EXPERIMENTAL STUDY ON PERFORMANCE OF HEAT PUMP AIR CONDITIONING SYSTEM FOR PURE ELECTRIC BUS WITH ECONOMIZER

by

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When the exhaust temperature of heat pump air conditioning system of pure electric bus is too high, the performance of the system is attenuated. In order to solve the problem, an alternative system with low pressure air supply is developed. The experimental platform is set up to reveal the main factors affecting the refrigeration and heating performance of the system. The results show that the low pressure air-supply technology can significantly reduce the exhaust temperature of the compressor.

Key words: *heat pump air conditioning, low pressure air-supply, performance, pure electric bus*

Introduction

New energy vehicles can effectively solve the current problems of environmental pollution and energy shortage faced by the sustainable economic development of China, and pure electric bus is the main direction of the development of new energy bus industry [1]. Due to the large activity area of pure electric bus, there will be many problems in the direct applications of traditional air-source heat pump air conditioning system to pure electric bus, such as the refrigeration at high temperature in summer and the heating at low temperature in winter. The exhaust temperature and exhaust pressure of the system compressor are very high, which seriously affect the service life of the compressor and will result in the attenuation of the refrigeration and heating performance of the system [2, 3].

In order to solve this problem, there are three methods used world widely. The first is two-stage compression cycle technology [4-6], this method requires large equipment investment and complex operation. The second method is cascade cycle technology [7-9], this method increases the number of cycles, reduces the thermal efficiency of the system, making the control of the system more complex, and is mostly used in the field of cryogenic medium with low temperature. The third method is the quasi-two-stage compression cycle technology. Compared with the ordinary system, the quasi-two-stage compression system adds an air-supply device, and through the air-supply technology, the exhaust temperature of the com-

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pressor is reduced and the performance of the heat pump system is improved [10]. Dutta *et al.* [11] carried out an experimental study on the quasi-two-stage scroll refrigeration compressor, Xu *et al.* [12] studied the effect of air-supply technology on the performance of heat pump system, Tang *et al.* [13] studied the heat pump performance of quasi-two-stage scroll compressor and single-stage scroll compressor experimentally, Yang *et al.* [14] applied air-supply technology to the research of screw compressor heat pump system, He *et al.* [15] also applied air-supply technology to the research of high temperature heat pump system performance. At present, there is relatively little literature on R407C in quasi-two-stage compression air-supply. Based on the principle of quasi-two-stage compression cycle, the performance of heat pump air conditioning system of pure electric bus is studied by using R407C as refrigerant, and applying the tube-finned heat exchanger inside and outside the vehicle and the low pressure air-supply technology with economizer, which provides experimental basis for optimizing the performance of heat pump air conditioning system of pure electric bus.

Low pressure air-supply type heat pump air conditioning system of pure electric bus

The system components include scroll compressor, outer tube-wing heat exchanger, inner tube-wing heat exchanger, economizer, device for drying and filtering, liquid reservoir, gas-liquid separator, two electronic expansion valves and several check valves. The system flow diagram is shown in fig. 1.

