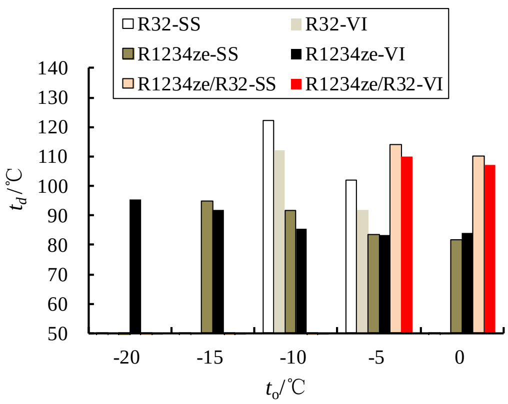

Fig. 3 The variation of discharge temperature with t_o

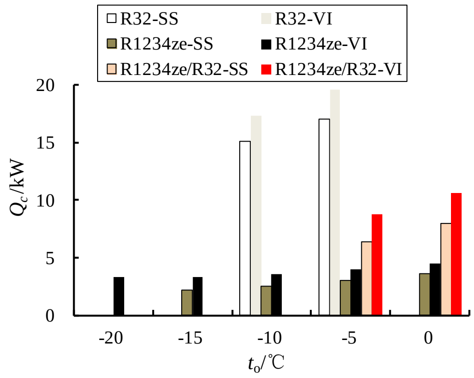

Fig. 4 The variation of Q_c with t_o

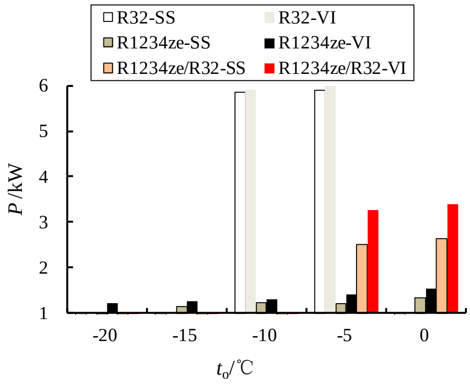

Fig. 5 Comparison of power input with t_o

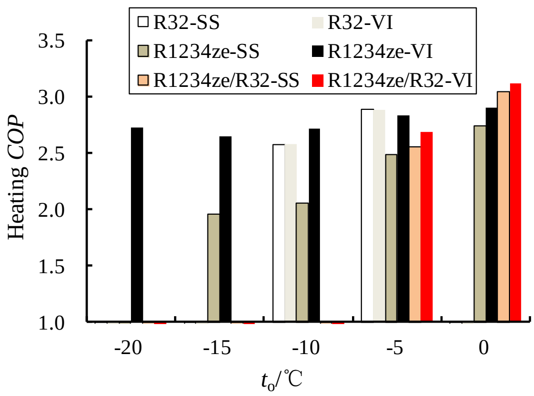

Fig. 6 The variation of heating COP with t_o

4.2. Effect of vapor injection

Fig. 3 to Fig. 6 also show the heating performance of vapor injection system. From Fig. 3 we can see that, vapor injection can decrease the discharge temperature 4 ℃～6 ℃, and this make R1234ze can run under the evaporating temperature -20 ℃. Fig. 4 shows the heating capacities obtained from the experiment results. Switching from single stage to vapor injection mode, the heating capacity of the R1234ze/R32 system can increase 32～37 %, which is a big advantage in meeting the required heating demand. As shown in Fig. 6, compared with the single stage system, the heating COP of R1234ze/R32 can increase 2.6 % to 5.5 %.

5. Conclusions

In this research, a low ambient temperature electric vehicles air conditioning using R1234ze and its binary mixture with R32, R1234ze/R32 (80%/20% by mass) as working fluid is designed, constructed and tested, and it is also camprated with vapour injection system. Based on the experimental results, the following conclusions were drawn:

1）R1234ze owns the lowest temperature and R32 owns the highest. R32 owns the highest heating capacity among the three refrigerants while R1234ze owns the lowest.

2）Vapor injection can make R1234ze can run under the evaporating temperature -20 ℃. Switching from single stage to vapor injection mode, the heating capacity of R1234ze/R32 system can increase 32～37 %. Compared with the single system, the heating COP of R1234ze/R32 can increase 2.6 % to 5.5 %.

Acknowledgements

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Reviewers' comments:

1. The paper need strengthen the experimental results analysis.
Answer: The paper has been strengthened and the experimental results analysis has been added in the revised paper.
2. Comparison should be carried out between the vapor injection mode and the single stage mode in the same figure, to show the impact of various parameters, such as discharge temperature, heat capacity and COP.
Answer: we have changed all the Figures, vapor injection mode and single stage mode are in the same Figure.
3. Add the table of the experiment results in paper, the comparison data will be more clear.
Answer: we have added experiment results in the revised paper.