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Advances on air conditioning and heat pump system in electric vehicles – A review

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ABSTRACT

There is a rising interest in electric vehicle's climate control system including cooling and heating. Electric vehicles (EVs, including hybrid electric vehicles and full electric vehicles) have inadequate waste heat to warm up the cabin and the climate control system has a very significant effect on the energy consumption efficiency and operating mileage. Heat pump (HP) is one approach for energy consumption efficiency improvement in EVs which can supply cooling and heating capacity. A literature review was performed on the vapor compression HP cycle design, performance characteristics, and challenges for variable working fluids for electric vehicles. The non-vapor compressor HP systems were also analyzed including the applications of magnetocaloric effect and thermoelectric effect. It seems heat pump system is a reasonable and feasible option in EV's climate control system if some essential issues could be solved. The mobile climate control systems based on magnetocaloric effect and thermoelectric effect could be the supplementary methods in future applications.

Contents

1. Introduction

Mobile climate control system includes air conditioning (AC, cooling) and heating, which is an essential subsystem in vehicles. It functions in two layers. One is operating safety in visibility

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(defogging and deicing), and the other is to maintain the cabin comfort including temperature, relative humidity and air velocity.

Considering the global warming and CO_2 emission, more efficient engines with less waste heat is being developed. At the same time, electric vehicles (EVs) are becoming increasingly popular. This trend is raising new challenges in mobile climate control system design. For example, in winter, the waste heat from gasoline engine will be used for cabin heating and window de-icing, whose amount is more than 5 kW. But in full hybrid electric vehicles, engine waste heat is insufficient (waste heat from an electric engine is about 2 kW at 40 °C) and more electric energy from the battery is needed, which will affect the driving mileage significantly. Hannan et al. [1] reviewed the challenges in hybrid electric vehicles (HEVs), but they did not mention the effect of climate control system on batteries' performance. Khoury and Clodic [2] experimentally studied the effect of electrical AC operation on the electricity consumption in a hybrid electric vehicle. In their study, the most important achievement was that some test procedures and testing conditions were proposed according to the driving conditions, climatic conditions and AC operation conditions based on the others studies [3]. The test results showed that AC system became the largest energy consumption system for a highly efficient hybrid vehicle and AC system had a high impact on vehicle overall fuel consumption. In full electric vehicles (FEVs), the newest heat pump (HP) technologies could reduce the driving distance with fully charged batteries by 8% in cold conditions [4,5]. The experimental data showed that AC full load driving characteristics of different road and speed cycles had a significant influence on the total driving range [6]. The reduction percentage was up to 16.7% and 50.0% for cooling and heating, respectively. It was concluded that the driving range reduction was very sensitive on cooling and heating system operations. The difficulty is improving the efficiency of climate control system and minimizing energy consumption in both cooling and heating modes.

In the present paper, the state-of-art technologies in air conditioning and heat pump systems available for electric vehicles will be comprehensively reviewed. The electric vehicles (EVs) include hybrid electric vehicles (HEVs, including full hybrid, mild hybrid, plug-in hybrid) and full electric vehicles (FEVs). The structure of the present review paper is organized as follows: First, the AC/HP systems based on vapor compression cycle are analyzed for EVs' applications. In this section, the technology, developments and challenges for different working fluids and system types are comprehensively reviewed. Second, the AC/HP systems based on non-vapor compression cycles including the applications of magnetocaloric effect and thermoelectric effect are mainly introduced from materials, system structures and performance. Finally, the conclusion is drawn according to the previous reviews and analysis.

2. AC/HP based on vapor compression cycle

The vapor compression cycle is still dominant in mobile air conditioning systems. Considering convenient replacement, low cost and easy maintenance, the mobile industry desires a direct transit from conventional vehicles to electric vehicles. From this point of view, there are some proposals based on the current mobile AC and heating technologies.

2.1. Advances in R134a systems

In general, air conditioning system plus electric resistance heater/fuel fired heater is the basic option for EVs. The option seems the easiest one with few changes. The changes are electrically driven compressor instead of mechanically driven compressor and electric heater instead of hot coolant heater core. A 42 V electric air conditioning system called E-A/CS was proposed, which consisted of a compressor, a blower, an integrated positive thermal coefficient (PTC) heater, inverter, pipes and other heat exchangers [7]. The biggest advantage of a 42 V AC system was reducing the system electric amperage below 100 A and increasing the component overall efficiency roughly to as high as 50–80%. The cabin temperature curve showed the E-A/CS could keep a more stable and comfortable interior environment compared with an externally controlled mechanical compressor system under hot weather conditions. The system could still achieve a relatively better thermal environment under very cold weather conditions, but its energy was derived from the battery electricity. The system also possessed advantages in environment protection, system configuration and safety. Currently, PTC heater is widely used as auxiliary heating in gasoline engine vehicles and EVs. There are some barriers for PTC heaters, such as high cost with high power (>2 kW) and more energy consumption (the ratio of heat output to electric input is less than 1.0). The PTC heater can lead up to 24% losses of the driving distance with fully charged batteries [5]. According to the second law of thermodynamics, the coefficient of performance (COP) of a heat pump system is larger than 1.0. From this point of view, a heat pump system appears a reasonable method to improve the efficiency of climate control system in EVs.

Suzuki and Katsuya [8] compared the air conditioning system between the conventional vehicle and electric vehicle and pointed out the necessary modifications for system efficiency improvement. They also proposed a heat pump system for electric vehicle, in which one 4-way valve, two expansion valves and several check valves were used to reverse the refrigerant flow direction as shown in Fig. 1. This system could provide cooling, heating, demisting and dehumidifying. The system details were published in the technical paper [8] including system diagram, electric compressor and electric expansion valve specifications. The working fluid was R134a and only two test data were published. The experimental results showed the system cooling and heating capacities under 40 °C and −10 °C ambient temperature were 2.9 kW and 2.3 kW, respectively, and the COPs were 2.9 and 2.3, respectively. This technical paper seems the first R134a heat pump system for EVs with open experimental data.

Promme [9] described a similar heat pump system for electric vehicle as Suzuki and Katsuya [8]. But he pointed out that there was an ice formation on the heat exchanger surface when the ambient temperature was below −10 °C. He proposed an improved heat pump system with an additional external heat source which could utilize the waste heat of the main battery, driven electric motor and its power control unit as shown in Fig. 2. This was an optimized and simplified system with the same cooling/heating functions. One specially designed device, called bi-directional receiver/expansion device, as shown in Fig. 3 could be used to realize the following functions: refrigerant filtering and drying, refrigerant accumulator, refrigerant expansion and cooling/heating mode operation. The bi-directional receiver/expansion device optimized the system and six components were replaced (2 expansion valves, 2 check valves, and 2 receivers). The bench test results of the improved system showed that 2.5 kW heating capacity was gained from the heat pump system under −10 °C ambient temperature, in which 0.5 kW heat was recovered from the battery. In this condition, the energy saving on the main battery was estimated to be about 15% compared with a PTC heater system. The improved one was less sensitive with frost formation on the external heat exchanger and more stable in winter conditions compared with the conventional heat pump system. In the AC mode, cabin temperature of 24 °C could be