



Performance assessment and optimization of a heat pipe thermal management system for fast charging lithium ion battery packs



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ABSTRACT

Thermal management system is critical for the electric vehicles and hybrid electric vehicles. This is due to the narrow operating temperature range for lithium ion batteries to achieve a good balance between performance and life. In this study, heat pipes are incorporated into a thermal management system for prismatic or pouch cells. Design optimizations focusing on increasing the cooling capacity and improving temperature uniformity of the system are undertaken through sensitivity studies. Subsequently, empirical study is carried out to assess the thermal performance of the optimized design integrated with prismatic cells at the unit level and the battery pack level. The results confirm that the optimized heat pipe thermal management system is feasible and effective for fast charging lithium ion battery packs. A delay quench cooling strategy is also proposed to enhance the performance of the thermal management system.

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1. Introduction

The lithium-ion battery is regarded as an optimum energy storage device for electric vehicles (EVs) and hybrid electric vehicles (HEVs) [1,2]. Its thermal management, however, is still one of the key issues restricting the application of lithium-ion batteries on EVs and HEVs. Various studies have concluded that the high temperature accelerates the capacity degradation and shortens the battery life [3,4]. Thermal management systems (TMSs) are therefore crucial for EVs and HEVs to control the operating temperature of batteries within an appropriate range. Besides, a TMS is also essential for preventing batteries from thermal run away and catching fire [5].

It has been elucidated by various studies that the appropriate operating temperature range for lithium-ion batteries is 25–40 °C, within which the lithium-ion battery achieves a good balance between performance and life [6,7]. For batteries operated under moderate conditions, many researchers adopted a maximum surface temperature limit of 50 °C when designing the battery TMS [8,9]. It is also desired to maintain the temperature difference within a module to be below 5 °C to avoid large cell-to-cell imbalance which may accelerate the degradation of batteries [6].

Besides, due to the limited space in an EV, a TMS is also required to be compact and lightweight [10].

There have been various types of TMSs developed for EVs. To date, most of the studies on TMSs are focused on the development of active cooling systems in which the coolant is air, oil, or water-ethylene glycol [1,11–16]. However, air cooling may not be sufficient if the battery module/pack is under stressful operating conditions (e.g. fast charging) or in a thermal abuse condition [17,18]. When using liquid as the coolant, preventing liquid leakage is challenging and costly. The use of dielectric fluids will also increase the cost of the system. Furthermore, the relatively high pressure drop across the liquid-cooled heat exchangers will lead to significant additional energy consumption [1]. On the other hand, the phase change material (PCM) TMS performs better in terms of battery-pack compactness [19] and temperature uniformity [20–22]. However, the PCMs alone are still insufficient for high heat fluxes due to the low thermal conductivity of the PCM.

Another relatively novel concept of a TMS is the heat pipe thermal management system (HPTMS). Heat pipes have been widely used in many industrial applications [23–27], and they are known as thermal superconductors operating on the principle of high heat transfer through evaporation [28]. The effective thermal conductivity of heat pipes can reach up to 90 times higher than that of a copper bar of the same size [29]. For heat pipes with a metal sintered powder wick, the heat transfer rate in the radial direction through liquid evaporation is much greater than the heat transfer

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Nomenclature

Symbols

A	battery area subjected to cooling (m^2)
C_p	specific heat capacity of the battery ($\text{J kg}^{-1} \text{K}^{-1}$)
k_i	thermal conductivity ($i = x, y, z$) ($\text{W m}^{-1} \text{K}^{-1}$)
Q	transient heat generation rate (W)
Q_{eff}	effective heat transfer rate gained by the cooling water (W)
T_f	coolant temperature ($^{\circ}\text{C}$)
T_i	condenser temperature ($i = 1, 2, 3, 4$) ($^{\circ}\text{C}$)
T_{in}	inlet temperature of the coolant ($^{\circ}\text{C}$)
T_j	battery surface temperature ($j = a, b, c$) ($^{\circ}\text{C}$)
T_{out}	outlet temperature of the coolant ($^{\circ}\text{C}$)
T_w	measured average temperature of the HPCP ($^{\circ}\text{C}$)

Greek letters

ρ	density of the battery (kg m^{-3})
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Subscripts, superscripts and acronyms