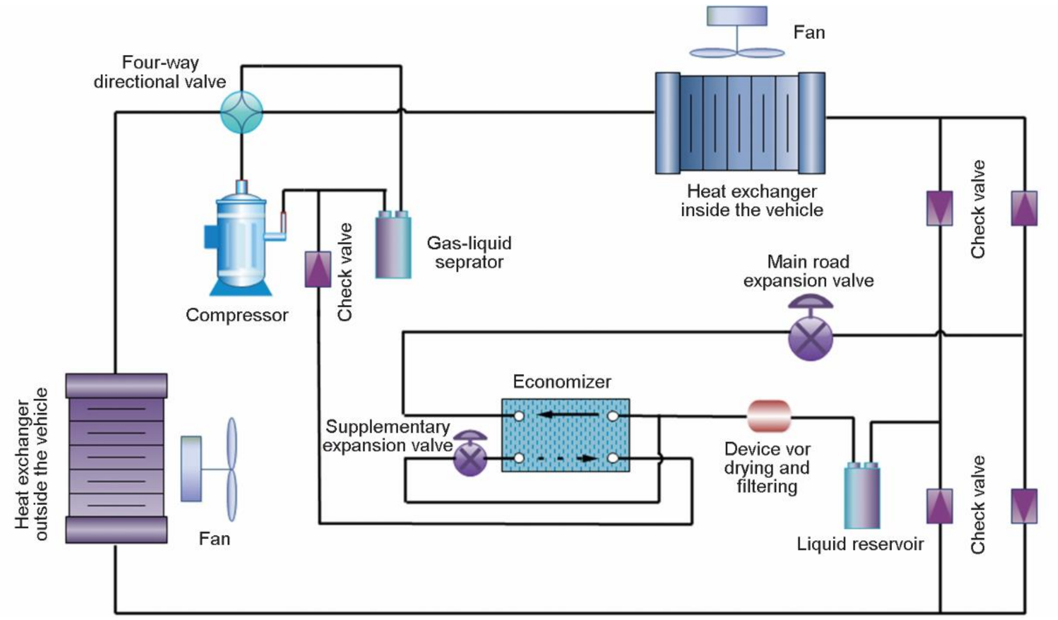

Figure 1. System flow chart

The principle of the low pressure air-supply circulation is that the high temperature and high pressure refrigerant gas is discharged from the air outlet of the compressor (State 2), and is divided into two ways after the condenser is cooled (State 2-5), and the main-way refrigerant is subcooled to the State 3 by the supplementary refrigerant in the economizer, the main expansion valve is throttled to the State 4, and is evaporated in the evaporator (State

4-1). The supplementary refrigerants are throttled by the supplementary expansion valve (State 5-6), and then enter the economizer for endothermic evaporation (State 6-7); the supplementary refrigerants have a small segment of the pipe to throttle before entering the low pressure air-supply inlet (State 7-8), the throttled supplementary refrigerants enter the low pressure air-supply inlet and mix with the main refrigerants (State 8-9), and the mixed refrigerants are compressed to form the exhaust State 2, so that the cycle is repeated to realize quasi-secondary compression of a single compressor. If the undercooling degree of refrigerants in the air-supply circuit is too high, the State 9 will be shifted to the State 9', and the corresponding State 2 will shift to State 2'. Figure 2 shows the theoretical cycle diagram of low pressure air supply. The thermodynamic cycle formula are:

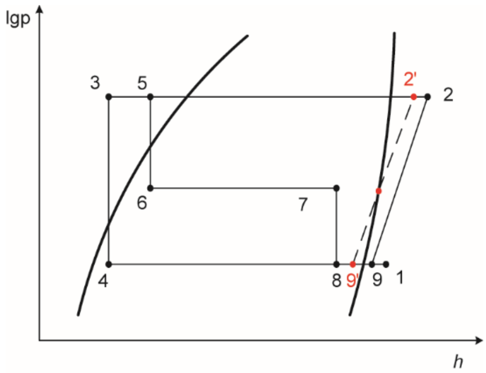

Figure 2. Cyclic pressure-enthalpy diagram of low pressure air-supply theory

– Heating capacity of heat pump system on the side of condenser:

$$Q_\mathrm{h} = \dot{m}_r (h_2 - h_{3'}) \tag{1}$$

– Compressor power:

$$W = \dot{m}_o (h_7 - h_1) + \dot{m}_r (h_2 - h_8) \tag{2}$$

– Refrigerating capacity of heat pump system on the side of evaporator:

$$Q_c = \dot{m}_o (h_1 - h_5) \tag{3}$$

– Refrigeration coefficient of heat pump system:

$$\mathrm{COP}_c = \frac{Q_c}{W} \tag{4}$$

– Heating coefficient of heat pump system:

$$\mathrm{COP}_\mathrm{h} = \frac{Q_\mathrm{h}}{W} = \frac{W + Q_c}{W} = 1 + \frac{Q_c}{W} \tag{5}$$

– Mass-flow rate of air-supply refrigerants:

$$\dot{m}' = \dot{m}_r - \dot{m}_o \tag{6}$$

– Heat transfer capacity of economizer:

$$Q' = \dot{m}_o (h_{5'} - h_5) \tag{7}$$

where $\dot{m}_o$ [kgs^{-1}] is the mass-flow rate of refrigerants entering evaporator, $\dot{m}_r$ [kgs^{-1}] – the mass-flow rate of compressor exhaust refrigerants, and $\dot{m}'$ [kgs^{-1}] – the mass-flow rate of air-supply refrigerants.

