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Study on thermal management of rectangular Li-ion battery with serpentine-channel cold plate

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ABSTRACT

In order to investigate a simple and efficient liquid cooling method for the rectangular Li-ion power batteries used in electric vehicles, the cold plate with serpentine-channel configuration shaped like U-tube is established. Subsequently, the effect of cooling channel number, the layout of channels and inlet temperature of coolant on cooling performance of battery thermal management system are analyzed. The numerical simulation results demonstrate that the layout of channels in length flowing-direction with 5-channels has the most efficient cooling performance. This design can reduce the maximum temperature by 26 °C compared with the 2-channels along width flowing direction. And the maximum temperature of cooling system rises with the increase of inlet temperature of the coolant. However, there exists an upper limit on the number of channels and the inlet temperature with the consideration of efficiency and safety of cooling system. The above results will be helpful to design cold plate for thermal management system of Li-ion power batteries.

1. Introduction

Nowadays, the development and utilization of clean energy into various industry departments is becoming the mainstream due to the serious energy crisis and environment pollution in the world [1]. In the automobile industry, the power battery could act as the power source for electric vehicle (EV) instead of internal combustion engines (ICE) [2]. There are various power batteries for electric vehicles, such as Ni-MH, lead-acid and lithium-ion (Li-ion) batteries. As we know, Li-ion battery can provide higher energy and longer cycle life compared with other batteries. Consequently, it has become a valuable and widely used product in electric vehicles [3,4]. In general, thousands of Li-ion battery cells are connected in series or parallel style to make up a high-capacity and large-scale battery pack. It could generate vast quantities of heat when working under extreme conditions, such as high ambient temperature and high ratio of current during charging or discharging progress [5]. Indeed, the performance of Li-ion battery is easily affected by the variation of temperature. According the Arrhenius theory, the electrochemical reaction rate of battery rises exponentially with the increase of temperature [6]. Furthermore, the uneven and non-uniform temperature distribution in the battery cells can also cause local temperature concentration [5,7]. Seriously, the heat of battery pack will be out of control. And the explosion can occur when its temperature exceeds a certain range [8,9]. Therefore, it is important to regulate the battery temperature within a desirable range and maintain a well-distributed temperature of battery pack [10]. Subsequently, the battery thermal management system (BTMS) has been attached much attention by the enterprises and academics in recent years [11,12].

There are numerous types of BTMS, which mainly include forced convection with air cooling, liquid cooling, as well as the use of phase change materials (PCMs) [7,13]. Among these types, forced air-cooling is the most commonly used due to its simple configuration and stable operating conditions for the small-scale battery packs [14–16]. However, air cooling still caused the non-uniform distribution, especially for the high-capacity packs [17,18]. The phase change materials (PCMs) can absorb a large amount of heat during the conversion process of solid state to liquid state, which has attracted much attention from scientists [19]. Although, this cooling method can maintain the uniform temperature distribution among the battery cells when the temperature is close to the melting point of PCMs [20,21]. It has insufficient thermal stability for long time working, which is caused by low thermal conductivity before phase change [22]. Furthermore, the high cost of materials and the limited temperature range of phase transition have also impeded its widely application. Compared with the air-cooling and cooling system with PCMs, the better

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Nomenclature

A	area of the contact surface between the battery and the cold plate (m^2)
A_c	cross-sectional area of the channel (m^2)
A_0	area of the bottom surface of cold plate (m^2)
c_p	heat capacity ($J \cdot kg^{-1} \cdot K^{-1}$)
D	hydraulic diameter of fluid channel (m)
f	friction factor
F	the shape factor for non-circular channels
h	heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$)
I	current (A)
k	thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
L	length along flowing channel (m)
p	pressure (Pa)
Δp	pressure drop (pa)
P	pump power (W)
P_h	heat generation power (W)
Q	heat generation rate (W)
q	heat generation rate per unit volume ($W \cdot m^{-3}$)
q_a	heat dissipated by convection (W)
q_m	mass flow rate ($kg \cdot s^{-1}$)
R	electric resistance (Ω)
S	wetted perimeter (m)
T	temperature (°C)
U	voltage (V)
V	volume (m^3)
v	velocity of fluid ($m\ s^{-1}$)

