Experimental Study on Heating Performance of a Vapor Injection ASHP for Electric Buses

Xinxin Han¹,²,³, Huiming Zou¹, *, Hongbo Xu¹, Changqing Tian¹
1 Beijing Key Laboratory of Thermal Science and Technology and Key Laboratory of Cryogenics, Technical Institute of Physics and Chemistry, CAS, Beijing 100190, China
2 Henan Polytechnic University, Jiaozuo 454000, China
3 University of Chinese Academy of Sciences, Beijing 100049, China

Abstract
In this paper, the heating performance and flow distribution of a vapor injection air source heat pump (ASHP) designed for electric buses is experimentally investigated under different working conditions by adjusting the opening of main-branch electronic expansion valve (EEV1) and injection-branch electronic expansion valve (EEV2). Under the condition of fixed EEV1 opening, the injection mass flow rate increases nearly linearly with the increasing of EEV2 opening and the main-branch mass flow rate has slight increase about 8.5%. The heating capacity increases with the increasing of injection ratio and there exists an optimum injection ratio to get the maximum COP 1.90. Under the condition of fixed EEV2 opening, the injection ratio decreases with the increasing of EEV1 opening. The heating capacity and COP both reach the maximum at 0.193 injection ratio, corresponding to 3.8°C superheat of evaporator.

Keywords: electric buses, vapor injection, heat pump

Nomenclature
Abbreviation
COP Coefficient of performance

Symbols
Q capacity
P pressure
t temperature
m mass flow rate
r ratio

Subscript
h heating
suc suction
inj injection
dis discharge
s supply air
m mass flow
1 main-branch
2 injection-branch

1. Introduction
In recent years, the industry of electric vehicles develops quickly in China. Air conditioning system plays an important role in providing comfort environment for the carriages. Compared with the combination of single refrigeration unit and Positive Temperature Coefficient (PTC) electric heater, Air Source Heat pump (ASHP) could provide both cooling and heating with one unit and has higher heating efficiency. Therefore, ASHP has got more and more application for its energy saving potential. However, the heating performance of conventional ASHP degrades dramatically with the dropping of ambient temperature. At extreme low ambient temperature, the conventional ASHP can’t supply enough heat for the carriages and even can’t work normally. Besides, in cold environment the decrease of COP will increase input power greatly, which will significantly reduce the driving mileage of electric vehicles. In order to improve the heating performance of ASHP at low ambient temperature, some techniques are provided, such as two stage compression, cascaded cycle, larger compressor displacement, vapor injection (VI) cycle etc. In all the techniques vapor injection is considered as a promising solution.
There are many researches on vapor injection heat pump for residential and commercial buildings [1-3]. Wang et al. [4] investigated an 11 kW vapor injection heat pump system using R410a as refrigerant. There was about 30% heating capacity improvement and 20% COP improvement compared with the conventional system at the ambient temperature of -17.8°C. Zhang et al. [5] built an economized vapor injection (EVI) ASHP with radiant floor heating and experimentally studied its heating performance. The results showed that the ASHP with EVI could improve thermal performance 4-6% than ASHP without EVI. Jie Xue et al. [6] experimentally studied a flash-tank (FT) vapor injection ASHP with R32. The COP of FT system is higher than conventional ASHP system as ambient temperature below -3°C and there exists an optimum injection ratio for maximum COP. Shuxue Xu [7] experimentally investigated the vapor injection heat pump using R1234yf, R32 and R1234yf/R32 mixture as refrigerant. Compared with no-injection system, heating capacity and COP were enhanced by 16%-20% and 13%-16%, respectively.

In electric vehicle industry, vapor injection ASHP also draws great attention, experimental and numerical studies are conducted [8-9]. Fei Qin et al. [10-11] carried out the experiment on vapor injection ASHP for electric cars at ambient temperature of -20°C. The results showed the heating performance of ASHP with three-porthole is better than that with single-porthole and the heating capacity of three-porthole system is improved by 28.6% compared with no-injection system. Young Uk Choi et al. [12] investigated the influence of injection positions and intermediate pressure on the heating performance of vapor injection ASHP for electric vehicle both in mathematical and experimental ways. It was concluded that the optimal injection port position was close to 300° and the optimal intermediate pressure ratio occurred below 0.25 in startup condition. Jongho Jung [13] Developed the simulation model of R134a vapor injection heat pump for electric vehicle and studied the effect of injection port shape and angle on heating performance of the system. The optimal angles of the single- and dual-injection ports were 440° and 535°/355°, respectively, with COP improvement by 7.5% and 9.8%, respectively.

As listed above, all the researches showed that vapor injection heat pump could improve heating performance and expand the applicable temperature range of ASHP. However, most studies are on application for residential and commercial buildings or electric cars, there are few studies on vapor injection ASHP for electric buses. Because heat pumps for electric buses have different characteristics from that for buildings or electric cars, more research work, especially experimental work at extreme low temperature, is needed. In vapor injection system, injection ratio has significant effect on the heating performance [14-15]. Some researchers investigated the effect of intermediate pressure or injection-branch electronic expansion valve (EEV) on the heating performance [6,12]. However, the effect of main-branch EEV on system heating performance and flow characteristic is not analyzed. In this paper, a vapor injection ASHP for electric bus is developed and the heating performance at ambient temperature -20°C is measured. The effect of main-branch EEV and injection-branch EEV on mass flow rate distribution and heating performance is analyzed.

