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Investigation of power battery thermal management by using mini-channel cold plate

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ABSTRACT

In order to guarantee the safety and extend the cycle life of Li-ion power batteries within electric vehicles, a mini-channel cold plate-based battery thermal management system is designed to cool a rectangular Li-ion battery. A three-dimensional thermal model of the cooling system was established and the effects of number of channels, flow direction, inlet mass flow rate and ambient temperature on temperature rise and distribution of the battery during the discharge process were investigated. The results suggest that the maximum temperature of the battery decreases with increases in the number of channels and inlet mass flow rate. The effect of flow direction on cooling performance was smaller after mass flow rate increased. The cooling performance improved with the increase of inlet mass flow rate but the increasing trend became smaller, and the mass flow rate as 5×10^{-4} kg s^{-1} was optimal. The simulation results will be useful for the design of mini-channel cold plate-based battery thermal management system.

1. Introduction

The power density of a conventional Li-ion power battery is 4–5 times higher than a typical lead-acid battery. As a result, Li-ion power batteries are currently receiving significant attention from the scientific community [1,2]. However, Li-ion batteries generate a large amount of heat due to electrochemical reactions during discharging process [3,4], which may overheat the battery or lead to non-uniform temperature distribution. As a result, the safety of the battery can be compromised and its cycle life may be reduced [5,6]. Hence, battery thermal management (BTM) is necessary to control the battery temperature within an acceptable range and maintain an uniform temperature distribution during operation [7–9]. Generally, the thermal management techniques that are employed for BTM include: forced convection with air and liquids, as well as the use of solid–liquid phase change materials (PCM) [10–14].

Because of the low thermal conductivity of air [15], extremely high velocities of air are required to sufficiently cool Li-ion batteries using active cooling techniques [10,11]. Compared with air, higher rates of cooling can be achieved in BTM systems that employ liquids due to their high thermal conductivities [12]. PCM are also excellent candidates for BTM due to the large amount of heat they can absorb during a solid–liquid phase transition [13,14]. Karimi and Li [16] obtained the temperature distribution within a battery module when air, silicon oil and PCM are used as heat transfer mediums that are embedded within cooling channels and located on the side of the battery module. Using numerical simulations, it was shown that the cooling performance of silicon oil was between air and PCM, but the characteristic of low thermal conductivity before phase change impedes heat spreading and thus limits the application of PCM for BTM [17,18]. BTM system based on liquid cooling can be subdivided into conventional liquid cooling system, cooling system with cold plates and cooling system with heat pipes. In conventional liquid cooling system, heat is taken away by channel arranged between battery module or by a jacket employed around the battery module. In our previous work [19], we established a two-dimensional single-phase convective heat transfer model, and obtained the maximum temperature of the battery using air and water as cooling medium, respectively. The results showed that when the cooling medium was changed to water from air, the battery maximum temperature fell from 55.82 °C to 49.59 °C.

Based on the large amount of liquid latent heat of vaporization, the use of heat pipes for BTM allows for a significant reduction in battery operating temperature [9,20–22]. Greco et al. [23] proposed a simplified thermal network based on the heat transfer principle associated with the use of heat pipes, with which a one-dimensional computational model was developed. The quantitative results of the one-dimensional computational model were compared with an analytical solution and a three-dimensional

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Nomenclature

c_p	heat capacity (J kg^{-1} K^{-1})
E	voltage (V)
h	convective heat transfer coefficient (W m^{-2} K^{-1})
I	current (A)
i	current density (A m^{-3})
k	thermal conductivity (W m^{-1} K^{-1})
P	pressure (Pa)
Q	heat generation rate (W)
$\dot{q}$	heat generation rate per unit volume (W m^{-3})
q	heat transfer rate per unit volume (W m^{-3})
R	electric resistance (Ω)
ΔS	entropy change per unit time (W K^{-1})
T	temperature (K or °C)
ΔT	local temperature difference (K or °C)
t	time (s)
V	volume (m^3)
$\vec{v}$	velocity vector (m s^{-1})
μ	viscosity (kg m^{-1} s^{-1})
ρ	density (kg m^{-3})
δ	distance (m)

Subscripts

a	air or ambient
w	water
b	battery
c	cold plate
g	generation
r	reaction
p	polarization
j	Joule
t	total
e	electric
m	maximum
oc	open circuit
σ	standard deviation

CFD (computational fluid dynamics) simulation. The results showed a good agreement for the battery temperature among the three models along the thickness direction of heat pipe, but agreement did not hold for each of the other directions.

