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# Thermal management of Li-ion battery with liquid metal

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## ABSTRACT

Thermal management especially cooling of electric vehicles (EVs) battery pack is of great significance for guaranteeing the performance of the cells as well as safety and high-efficiency working of the EVs. Liquid cooling is a powerful way to keep the battery temperature in a proper range. However, the efficiency of conventional liquid cooling is still limited due to the inherently low thermal conductivity of the coolant which is usually water or aqueous ethanol. In this paper, a new kind of coolant, liquid metal, is proposed to be used for the thermal management of the battery pack. Mathematical analysis and numerical simulations are conducted to evaluate the cooling capability, pump power consumption and module temperature uniformity of the liquid metal cooling system, in comparison with that of water cooling. The results show that under the same flow conditions, a lower and more uniform module temperature can be obtained and less pump power consumption are needed in the liquid metal cooling system. In addition, liquid metal has an excellent cooling capability coping with stressful conditions, such as high power draw, defects in cells, and high ambient temperature. This makes it a promising coolant for the thermal management of high driving force EVs and quick charge batteries.

## 1. Introduction

Electric vehicle (EV), which is fossil fuel independent and carbon emission free, is a promising means for future transportation under the increasingly serious issues on fuel shortage and air pollution. Battery is the heart of EVs and can directly influence the working performance of the whole vehicle. Such component is generally very sensitive to temperature. High temperature accelerates its degradation and shortens its life span, while low temperature increases the internal electric resistance of the battery and reduces its efficiency [1,2].

Heat is generated in the cell during charge/discharge process, which is mainly composed of Joule heat and electrochemical reaction heat. The power that one cell can provide is very limited, thus a large number of cells are needed for strong driving force for EVs. Those cells are closely packed, thus the heat generation in the pack is notable, especially under quick charge/discharge situations. Temperature increase of 1 °C would lead to the decrease of battery life by 2 month in the operation temperature range of 30–40 °C [3]. Overheating of the battery will result in short lifespan, degradation of capacity and power and even thermal runaway [4]. In addition, uneven temperature distribution among the cells in the pack/module significantly affects the life and performance of the battery system. Hence, an effective thermal management system is critical for the safe and high-efficiency working of EVs. The main targets of the thermal management system for EV battery lie in two aspects: (1) keep the temperature of each cell in a proper range, usually 20–45 °C; (2) maintain the temperature of the whole pack uniform, usually 5 °C difference are tolerated [1].

Both cooling and heating are needed in the thermal management system. In this paper, attentions are only focused on the cooling process and the conclusions can also be applied to the heating issue. Air cooling [5–8], liquid cooling [9–12], heat pipe cooling [13–16], phase change cooling [17–21] and the combination of them [22,23] are the most commonly used technologies for the thermal management of EV battery system. Air cooling system is low cost, light weight and easy construction and maintenance, while is normally suitable for relatively low heat generation and small size module situations due to the low specific heat capacity of air. As for more stressful conditions, such as quick charge/discharge process, or high ambient temperature situations, the battery cooling would become very challenging and liquid cooling may be a better option [24]. Water or aqueous ethanol is usually used in liquid cooling system and a better cooling capability and more uniform temperature distribution can be obtained than that of air cooling [25]. However, the cooling efficiency of liquid cooling

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## Nomenclature

| | |
|---|---|
| $A_c$ | cross-sectional area ($m^2$) |
| $c_p$ | specific heat capacity (J/kg/K) |
| $D$ | hydrodynamic diameter of the channel (m) |
| $d$ | half width of the channel (m) |
| $E_o$ | open circuit voltage (V) |
| $f$ | fractional coefficient |
| $h$ | convection heat transfer coefficient ($W/m^2/K$) |
| $I$ | electric current (A) |
| $k$ | thermal conductivity (W/m/K) |
| $L$ | length (m) |
| $Nu$ | Nusselt number |
| $P$ | pump power (W) |
| $p$ | pressure ($N/m^2$) |
| $Pr$ | Prandtl number |
| $\dot{q}$ | heat generation density ($W/m^3$) |
| $R_i$ | internal resistance (Ω) |
| $r$ | radius (m) |
| $Re$ | Reynolds number |
| $T$ | temperature (K) |
| $u$ | velocity along $x$ direction (m/s) |
| $v$ | velocity along $y$ direction (m/s) |
| $\bar{v}$ | surface average velocity along $y$ direction (m/s) |
| $V$ | volume ($m^3$) |
| $W$ | rate at which work is performed (W) |
| $x, y, z$ | rectangular coordinates (m) |