Experimental process

According to the flow chart of the system, the experimental platform is built. The experiment is carried out in the constant temperature and humidity test room. According to QC/T656-2000 *Performance Requirements of Automobile Air Conditioning Refrigeration Unit*, QC/T657-2000 *Test Method of Automobile Air conditioning Refrigeration Unit*, GBT12782-2007 *Automobile Heating Performance Requirements and Test Methods*, GBT21361-2008 *Automotive Air Conditioner* and GB7725-2004 *Room Air Conditioner* and other national and industry standards. In the course of the experiment, the rotating speed of the compressor is 5000 rpm, the refrigeration condition was 21 °C, 35 °C, and 50 °C, respectively, and the heating condition was 7 °C, 0 °C, –5 °C, –10 °C, and –20 °C, respectively.

Analysis of experimental results

Figure 3 shows the variation curve of compressor exhaust temperature with ambient temperature outside the vehicle. It can be seen from fig. 3 that the exhaust temperature of the compressor increases gradually with the increase of the ambient temperature outside the vehicle under the refrigeration condition, and the exhaust temperature of the non-air-supply system is higher than that of the low pressure air-supply system at the same parameter points. Through the low pressure air-supply technology, the exhaust temperature of the system is less than 90 °C, especially at high temperature 50 °C of environment, the exhaust temperature of the non-air-supply system is as high as 97.59 °C, and the exhaust temperature of the low pressure gas supply system is 84.05 °C, which is 13.54 °C lower than that of the low pressure air-supply system. Figure 4 shows the variation curve of the refrigerating capacity of the system with the ambient temperature outside the vehicle. It can be seen from fig. 4 that under the refrigeration condition, with the increase of ambient temperature, the refrigerating capacity of the system increases at first and then decreases, and at each point of the same parameter, the refrigerating capacity of the non-air-supply system is larger than that of the low pressure air-supply system. When the ambient temperature outside the vehicle rises from 21 °C to 50 °C, the refrigerating capacity of the low pressure air-supply system is 1.2%, 1.8%, and 2.0% lower than that of the non-air-supply system, respectively. Among them, the temperature of dry bulb outside the vehicle is 21 °C, the temperature of dry bulb inside the vehicle 21 °C, the temperature of wet bulb is 15.5 °C, the temperature of dew point inside the vehicle is

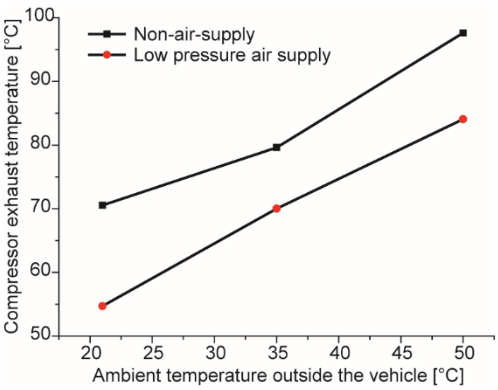

Figure 3. Variation of exhaust temperature of compressor with ambient temperature outside the vehicle

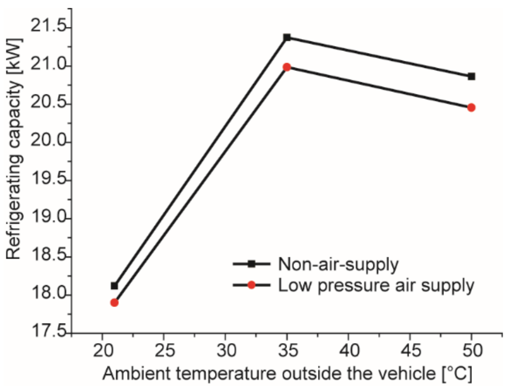

Figure 4. Variation of refrigerating capacity of the system with ambient temperature outside the vehicle

12.25 °C, and the evaporation temperature is lower than the dew point temperature and below zero, which results in serious frosting of the heat exchanger inside the vehicle and makes the refrigeration capacity decrease seriously.

