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Experimental investigation on an integrated thermal management system with heat pipe heat exchanger for electric vehicle

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ABSTRACT

An integrated thermal management system combining a heat pipe battery cooling/preheating system with the heat pump air conditioning system is presented to fulfill the comprehensive energy utilization for electric vehicles. A test bench with battery heat pipe heat exchanger and heat pump air conditioning for a regular five-chair electric car is set up to research the performance of this integrated system under different working conditions. The investigation results show that as the system is designed to meet the basic cabinet cooling demand, the additional parallel branch of battery chiller is a good way to solve the battery group cooling problem, which can supply about 20% additional cooling capacity without input power increase. Its coefficient of performance for cabinet heating is around 1.34 at −20 °C out-car temperature and 20 °C in-car temperature. The specific heat of the battery group is tested about 1.24 kJ/kg °C. There exists a necessary temperature condition for the heat pipe heat exchanger to start action. The heat pipe heat transfer performance is around 0.87 W/°C on cooling mode and 1.11 W/°C on preheating mode. The gravity role makes the heat transfer performance of the heat pipe on preheating mode better than that on cooling mode.

1. Introduction

Electric vehicle (EV) is an important development orientation to alleviate the traditional automobile exhaust problem. However, thermal management including battery temperature control and cabinet air conditioning is a big challenge for EV, as the traditional engine and oil tank are replaced by electric motor and battery groups.

Lots of heat inside of the battery generated by the electrochemical reaction will raise the battery temperature up sharply, affect its working efficiency badly and even cause safety problem [1,2]. Sato [3] analyzed the thermal behavior of lithium-ion batteries showing that when the battery temperature was over 50 °C, charging efficiency and life cycle would be considerably diminished. Khateeb et al. [4] pointed out that the safety of the Li-ion battery would descend when it operated at the temperature range of 70–100 °C. Studies have shown that there is a necessary temperature range for battery to make sure its performance and service life. Pesaran [5] presented that the best range of operating temperature for batteries such as lead-acid, NiMH, and Li-ion are from 25 to 40 °C and suitable temperature distribution from module to module is below 50 °C. To control the batteries in the suitable temperature range, there are several methods presented [6–12], such as by air directly, by liquid with plate heat exchanger or by refrigerant phase change with plate or pipe heat exchanger. However, investigations on the thermal behavior of batteries [5,4,13] show that the relationship between the generated heat and discharge rate is nonlinear direct ratio and the higher the discharge rate is, the quicker the increase rate of the generated heat will be. While the discharge rate changes with the working conditions such as acceleration, deceleration, uphill, and downhill. So generated heat of the battery is variable and its instantaneous value is very high. This means the cooling capacity of the battery temperature control system with these normal methods has to be set high enough to avoid the battery on extremely high temperature and lead to an over-size thermal management system. Therefore it is very significant to search for a more efficient battery heat-transfer method to simplify the EV thermal management system.

Heat pipe, as a high efficient heat-transfer device combining the principles of both thermal conductivity and phase transition, is a

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Nomenclature

A_{hp}	contact superficial area with coolant of each heat pipe (m^2)
c_{b}	specific heat of battery group (kJ/kg °C)
c_{c}	specific heat of coolant (kJ/kg °C)
m_{b}	mass of battery group (kg)
m_{c}	mass of coolant (kg)
n	heat pipe number
Q_{bi}	batteries internal heat variation (kW)
Q_{c}	cooling capacity by battery chiller (kW)
Q_{ci}	coolant internal heat variation (kW)
Q_{g}	generated heat by batteries (kW)
Q_{p}	preheating heat by PTC (kW)
Q_{t}	transferred heat by HPHE (kW)
q_{hp}	heat transfer coefficient of each heat pipe (W/°C)
T_{ba}	average temperature of battery group (°C)
T_{bo}	coolant outlet temperature (°C)
T_{bi}	coolant inlet temperature (°C)
T_{ca}	coolant average temperature (°C)
ΔT	average temperature difference between the battery group and the coolant (°C)
t	time (s)

