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Research Paper

Experimental study on combined defrosting performance of heat pump air conditioning system for pure electric vehicle in low temperature

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HIGHLIGHTS

- A test rig of air conditioning system for pure electric vehicles is designed and established.
- A composite defrost technology is proposed and applied.
- Defrosting time of heat exchanger outside the vehicle can be controlled within 100 s.

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ABSTRACT

The development of defrosting technology is a crucial technical barrier to the application of the heat pump air conditioning system for the pure electric vehicle. The frosting on the air conditioning system significantly affects systematic performance and reliable operation especially in low temperature and high humidity climate condition. Therefore, in this paper, an experimental study of low-temperature heat pump air conditioning system with the combined defrost technology of increasing enthalpy and temperature is carried out to find proper thermal management solutions. Based on the reverse-cycle methods, the combined defrost technology makes full use of the compressor air-supplying enthalpy-adding, air-cooled heat exchanger inside the vehicle preheating, temperature-raising, enthalpy-adding and the external heat exchanger condensation temperature-increasing technologies. The fast defrosting process can be realized by means of releasing the condensation heat and volume significantly while the outer heat exchanger is conducting a defrosting operation. Meanwhile, the cold cabin sensitivity can be reduced while defrosting process taking place correspondingly. Experimental results show that under the operating condition of −20 °C outside environment temperature and 80% relative humidity, instant defrosting time at fully defrosted air-cooled heat exchanger outside the vehicle can be controlled within 100 s.

1. Introduction

With the intensifying energy crisis and the increasing environmental problems, it is imperative to take actions for energy saving and environmental protections on automotive industries. Pure electric vehicle (PEV) as disruptive technology provide an alternative way to replace traditional automotive industry to achieve sustainable development shortly. To maintain the PEV working at proper temperature and humidity condition, vehicular air conditioning system becomes an indispensable sub-system that it not only provides the thermal comfort in the cabin but also contributes to the safeties of traction batteries and power electronics [1,2]. The wide-ranging features of the evolving environment outside the car has also raised the requests on the air conditioning system performance in the PEV. And the heat pump air conditioning system has such advantages as high efficiency, energy saving, environmental protection that it is becoming the priority of vehicular air conditioning in the PEV [3–6]. There are, in spite of merits mentioned above, still some issues of itself especially in low temperature and high humidity ambient. The exterior heat exchanger of the heat pump prone to frost while the system is in heating mode. It not only causes both blockages of air channels and increase of ventilation resistance but also the overall thermal resistance of exterior heat exchanger. Consequently, the frost will be accumulated and thickened resulting in severe deterioration of working performance and reliability of vehicular conditioning system [7–9]. Therefore, it is important to find out the main factors of influencing

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defrost in the exterior heat exchanger to reduce defrosting time through reasonable and effective control strategies.

An evaporator is a unit where it is easy to frost, so to analyze operating characteristics of the evaporator in the case of defrosting is the key to studying the defrosting of the heat pump system. In the 1970s, Sanders, a Dutch [10] began the study on defrosting of air-conditioning evaporators, who created a model of evaporator defrosting of the air-conditioning system in his doctoral thesis, and recorded the whole course of defrosting through experiments and analyzed the distribution of energy consumption in the system during the defrosting. In the 1980s, E.N. АНДРАЧНИКОВ, a scholar of the former Soviet Union [11] proposed an efficient way of automatic evaporator defrosting, and the system was designed with main and secondary evaporators, and a 2 PM time relay was used for control over the two evaporators defrosting alternately. O'Neal and Payne [12] studied the effect of the air volume of the evaporator fan on the defrosting performance. Based on the basic air volume of 72 m^3/min, experiments were conducted at a low air volume of 40 m^3/min and a high air volume of 88 m^3/min respectively. The results showed that compared with the basic air volume, the defrosting time and water accumulation after defrosting were significantly reduced in the low air volume, yet it lowered the evaporating temperature of the system and increased the frosting rate of heat exchanger; under the high air volume, the heat exchange of the system was increased, meanwhile, the defrosting time was prolonged, yet it increased the evaporating temperature of the system which lowered the frosting rate of the heat exchanger. Padhmanabhan [13] compared the performance difference between finned evaporator and microchannel evaporator during defrosting and found that the defrosting time of the finned evaporator was about twice of that of microchannel evaporator, but the frosting rate of the micro-channel was apparently higher than that of the finned evaporator.