*Greek letters*

| | |
|---|---|
| $\alpha$ | thermal diffusivity ($m^2/s$) |
| $\rho$ | mass density ($kg/m^3$) |
| $\zeta$ | local pressure loss coefficient |
| $\mu$ | viscosity (kg/s/m) |
| $\gamma$ | surface tension (N/m) |
| $\eta$ | pump efficiency |

*Subscripts*

| | |
|---|---|
| $c$ | cell |
| $co$ | coolant |
| $in$ | inlet condition |
| $j$ | jacket |
| $lm$ | liquid metal |
| $m$ | mean value over a channel cross section |
| $max$ | maximum |
| $s1$ | cell surface |
| $s2$ | jacket surface adjoined to the cell |
| $s3$ | jacket surface adjoined to the coolant |
| $w$ | water |

is still limited due to the intrinsically low thermal conductivity of water.

In 2002, Liu and Zhou [26] proposed for the first time that using room temperature liquid metal, typically gallium and its alloys, as the coolant for the thermal management of computer chip. Soon afterward, many works have been done to investigate the liquid metal based cooling system for high performance CPUs [27–31], large power LEDs [32] and lasers [33,34], etc. All of these works showed that liquid metal has an excellent heat extraction and spreading capability and can effectively cope with high heat flux situations, which mainly benefits from its inherent high thermal conductivity.

This paper is dedicated to investigate the feasibility and superiority of using liquid metal for the thermal management of Li-ion battery. Mathematical analysis and numerical simulations were conducted to investigate the cooling capability, pump power consumption and temperature uniformity of the liquid metal cooling system, in comparison with that of water cooling. In addition, some other factors, such as cost, weight, maintenance, corrosion, leakage, and complexity of the cooling system were also discussed.

## 2. Mathematical analysis

### 2.1. Analysis model

Li-ion battery, which has advantages such as long cycle life, high energy and power density, is considered to be the best candidate for future vehicles. In this paper, a prismatic Li-ion battery ($LiFePO_4$, 100 Ah, ZhongHang Li-ion Battery Co. Ltd, China) was selected as an example for investigation, and a battery module composed of 24 cells with jacket liquid cooling for each cell was constructed, as shown in Fig. 1(a). The main technical parameters of the cell are listed in Table 1. Since the main purpose of this paper is to explore the thermal management capability of liquid metal for battery pack in comparison with water cooling, the thermal behavior in the cell core was not considered in detail and a system level thermal analysis was conducted. For system level thermal analysis, the cell is simplified to a uniform heat source and its thermophysical properties are considered to be uniform and constant. The cell shell is neglected and the influence of the two electrode terminals are out of account.

The energy conservation equation in the cell region can be expressed as

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial T}{\partial z}\right) + \dot{q} \tag{1}$$

where $\rho$, $c_p$ and $k$ are the equivalent density, heat capacity and heat conductivity of the cell, values of which are listed in Table 1. $\dot{q}$ denotes the heat generation density in the cell, which is mainly caused by electrochemical enthalpy change and electrical resistive heating during discharge process [35–37] and can be expressed as

$$\dot{q} = \frac{I}{V_c}\left(IR_i - T\frac{\partial E_o}{\partial T}\right) \tag{2}$$

where $V_c$, $R_i$ and $\frac{\partial E_o}{\partial T}$ are the volume, internal electric resistance and entropic coefficient of the cell, respectively; $I$ and $T$ are the discharge current and temperature of the cell. It is obvious that large current and high temperature lead to large heat generation in the cell.

### 2.2. Cooling capability evaluation

The cooling channel of the analysis model used in this paper is a single straight channel along $y$ direction, without any serpentine bend. Considering a steady state situation and neglecting the heat dissipation on the top and bottom of the module, one has $\frac{\partial T}{\partial t} = 0$ and $\frac{\partial T}{\partial z} = 0$, thus the analysis model is simplified to a two dimensional steady state situation, as shown in Fig. 1(c). Considering that the geometry model is symmetrical and neglecting the asymmetric cooling condition of the 8 cells on both sides of the battery module along $x$ axis, only half of the cell, one side of the jacket and half of the coolant region were selected as the analysis objective, in Fig. 1