novel idea to apply on the temperature control of EV battery [14]. Actually, because of its highly effective thermal conductivity, heat pipe has been applied successfully in many fields such as electron cooling, solar heater and energy recovering [15,16]. As for the above mentioned EV battery thermal characteristics, heat pipes between the batteries can help transfer the heat out to the coolant so that the batteries can be maintained in the best operating temperature range under variable working conditions and the temperature difference between batteries can be eliminated [17]. Moreover, because the coolant system has enough thermal capacity, the cooling load can be much lower than that of the instant cooling method. It just needs to meet the average heat dissipation demand instead of the peak generated heat during high discharge rate conditions. Therefore, heat pipe is a promising development orientation for batteries thermal management of EV. Authors' initial investigations have shown that the heat pipe cooling is an effective method [18]. However, the previous study results were mainly concentrating on the basic thermal performance of a single heat pipe unit with a simple experimental apparatus. The thermal performance of the heat pipe heat exchanger (HPHE) for the practical EV battery group still has not been researched, which might be different from that of the single heat pipe because of cluster effect.

On the other hand, since EV has no engine to drive compressor for cooling and no waste engine heat for heating, heat pump system with motor-driven compressor is an important development trend. The investigation on the performance of heat pump system has become a major topic of EV air-conditioning. Suzuki and Katsuya [19] proposed a heat pump system for electric vehicle with functions of cooling, heating, demisting and dehumidifying and their experimental results showed the feasibility of heat pump. However, heat pump system has a shortcoming that its heating capacity drops sharply with the decreasing outdoor temperature. Hosoz and Direk [20,21] indicated this feature by investigating the performance of R134a heat pump system transformed for the original automobile air conditioning system. In recent years many advances on heat pump system for EV have been presented [22]. Authors [23,24] have also engaged in the heat pump performance improvement with injection technology and got notable achievement in system heating capacity and coefficient of performance (COP) under extremely cold condition. However when it comes to practical performance of the heat pump system combining with battery temperature control system, there is few literature either.

In this paper, an integrated thermal management system combining a HPHE for battery cooling/preheating with a heat pump air conditioning is presented to investigate its performance characteristics on different working conditions. Cooling and heating performances of the system, as well as the thermal performance of HPHE, are investigated by bench test, hoping to present a significative reference for the EV thermal management.

2. System description and experimental bench setup

2.1. System description

Fig. 1 shows the diagram of the heat pump coupling with battery cooling/preheating system based on regular five-chair electric cars and takes R134a as refrigerant. Its working temperature ranges from −20 °C to 45 °C. The heat pump system mainly consists of a variable-frequency scroll compressor, an outside heat exchanger with a fan, a liquid vapor separator, four refrigerant valves (RV), a condenser followed by an expansion valve (EXV1) for cabinet heating, an refrigerant–air evaporator following with EXV2 for cabinet cooling and a refrigerant–water evaporator for battery cooling called battery chiller. The refrigerant–air evaporator and condenser are installed in the ventilation duct. The system is switched by the RVs for cooling or heating. The battery cooling/preheating system also applies a water–air heat exchanger in front of the car to utilize the natural cooling source and a Positive Temperature Coefficient (PTC) heater to preheat the battery in cold season. A HPHE is installed among the battery group, called battery heat exchanger box here. Please refer Ref. [19] for more details of the HPHE.

2.2. Experimental bench

Correspondingly a test bench is set up inside of a psychrometer testing room to investigate the performance of this system. The experiments are carried out on cooling and heating mode respectively under different working conditions. On cooling mode, the refrigerant valve RV1 and RV4 are open while RV2 and RV3 are closed. The opening of expansion valves EXV2 and EXV3 are changed repeatedly to get the optimum branch refrigerant flow rate of the cabin evaporator and battery chiller. On heating mode, the refrigerant valve RV1 and RV4 are closed while RV2 and RV3 are open. The battery is preheated by the PTC heater. The coolant pipe system and battery heat exchanger box are isolated to prevent unmeasured heat loss. There are 30 real battery modules in the bench for electric cars, but the generated heat during discharging process is simulated by electric films for the sake of safety. The electric films are pasted on the two wide sides of each battery module and thermocouples are pasted on the other two narrow sides to measure the temperature response of the batteries. Each side has three thermocouples. The measurement devices of the bench are shown in Fig. 1 and their parameters are shown in Table 1. The relative parameters of the bench are shown in Table 2.

2.3. Calculation methodology

To investigate the heat transfer performance of HPHE of battery group, the experiment is carried out to simulate different working