Figures 5 and 6 show the variation of compressor power and COPc with ambient temperature outside the vehicle, respectively. It can be seen from figs. 5 and 6 that under the refrigeration condition, with the increase of ambient temperature, the compressor power of the system increases gradually, and the COPc of the system decreases gradually, and at each point of the same parameter, the compressor power of the non-air-supply system is higher than that of the low pressure air-supply system. The non-air-supply system COPc is less than the low pressure air-supply system and when ambient temperature outside the vehicle rises from 21 °C to 50 °C, the compressor power of the non-air-supply system is 7.6%, 5.6%, and 3.4% higher than that of the low pressure air-supply system, respectively, compared with the low pressure air-supply system, the COPc of the non-air-supply system is decreased by 6.1%, 3.7%, and 1.4%, respectively.

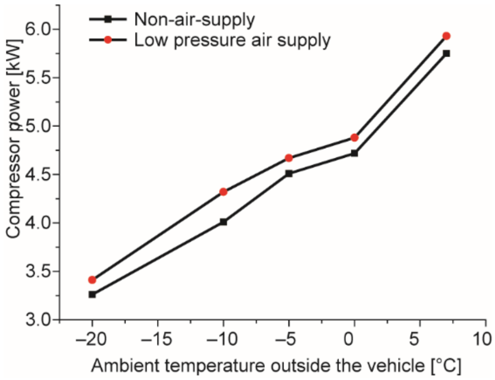

Figure 5. Variation of compressor power with ambient temperature outside the vehicle

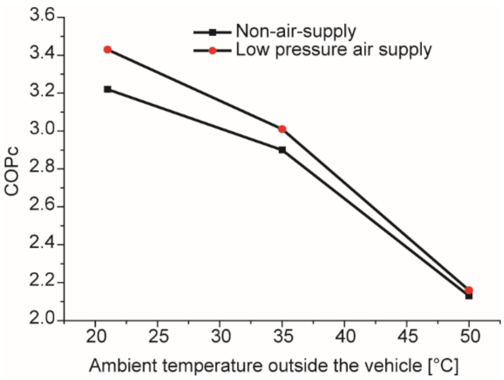

Figure 6. Variation of system COPc with ambient temperature outside the vehicle

Figure 7 shows the variation curve of compressor exhaust temperature with ambient temperature outside the vehicle. It can be seen from fig. 7 that the exhaust temperature of the compressor increases gradually with the decrease of the ambient temperature outside the vehicle under the heating condition, and the exhaust temperature of the non-air-supply system is higher than that of the low pressure air-supply system at the same parameter points. When the ambient temperature outside the vehicle decreases from 7 °C to –20 °C, the exhaust temperature of the low pressure air-supply system is 37.7 °C, 35.5 °C, 37.9 °C, 37.0 °C, and 26.2 °C lower than that of the non-air-supply system, respectively. Especially at ultra-low temperature –10 °C and –20 °C, the exhaust temperature of the non-air-supply system is more than 100 °C, while the exhaust temperature of the low pressure air-supply system is lower than 80 °C, which ensures the smooth operation of the system. Figure 8 shows the variation curve of heating capacity of system with the ambient temperature outside the vehicle. As can be seen from fig. 8, under the heating condition, with the decrease of the ambient temperature, the heating capacity of the system is reduced, and at all the same parameter points, the heating capacity of the non-air-supply system is less than that of the low pressure air-supply system and when the ambient temperature outside the vehicle is reduced from 7 °C to –20 °C, compared with the non-air-supply system, the heating capacity of the low pressure air-supply system is increased by 7.3%, 5.9%, 28.4%, 44.1%, and 46.2%, respectively.