A liquid cooling system with cold plates removes heat from the Li-ion battery using a metal thin-wall structure with several liquid channels. This system is able to decrease the operating temperature and maintain uniform temperature distribution. Jarrett and Kim [24] designed a liquid cooling system model that employed serpentine channel and used CFD simulation to optimize the model based on weighted average pressure drop, as well as the mean and standard deviation of the temperature of the cold plate. Zhang et al. [25] used the de-ionized water with 2% mass content sodium polyacrylate as a cooling material and investigated its ability to dissipate heat by experimental and simulation methods. It was shown that with the new cooling material, the internal electric resistance increased due to low electron mobility at low temperature, and a lower capacity fading rate could be observed. Jin et al. [26] designed an oblique fin cold plate to cool the batteries of electric vehicle. When heat load was 1240 W, the oblique fin cold plate could maintain the surface average temperature of the battery below 50 °C in the case of flow rate as 0.9 l min^{-1}.

The performance of a liquid cooling system with cold plates is dictated by various factors such as liquid mass flow rate and ambient temperature (the temperature external to the battery casing). In this paper, a mini-channel cold plate-based battery thermal management system was designed and a three-dimensional model was established. The effects of number of channels, flow direction, inlet mass flow rate and ambient temperature on temperature rise and distribution of the battery during discharge process were investigated in detail.

2. Numerical model

2.1. Physical problem

Fig. 1(a) shows the schematic of the Li-ion battery pack. Each single battery in the middle of the battery pack is sandwiched by two cold plates. The quantity of single batteries is enough so that the battery pack can be simplified, as shown in Fig. 1(b). Boundary condition of symmetry is applied to the top and bottom surface in Fig. 1(b). The single battery investigated in this paper is rectangular in shape and has a capacity of 7000 mA h. Each size of the cooling system model is listed in Table 1. In Fig. 1(b), $d1$ and $d2$ represent the length and width of battery respectively, and the battery thickness is $2 \times d3$ resulted from the boundary condition of symmetry. The positive current tab and negative current tab are placed at the end of battery, whose sizes are $d4$, $d5$ and $2 \times d6$. The length and width of the cold plate are equal to $d1$ and $d2$. The top surface of the model is bound by an axis of symmetry, making the true thickness of the cold plate equal to $2 \times d7$. Along the width of cold plate, cooling channels distribute equidistantly. The width and thickness of the channel are $d8$ and $2 \times d9$ respectively. The number of cooling channels considered in this paper are 2, 3, 4, 5 and 6. In this paper, the Li-ion battery and cold plate are assumed to be homogenous and isotropic for numerical simplicity. Aluminum was used for the cold plate. Considered thermal conductivity and viscosity, liquid water was employed as cooling medium. The thermophysical properties for the battery, cold plate and cooling fluid are listed in Table 2 [13].

Based on the mass flow rate defined at the cooling channel inlet, Reynolds number can be calculated to confirm the use of a viscous model. The maximum mass flow rate in this paper was 10^{-3} kg s^{-1}, which corresponds to a Reynolds number of 419.79. Therefore, a laminar flow model was used. The temperature of the inlet cooling water was equal to ambient temperature. A pressure of 0 Pa was defined at the channel outlet. The battery investigated in this study discharged at 5C rate, which could last 720 s.

ICEM CFD was used to mesh the model and FLUENT 14 was used as the simulation software. Rigorous independent test of grid number was performed to guarantee accuracy, as shown in Fig. 2(a). Besides, independent test of time step was also performed and time step of 1 s was chosen in this paper considered the cost of calculation, as shown in Fig. 2(b). The convergence criteria for this study were chosen to be 10^{-4} and 10^{-6} for flow and energy, respectively.

2.2. Conservation equations

At a high discharge rate, a large amount of heat will be generated in the Li-ion battery because of the electron transfer during electrochemical reactions. The heat generation Q_g (W) of the Li-ion power battery can be divided into three parts, reaction heat Q_r (W), polarization heat Q_p (W) and Joule heat Q_j (W), namely [3,27–30]:

$$Q_g = Q_r + Q_p + Q_j \tag{1}$$