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Experimental investigation on heat pipe cooling for Hybrid Electric Vehicle and Electric Vehicle lithium-ion battery

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HIGHLIGHTS

- A heat pipe cooling system was designed and a full size prototype was built.
- Experimental investigation was performed under 3 input power levels.
- Several cooling conditions were experimented to minimize the power consumption.
- The system's performance was evaluated under different grade road conditions.

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ABSTRACT

In this work, we explored the use of heat pipe as cooling device for a specific HEV lithium-ion battery module. The evaporator blocks of heat pipe modules were fixed to a copper plate which played the role of the battery cooling wall. A flat heater was glued to the other surface of the copper plate and reproduced heat generated by the battery. The temperature at the cooper plate/heater interface corresponds to that of the battery module wall. An AMESim model of the battery was developed to estimate the cells' temperature within the battery. In inclined positions, a very slender evolution of the cooper plate/heater interface temperature was noticed, which means heat pipe works efficiently under different grade road conditions. Even though natural convection and chimney effect are not enough, coupling heat pipes with a confined ventilation structure is an efficient way to keep cells' temperature within its optimal range with an even temperature distribution. Furthermore, only low rate ventilation is necessary, which helps avoid parasitic power consumption and noise level in the vehicle.

1. Introduction

Lithium-ion batteries possess a high energy density compared with other secondary batteries; consequently, they are highly recommended as power sources for hybrid and electric vehicles (HEV/EV) to provide longer driving range and faster acceleration. However, lithium-ion batteries are extremely sensitive to low and high temperatures. As the temperature falls to below −10 °C, the performance of lithium-ion batteries deteriorates drastically [1,2]. At high temperature, lithium-ion batteries are extremely prone to thermal runaway [3]. For security reasons, a battery thermal management system (BTMS) always includes an internal switch which is opened if the battery is operated outside of its operating temperature range. This can prevent fire or explosion risks but the battery would be temporarily unavailable. Fuel economy of HEV and the driving range of EV are consequently affected. Furthermore, a number of works have elucidated that lithium-ion batteries calendar life [4,5] and cycle life [6–8] degrade quickly if kept or used at high temperature.

The goal of a cooling system is to keep the cells within its optimal temperature range, which offers the best balance between performance and ageing. The temperature distribution within the pack should be even because temperature gradient could lead to different ageing levels between cells and therefore, different charge/discharge behaviours for each cell [9,10]. For a Li-ion battery, the cells' temperature should not exceed 50 °C, the optimal temperature range is between 35 and 40 °C and the temperature gradient should be less than 5 °C [11,12]. In addition, the cooling system has to meet the requirements of the vehicle such as:

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Nomenclature

A	cooling wall area [m^2]
Cp	specific heat capacity [kJ kg^{-1} K^{-1}]
dU_o/dT	entropy coefficient [V K^{-1}]
dt	time step [s]
h	overall heat transfer coefficient [W m^{-2} K^{-1}]
i	number of the surrounding nodes [–]
I	cell current intensity [A]
m	mass [kg]
q	heat exchanged [W]
R	thermal resistance [°C W^{-1}]
T	temperature [K]
U_o	open-circuit potential [V]
U	measured cell potential [V]
V	velocity [m s^{-1}]
P	heat produced by heater [W]

Indices

a,b	resin nodes
amb	ambient
air	air
cell	cell
condenser	fin block
equi	related to the heat pipes cooling system
evaporator	copper plate/heater interface
i	related to the surrounding nodes
max	maximal value
resin	resin matrix
wall	battery module wall

Greek symbols

λ	thermal conductivity [W m^{-1} K^{-1}]
Φ	heat generated by cell [W]

reliable, compact, lightweight, easily accessible for maintenance, low cost, and low power consumption.

