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Experimental investigation on heating performance of heat pump for electric vehicles at −20 °C ambient temperature ☆

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ABSTRACT

Since the performance of conventional air source heat pump (ASHP) for electric vehicles (EVs) is apt to decline sharply in low ambient temperature, it will consume more electricity of the cell, and affect driving mileage in cold regions. Aiming at developing high efficiency heating system for EVs in cold regions, an ASHP system applying refrigerant injection for EVs is designed, as well as the test bench is built to investigate its performance. According to the operation condition of EVs, heating performances are tested on different in-car inlet air temperature and various fresh air ratios under −20 °C ambient temperature. The system cycle process with refrigerant injection, as well as the influences of refrigerant injection and dryness are also analyzed and discussed. The results show that the heating capacity of the ASHP with refrigerant injection can be increased up to 31%, and in comparison with the conventional heat pump system its heating performance is better when in-car inlet temperature is above −10 °C. Therefore, ASHP with refrigerant injection has great potentiality to be applied for the EVs in cold regions.

1. Introduction

In electric vehicles (EVs), the air-conditioning (AC) system plays a significant role [1], in providing comfortable, safe driving conditions and energy utilization [2]. Unlike the traditional cars with internal combustion engines (ICE), EVs cannot utilize the waste heat of ICE to keep warm inside the car in winter. The AC system is also driven by cell electricity, which severely affects the power consumption and driving performance.

Electric heating, such as PTC electric heater, is employed to auxiliary raise supply air temperature. However, the pure electrical heating system will decrease the driving mileage up to 50%, so it could be developed broadly because of its low efficiency [3]. Alternatively, air source heat pump (ASHP) is a promising way to meet both the heating and cooling demand with a sole system [4]. Esen et al. [5] analyzed the economy of ASHP, and calculated the daily mean COP of it which is 3.1 in building. Meyer et al. [6] compared the experimental performance of HP with the date in literature using traditional car heating methods which showed the application of HP can improve the vehicle driving performance. Direk et al. [7] tested the performances of an ASHP in vehicle under different compressor speeds. Xie [8] investigated the performance of an ASHP in EVs by simulation and experimentation. All these researches show that the ASHP is able to utilize less energy to make better performance and drivability. However, its heating performance of ASHP will decline sharply in low ambient temperature (low than −5 °C), which is opposite to the variation trend of heating load. Therefore, developing high efficiency HP system to save battery power and raise EVs driving mileage for low ambient temperature has become a hot research topic. So far, the ambient temperature of the HP system being researched for EVs is normally around at 0 °C, and rare researches are taking under −5 °C.

In building or household, some technical approaches are used to solve the problem on heating performance in low ambient temperature, such as two-stage compression cycle [9,10], vapor pass way before compressor, and refrigerant injection during compressing. While the structure of first system is too complicated, and effect of the second one is smaller than refrigerant injection to

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Nomenclature

Symbols

A	area
Cond.	condenser
c_p	specific heat
Diff.	difference
Evap.	evaporator
h	enthalpy (kJ kg^{-1})
m	mass flow rate (kg s^{-1})
P	pressure (MPa)
Q	quality, heating capacity
V	voltage
v	velocity
W	power (kW)
Q	heating capacity (kW)
R	ratio
RQ	heating capacity changing ratio
RSH	discharge superheat changing ratio
SH	superheat (°C)
T, Temp.	temperature (°C)
x	dryness
ε	relative thermo-dynamical perfectness
ρ	density