Greek symbols

Δ	change in variable
ρ	density ($kg \cdot m^{-3}$)
μ	dynamic viscosity (p·s)
Φ	heat flux ($W \cdot m^{-2}$)
σ	standard deviation

Subscripts

a	air or ambient
avg	average
b	battery
c	cold plate
j	Joule
l	liquid
m	maximum
OCV	open circuit voltage
w	wall
x	X-axis direction
y	Y-axis direction
z	Z-axis direction

Acronyms

BTMS	battery thermal management system
CFD	computational fluid dynamics
EV	electric vehicles
ICE	internal combustion engines
PCM	phase change materials

cooling performance can be achieved by using the liquid coolant, such as water, glycol, and water-ethylene, etc. At present, the most commonly used liquid-cooling techniques for the BTMS include heat pipe and cold plate. The heat pipe is a hermetic container consisted of compensator and evaporator. The liquid coolant in the evaporator can absorb heat from battery cells and release heat in compensator [23–25]. But its complexity of structure and high cost in manufacturing with expensive materials, such as capillary and wick has limited its popularization [24]. A liquid cooling system with cold plate can remove heat from the battery through the thin metal fabrications of internal channels within the coolant. Huo et al. [26] established a three-dimensional thermal model of cold plate with straight channels to study the effects of channel number, flowing-direction of the coolant, inlet mass flow rate and ambient temperature on cooling performance of a Li-ion battery. Jarret and Kim [27] designed a cold plate with a circuitous rectangular channel and used numerical optimization to determine the optimum design with respect to pressure drop, average temperature and temperature uniformity. The numerical result indicated that the above three-objective functions cannot be obtained at the same time. They also studied the influence of different operating conditions on the optimum cold plate design. And they found that the temperature uniformity was most likely to be affected by the working conditions, especially with consideration of the import heat flux and the mass flow rate of the coolant [28]. Jin et al. [29] designed a novel cold plate with the oblique channels and compared with the straight channel. The experimental results showed that the new structure had better cooling performance with smaller average temperature and higher heat transfer coefficient. Zhang et al. [30] designed a cooling plate with some aluminum flat oblong shape tubes as the coolant channels. The flexible graphite was arranged between the battery and cold plate. This cooling structure can keep the maximum temperature difference below 5 °C after experiment. Panchal et al. [31,32] designed a cold plate with a rectangular channel and tested the mesh independence during the simulation. Then they studied the difference between the temperature field and velocity field of cold plate when inlet temperature and discharge rate were different. But they did not study the influence of the channel structure on the cooling performance of the cold plate. In addition, compared with heat pipe, the cold plate made of metal aluminum can reduce weight of BTMS. The main concern of cold plate focuses on ensuring the good seal performance of the coolant channels.

The cooling performance of cold plate is affected by numerous factors such as inlet mass flow rate of the coolant and numbers of channel. Previous studies have rarely considered the layout of cooling channel and most shape of channels were straight along flow direction. It will lead to an increase in flow resistance at the corner of the right angle. In this paper, the cold plate with serpentine-channel configuration is designed and the fillet at the corner can reduce the flowing resistance. Three-dimensional computational fluid dynamics (CFD) models of different channel layouts are established. Moreover, we preliminarily study the effect of cooling channel numbers, the layout of channels and inlet temperature on the cooling performance of a battery cell in detail.

2. Numerical modeling

2.1. CFD modeling

The configuration of battery pack is usually made up of a stack of thin rectangular battery cells. There are mini-channel cold plates with same dimension as the cells between each pair of battery cells. Besides, there are welded several thin metal channels within interior of the cold plates. And the coolant can flow through these channels. The generated heat is conduced into the cold plate and then transmitted by the coolant. The outer dimensions of cold plate are set to be as following: Length: 176 mm; Width: 130 mm;