In recent years, computers are used to simulate and analyze the defrosting performance of the heat pump system, which has made rapid progress. Liu [14], based on the energy conservation equation, created a hot air defrosting dynamic cycle model, aiming to simulate the performances of evaporator and condenser at reverse cycle defrosting. Through experiments, the model proved that it could not only simulate characteristics of defrosting of the system, but also affect the whole defrosting course. Dopazo [15] created a heat pump evaporator defrosting model on the basis of hot air, the model divided the defrosting process into six stages: preheating, defrosting outside tubes, defrosting of fins, induced air, water film formed on fins surfaces, drying and heating, the control volume in each stage was represented by a node in the system model. A finite difference method is used to solve the equation, and the results included time needed for defrosting, energy distribution during defrosting, characteristics of instantaneous refrigerant and temperature distribution of finned tubes. Qu [16,17] firstly studied features of the multi-tube heat exchanger in defrosting, and the results showed that the defrosting time of upper layers of tubes was faster than that of the lower ones, the defrosting efficiency was estimated to be 34.5%. In order to quantitatively analyze the effect of various layers of tubes on defrosting, he created a semi-empirical mathematical model and the defrosting time trend calculated for different layers from top to bottom was the same as the conclusion of the experiment, and pointed out that the frosting time of lower layers of tubes reduced the defrosting efficiency of the system.

At present, it is still at the preliminary stage that there are few researches on defrosting of heat pump PEV air conditioning system. Zhong and others make defrosting control regarding traditional vehicle design in combination with the electronic expansion valve, and enhance air volume of the evaporator while increasing the electronic expansion valve opening [18]. Wu et al. find out through experiment that while the heat pump air conditioning system for PEV is supplying heat at low temperature, the outdoor micro channel heat exchanger was frosted severely, which influences the heating capacity of the system and the coefficient of performance, but the defrosting solution is not proposed [19]. Therefore, the temporary tables of low-temperature heat pump air conditioning system for PEV is designed [9], and the condensation temperature and defrosting speed under different working conditions are tested. In addition, the variants are analysed such as system cooling capacity, exhaust temperature, outlet air temperature and the import and export temperature of exterior heat exchanger along with the changes of system defrost operating time. The influence on exterior heat exchanger defrosting performance by different factors is also studied in order to determine the fast and reliable defrosting methodand provide an experimental basis for further improvement of the performance of PEV air conditioning system.

2. Heat pump type air conditioning system for PEV

The test rig of a low-temperature heat pump air conditioning system for PEV is designed and established using the quasi-two-stages compression principle. It combines with both the characteristics of low-temperature heat pump technology and automotive air conditioning conditions as shown in Fig. 1. This test rig consists of a compressor, four-way valve, air-cooled heat exchanger outside the vehicle, one-way valve, liquid storage drer, main expansion valve, air-cooled heat exchanger inside the vehicle, air-supplying expansion valve, and intermediate heat exchanger as well as other auxiliary parts.

The system can achieve multiple basic working modes of electric vehicle cooling, battery electric heating, and air-cooled heat exchanger outside the vehicle defrosting under different working conditions. In cooling mode, the four-way valve switches into the cooling channel which is the same as conventional car air conditioning cooling processes. The circulating refrigerant is discharged through compressor with high pressure and subsequently flow into air-cooled heat exchanger outside the vehicle for condensation process. After that, it flows into liquid storage drier through the one-way valve. Then the refrigerant flows into the main expansion valve after going through the intermediate heat exchanger, and then low pressure and low-temperature flow enter into an air-cooled heat exchanger inside the vehicle for evaporation through the one-way valve. Eventually, it is absorbed by the compressor after going through the four-way valve.

In heating mode, the four-way valve switches into the heating channel, the circulating refrigerant is discharged from the

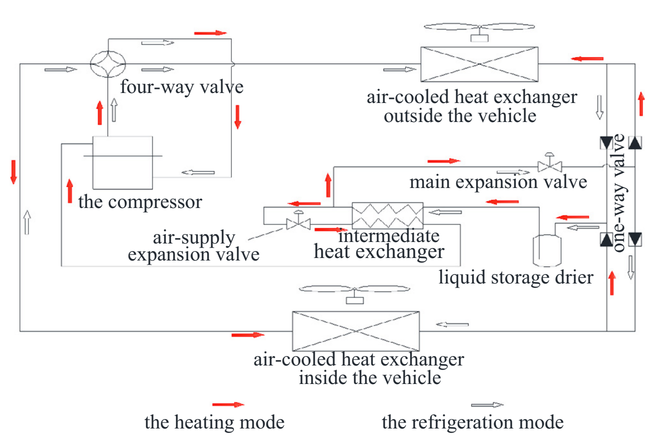

Fig. 1. Diagram of the heat pump air conditioning system of the pure electric vehicle.