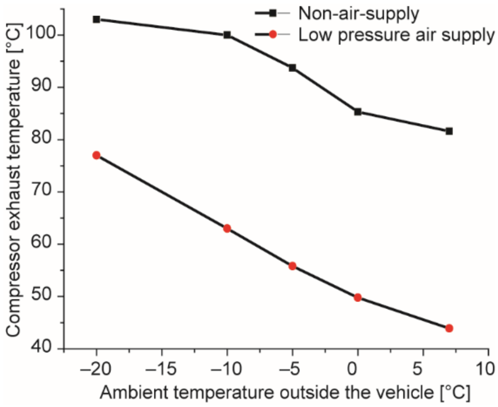

Figure 7. Variation of exhaust temperature of compressor with ambient temperature outside the vehicle

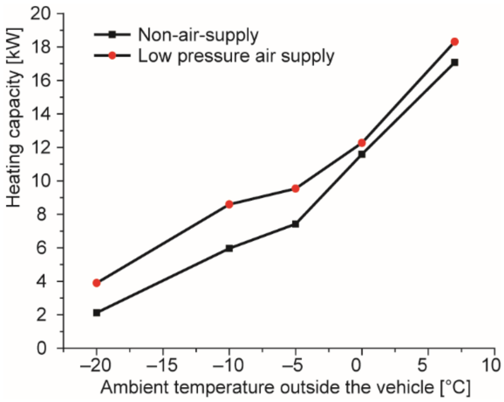

Figure 8. Variation of heating capacity of system with the ambient temperature outside the vehicle

Figures 9 and 10 show the variation of compressor power and of COP_h with ambient temperature outside the vehicle, respectively. It can be seen from figs. 10 and 11 that under heating conditions, the compressor power and COP_h of the system decrease gradually with the decrease of ambient temperature, and the compressor power and COP_h of the low pressure gas supply system are higher than those of the non-air-supply system at the same parameter points. When the ambient temperature outside the vehicle decreases from 7 °C to –20 °C, the compressor power of the low pressure air-supply system is 3.1%, 3.4%, 3.5%, 7.7%, and 4.6% higher than that of the non-air-supply system, respectively. Compared with the non-air-supply system, the COP_h of the low pressure air-supply system is increased by 3.7%, 2.4%, 24.2%, 33.6%, and 41.2%, respectively.

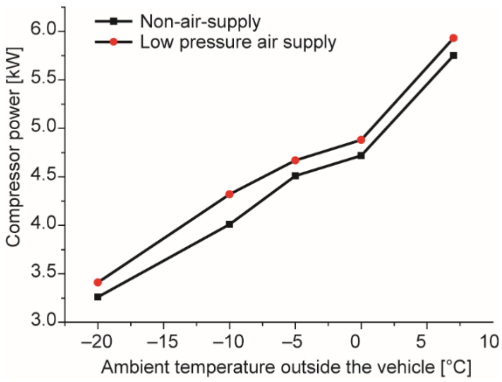

Figure 9. Variation of compressor power with ambient temperature outside the vehicle

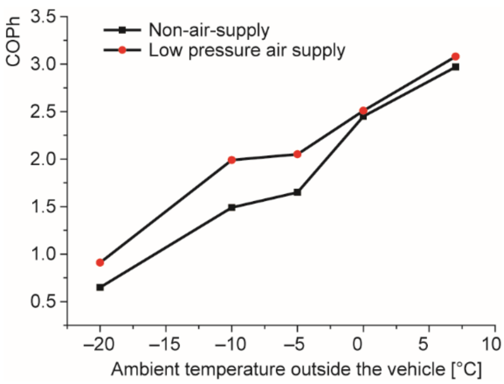

Figure 10. Variation of COP_h with ambient temperature outside the vehicle

Conclusions

- Under the refrigeration condition and the heating condition, the low pressure air-supply technology can significantly reduce the exhaust temperature of the compressor.

- Under the refrigeration condition, with the increase of the ambient temperature, the refrigerating capacity of the system increases at first and then decreases. At the high temperature of 50 °C, compared with the non-air-supply system, the refrigerating capacity of low pressure air-supply system is reduced by 2.0%, the compressor power is reduced by 3.4%, and the COPc is increased by 1.4%.
- Under the heating condition, with the decrease of ambient temperature, the heating capacity is improved. At ultra-low temperature of –10 °C and –20 °C, compared with the non-air-supply system, the heating capacity of the low pressure air-supply system is increased by 44.1% and 46.2%, and the compressor power is increased by 7.7% and 4.6%, respectively. The COP_h is increased by 33.6% and 41.2%, respectively.

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