Up to now, battery cooling systems may use air, liquid (water/oil/refrigerant), phase change materials (PCM), or a combination of these methods. Each solution has its advantages and weaknesses. Air cooling solution can be passive (i.e., only the ambient environment is used) or active (i.e., a built-in source provides heating and/or cooling) [13]. The obvious benefit of air-cooled systems is the elimination of on-board chiller unit and coolant pump; leading to savings in energy consumption and weight. However, air convection can't be sufficient for heat dissipation from battery under stressful and abuse conditions. Consequently, the non-uniform distribution of temperature within battery pack becomes inevitable [14,15]. Compared with air cooling, liquid cooling offers higher cooling capacity at similar parasitic pump/fan power [13] but is heavier, and costlier due to the use of pump, tank, heat exchanger … Maintenance and repair of liquid cooling systems are also complicated and costly. PCM systems have high thermal energy storage capacity thanks to the use of latent heat and therefore can maintain the battery temperature relatively constant and near to the melting point during operation [16–18]. However, the weak point that has limited widespread use of PCM system is its insufficient long term thermal stability.

It is well known that heat pipe has very high thermal conductivity and can maintain homogeneously the evaporator surface at nearly constant temperature. Moreover, this device has flexible geometry which can fit variable area spaces. These attractive characteristics make heat pipe a promising candidate for HEV/EV battery cooling. Up to now, the only concern that has limited the large use of heat pipe system is its high cost due to the complicated fabrication process and the use of copper, an expensive metal, as wick and wall material. However, recent researches on aluminium heat pipe manufacturing [19,20] have revealed efficient and reliable way to decrease the heat pipe cost. Furthermore, the use of aluminium also helps reduce the weight of the cooling system, which is highly appreciable in HEV/EV application.

Previously, Mahefkey et al. [21] and Zhang et al. [22] have judged heat pipe to be suitable to mitigate the temperature of Ni–Cd and the Ni–MH battery respectively. Concerning Li-ion battery, Wu et al. [23] have reported that the cell temperature could be significantly reduced using heat pipe with aluminium fin on the condenser section, especially with the help of a cooling fan at the condenser section. More recently, Rao et al. [24] have investigated experimentally the cooling performance of tube heat pipes with condenser sections cooled by a water module. The battery maximum temperature has been controlled below 50 °C when the heat generation rate was lower than 50 W. Coupled with the desired battery temperature gradient, the heat generation rate should not exceed 30 W. In other words, with well-designed heat pipes, the temperature rise and temperature difference of power batteries can be effectively controlled within desired range.

In this work, we explored the use of tube heat pipe as cooling device for a specific HEV lithium-ion battery module. The thermal behaviour of the heat pipe cooling system was evaluated under various inclined positions corresponding to different grade road conditions. Natural cooling and chimney cooling at condenser section were also experimented. In addition, to enhance heat evacuation at the heat pipe condenser, two different air forced convection configurations were considered and compared. Finally, we investigated the thermal performance of the heat pipe system under a wide range of evaporator input power, corresponding to heat generated by the battery under different HEV power demands.

2. Experimental set-up

2.1. The battery module description

The battery module was made of 14 cylindrical cells (6.5 Ah of capacity, 38 mm in diameter, 142 mm in height). Cells were implemented in a thermally conductive and electrically insulating resin matrix which helped keep cells in place and increase the mechanical rigidity of the module. Moreover, the matrix enhanced the heat transfer between the cells and the aluminium module walls, as well as the electric insulation between the cells.

During charge and discharge, heat generated by cells can be considered to be the sum of the resistive heat and the entropic heat [25–29]. Consequently, the global heat generated can be determined by:

$$\phi = (U_o - U) - IT\frac{dU_o}{dT} \quad (1)$$

In order to maintain the cells within their optimum temperature range, heat generated needed to be evacuated through the module walls. The two walls corresponding to the two ends of the cells could not be used for cooling purpose. Indeed, one of the two walls was intended for bus bars and electric module installation and the other was used for degassing system implement. Among the four