2. Experimental setup and test procedure

Fig 1 illustrates the test bench of ASHP with internal heat exchanger (IHX) for electric buses. The unit is set up with two independent cycle systems and the two indoor heat exchangers are shared by the two systems. Thus, the supply air temperature of two supply air ducts can be kept same at any time.

Compared with single-stage cycle, the compressor of vapor injection cycle has three portholes: suction, discharge and injection. Besides, the IHX is added and two EEV are used. The main-branch valve EEV1 and injection-branch valve EEV2 both have 500 steps. The superheat of evaporator and injection pressure can be
regulated by EEV1 and EEV2, respectively. The single-stage cycle and vapor-injection cycle can be switched by the opening of EEV2. As it is set to 0, it’s single-stage cycle. Otherwise, it’s vapor-injection cycle.

The vapor-injection ASHP was measured in psychrometric test room and the test points were shown in Fig 1. The test parameters of refrigerant side include temperature, pressure and mass flow rate. The instrumentation and uncertainties are summarized in Table 1.

The experimental test conditions are: outdoor dry temperature -20°C, indoor dry temperature 15°C, outdoor air flow rate 3500 m³/h, indoor air flow rate 2600 m³/h, compressor frequency 80 Hz. Under this condition, experiments on EEV adjustment are conducted: (1) the relative opening of injection-branch EEV2 is adjusted from 0 to 1 as main-branch EEV1 opening is fixed at 0.21, (2) the relative opening of EEV1 is adjusted from 0.16 to 0.23 as EEV2 opening is fixed at 0.5.

<table>
<thead>
<tr>
<th>Table 1 Heat pump test conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>Temperature/°C</td>
</tr>
<tr>
<td>Pressure/MPa</td>
</tr>
<tr>
<td>Mass flow rate of Ref./(kg/h)</td>
</tr>
</tbody>
</table>

3. Results and discussion

3.1 The effect of injection-branch EEV2

Fig 2 shows the effect of injection-branch EEV2 on the heating performance. Fig 2(a) shows with the increasing of EEV2 opening, compressor suction pressure is nearly unchanged and discharge pressure has a slight increase. That’s because the suction pressure and discharge pressure are mainly determined by the outdoor and indoor air temperature. The injection pressure increases from 0.52 MPa to 0.83 MPa. Fig 2(b) shows the variation of mass flow rate. With the increasing of EEV2 opening, the main-branch mass flow rate m₁ increases slightly by 8.5% and the injection mass flow rate m₂ increases nearly linearly. Therefore, the injection ratio r_m, ratio of m₂ to m₁, increases from 0 to 0.45.

Fig 2(c) shows as the injection ratio r_m increases from 0 to 0.45, the discharge temperature t₁ decreases from 76°C to 49°C. It reflects injection could reduce discharge temperature apparently. The supply air temperature tₙ increases from 20.7 °C to 22.2 °C, which is related with heating capacity. Fig 2(d) shows the heating capacity increases gradually as the injection ratio rising. The maximum heating capacity at 0.45 injection ratio increases by 23.4% compared with single-stage cycle. The COP goes up firstly and then goes down. It reaches the maximum value 1.90 at 0.193 injection ratio.
3.2 The effect of main-branch EEV1

Fig 3 shows the effect of main-branch EEV1 on the heating performance. Fig 3(a) shows with the increasing of EEV1 opening, compressor injection pressure and discharge pressure are nearly unchanged and suction pressure has a slight increase. Fig 3(b) shows the main-branch mass flow rate m1 increases from 102 to 146 kg/h and the injection mass flow rate m2 decreases from 42 to 23 kg/h with the increasing of EEV1 opening. Therefore, the injection ratio decreases from 0.41 to 0.16.

Fig 3(c) shows with the increasing of injection ratio, the discharge temperature and supply air temperature both have a maximum. The variation of discharge temperature is the result of combined effect of suction mass flow rate and injection mass flow rate. With the increasing of injection ratio, the suction mass flow rate decreases and injection mass flow rate increases, which will cause the opposite effect on discharge temperature. Therefore, it firstly goes up and then goes down. Fig 3(d) shows the heating capacity and COP have similar change trend and they both reach a maximum at 0.193 injection ratio. The optimum superheat at evaporator outlet responding to the optimum injection ratio 0.193 is 3.8°C.

4. Conclusions

In this paper, the heating performance of ASHP with internal heat exchanger under working condition -20/15°C at different main-branch EEV opening and injection-branch EEV opening are investigated. The following conclusions are drawn:

1) As main-branch EEV opening is fixed, the injection mass flow rate increases nearly linearly with the opening of injection-branch EEV and the main-branch mass flow rate has slight increase about 8.5%. The heating capacity increases with the increasing of injection ratio and there exists an optimum injection ratio to get the maximum COP 1.90.

2) As injection-branch EEV opening is fixed, the main-branch mass flow rate increases with the opening of main-branch EEV. However, the injection mass flow rate decreases. Therefore, the injection ratio decreases. For heating capacity and COP, they both reach the maximum at 0.193 injection ratio, corresponding to 3.8°C superheat of evaporator.

Acknowledgement

We would like to thank the support by the National Key Research and Development Program of China (No.2017YFB0103801) and the Natural Science Foundation of China (No. 51676201).
Reference