EV	electric vehicle
HEV	hybrid electric vehicle
HPCP	heat pipe cooling plate
HPTMS	heat pipe thermal management system
PCM	phase change material
TMS	thermal management system

rate along the heat pipe envelope. As a result, an isothermal temperature profile can be achieved along the evaporator section of the heat pipe [30], and therefore ensures a good uniformity of the battery temperature when heat pipes are applied to the thermal management of batteries. Wu et al. [31] attached two heat pipes with aluminum fins to the battery wall to improve the heat transfer process. Their simulation results showed that the application of the heat pipe can significantly reduce the temperature rise. Rao et al. [9] developed a HPTMS for prismatic cells, and the experimental results showed that the maximum temperature can be controlled below 50°C when the heat generation rate of the cell was lower than 50 W . A similar design utilizing an aluminum cooling plate embedded with heat pipes was numerically investigated by Greco et al. [32]. Wang et al. [33] proposed a HPTMS design for cooling and heating purposes, the system is able to control the battery temperature below 40°C if the heat generation is less than 10 W/cell . Most of these TMSs are focused on low C_{rate} s (i.e. less than 1 C [31]; 2 C [33]; 3 C [34]) operating conditions where the heat generation in the cell is relatively small. A C_{rate} is a measure of the rate at which a cell is charged/discharged relative to its maximum capacity. A $1 \text{ C}_{\text{rate}}$ current will discharge the entire capacity of the cell in 1 h , and an $n \text{ C}_{\text{rate}}$ current is n times that of a $1 \text{ C}_{\text{rate}}$ current [35]. Besides, the optimization of these HPTMSs has not been attempted and most of the systems have not been experimentally validated with integration of real cells.

In fast-charging applications, the battery cell needs to be charged at high C_{rate} to achieve full capacity in 10 min [36]. A large amount of heat is generated which will cause a rapid temperature rise of the cell [37]. Besides, under some severe conditions, such as sharp acceleration, over-discharge of cell, cell internal short circuit, etc., the heat generation within cells would be significantly increased. This may possibly lead to excessive temperature throughout a module/ pack or thermal runaway of cells. Hence, a reliable thermal management system must be designed to cater for these severe operating conditions and maintain the cell within the optimum operation temperature limits. Existing TMSs utilizing heat pipes are not designed to dissipate a large amount of heat generation from the battery pack. The heat pipe may reach its dry-out point when the heating power at the evaporator section exceeds a critical value [38]. In addition, due to the poor thermal conductivity of the active material layer and separator in the battery, the internal temperature of the cell is higher than the skin temperature of the cell [37]. Hence, a lower limit of the maximum surface temperature of 40°C is a safer criterion than 50°C when designing a TMS.

In view of the above, the aim of this work is two fold: first, to design and optimize a HPTMS, so that the thermal management system can meet the requirements for fast charging and extreme

operating conditions. In order to meet this target, sensitivity studies on various design parameters, including the working fluid of heat pipes, flow rate, coolant temperature, operating orientation, the number of heat pipes in a HPCP and with/without cooling fins, will be carried out to identify the influence of each factor on the thermal response of the HPTMS. Second, the effectiveness of the system will be assessed with actual prismatic cells, and a numerical model was developed to predict the thermal performance of the HPTMS. Finally, the effectiveness of different cooling approaches, viz. “constant 25°C ”, “constant 15°C ”, “decreasing”, “quench”, and “delay quench” cooling, in controlling the cell temperature were investigated.

2. Conceptual design of a HPTMS

Fig. 1(a) shows a battery pack design, in which there are 110 prismatic cells ($140 \times 65 \times 15 \text{ mm}$, 10 Ah) in a 10×11 arrangement. In the design, cells and heat pipe cold plates (HPCPs) are stacked alternately. That is, each HPCP is sandwiched between two cells and each cell is sandwiched between two HPCPs. HPCPs are in contact with both sides of each cell, a layer of thermal grease is applied at the interfaces between the cells and the HPCPs, such that good thermal contact can be ensured. The HPTMS is designed for the thermal management of the battery pack during $8 \text{ C}_{\text{rate}}$ of fast-charging. During the operation, the heat generated within the cells is conducted through the evaporator sections of the heat pipes to the condenser sections, and from there to the circulating coolant over the condenser sections. A typical unit of the HPCP is shown in Fig. 1(b). Each of the HPCP comprises a number (e.g. 4) of heat pipes and two copper-plate heat spreaders of size matching the battery cell side surface. The evaporator sections of the heat pipes are flattened, and the two copper plates are soldered to the

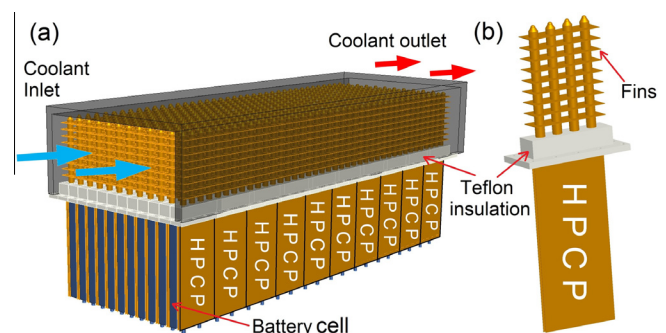


Fig. 1. Schematic of the conceptual design of the HPTMS for a battery pack.

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