Subscript

a	air
cond	condenser
dis	discharge
evap	evaporator
h	heat
in	inlet
inj	injection
liq	liquid
max	maximum
s	supply
suc	suction
vap	vapor
0	original, no-injection

compressor [11]. Taking the overall consideration, the refrigerant injection technique is a viable method to improve the HP performance, which will increase refrigerant mass flow rate of compressor discharge and decrease the enthalpy of evaporator inlet [12]. In building and household AC system, studies on refrigerant injection have attracted great attention [13]. Ma et al. [14–16] conducted a series of researches to analyze the cycle process and system performance of refrigerant injection system. Wang et al. [17–19] investigated refrigerant injection process and system by experiment and built a dynamic model to analyze the influence factors. Heo et al. [20,21] put forward various system derived forms. Cho et al. [22] aimed at liquid refrigerant injection system, and analyzed the influence. Roh et al. [23] compared the heating performance of vapor injection into compressor and accumulator (before compressor suction) with experiment, and the results showed that the vapor injection into compressor displayed considerable improvement of heating capacities rather than into accumulator. Almost all researches showed that the refrigerant injection would improve the heating performance of HP system in cold region [13]. However, the refrigerants in these researches are usually used in household AC system such as R22, R410A and R32, whose performances are much different to R134a, the refrigerant used in vehicle AC system. These research results can only be for reference, and more research forces on HP for EV need to operate. With the difference from buildings and household, AC system for EVs owns its distinct characteristics, such as lightness, small, anti-knock and big as well as various loads. Moreover, based on the demand of moisture condensation control on the window screen of EVs, big ratio of fresh air supplement, even all fresh air, is necessary, which means the in-car inlet air temperature is very low, even less than −20 °C. It is rare in buildings or household ACs, and little research has been presented the on this operation condition.

Aiming at the cold region, an ASHP system for EVs using refrigerant injection and test bench has been built to investigate the performance in the present work. According to the operation condition of EVs, the heating performances are tested on various fresh air ratios, showed as different in-car inlet air temperature conditions, at −20 °C ambient temperature. Combining with our former research about numerical simulation of refrigerant injection [24], the system cycle process with refrigerant injection for EVs, as well as the influence of refrigerant injection and dryness of refrigerant injected will be analyzed and discussed. The development of ASHP and investigation of system performance will also promote the industrialization and practicability of EVs.

2. Experimental setup and procedure

2.1. Test bench setup

A test bench of ASHP for EVs using scroll compressor with refrigerant injection has been built to investigate the heating performance on the HP system. Fig. 1 illustrates the schematic diagram of the test system.

There are three refrigerant-air heat exchangers in the ASHP prototype system, separately as in-car condenser, in-car evaporator, and out-car heat exchanger. These heat exchangers are all of light-weight, high-efficiency aluminum micro-channel heat exchangers for EV. The system employs two electric three-way valves (TV), as TV1 and TV2 shown in Fig. 1, to switch the cooling mode or heating mode by bypassing the in-car condenser or in-car evaporator. The driving force of the HP cycle is an electric scroll compressor with refrigerant injection, which is reprocessed from a traditional electric compressor for EVs (27cc) by adding injection points and one-way discs valve. The system adopts an intermediate heat exchanger before injection process to reduce the evaporator inlet enthalpy and raise the dryness of injection refrigerant. In the experiment, the No. 2 valve in the injection branch (V2 in Fig. 1) is employed to control the refrigerant injection running or not by on-off.

The heating mode of the HP system is tested in this study. The three-way valve 1 (TV1) is adjusted to connect the compressor outlet and in-car condenser inlet, and the three-way-valve 2 (TV 2) is adjusted to pass by the in-car evaporator. The refrigerant cycle direct are shown in Fig. 1 by the arrows. It should be explained that the refrigerant is divided into two branches as injection branch and main branch. In injection branch, refrigerant passes through electronic expansion valve 2 (EXV 2) to injection pressure, and is heated by refrigerant in main branch to evaporate, then injected to the compressor working chamber. The refrigerant in main branch is cooled by injection refrigerant to subcooled liquid, and throttled by electronic expansion valve 1 (EXV1).

An enthalpy difference test bench is employed to test the system performance. The in-car heat exchangers (in-car condenser and in-car evaporator) and out-car heat exchanger are placed in