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Investigation on the thermal performance of a battery thermal management system using heat pipe under different ambient temperatures

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ABSTRACT

The thermal performance of a battery thermal management system (BTMS) can be enhanced by cooling strategies, which are seldom taken into account in the study of heat pipe-based BTMS (HP-BTMS). The effects of coolant flow rate, ambient temperature, coolant temperature and start-up time on the thermal performance of HP-BTMS are crucial for the development of cooling strategies and are experimentally investigated in the present study. Results show that the thermal performance of HP-BTMS increases slightly with the decrease of ambient temperature as it is under 25 °C. When the ambient temperature is under 35 °C, the thermal performance of HP-BTMS can be kept nearly unchanged by reducing coolant temperature. The enhancement is little when ambient temperature is under 25 °C. Additionally, a drastic rise in the non-uniformity of battery temperature is observed at the moment of HP-BTMS initiation if HP-BTMS starts operating after battery temperature exceeds equilibrium value. Finally, intermittent cooling and constant cooling can achieve similar battery cooling performance, which indicates that the power consumption can be reduced by decreasing running time of HP-BTMS.

1. Introduction

As a result of high energy density and no memory effect, Lithium-ion (Li-ion) batteries have become the optimum energy storage device for electric vehicles [1]. A large amount of heat generated within the battery during operation will lead to a drastic rise in the battery temperature, which contribute to low life expectancy of battery and even explosion. Battery thermal management system (BTMS) was proposed to maintain the temperature of battery within the optimum range during operation, thus prolonging the battery cycle life and preventing explosion [2]. BTMS has received an increasing attention in scientific community and auto manufacturer.

Generally, the cooling medium used in BTMS includes air, liquid and phase change material (PCM). The air-based BTMS has the advantage of low cost and light weight, but it is limited by its space inefficiency and incapability in severe working conditions [3,4]. Liquid-based BTMS shows a better performance using water, oil, mixture [5] or liquid metal [6] as coolant. But the leak of coolant and the higher additional power consumption are the potential problems. Basu et al. [7] designed a liquid cooling system for cylinder batteries using conduction elements to avoid leakage. Nevertheless, such design of liquid-based BTMS may be insufficient for the large size battery with higher heat generation rate. Mini channel cooling with liquid coolant therefore was proposed [8–10]. The effects of mini channel number, flow rate and flow direction on the performance of BTMS using mini channel cold plate were investigated [11,12]. However, leak-proof design is needed again and the control system will be more complex. PCM-based BTMS includes solid-liquid [13] and liquid-gas [14,15] phase change. It performs well in maintaining temperature uniformity across battery pack due to the high latent heat in the phase change process. But the thermal conductivity of the PCM is low. As a result, PCM-based BTMS should be assisted by embedding fins [16], graphite [17], metal mesh [18] or metal foam [19]. Besides, volume expansion after phase change requires leak-proof design. More importantly, PCM-based BTMS should be initially designed to have good performance in some severe working conditions, resulting in the waste of materials and low energy density of battery pack.

Heat pipe, operating on the principle of high heat transfer rate through evaporation, has been widely applied in lots of industrial fields. The heat sinks and the heat sources are separated using heat pipe so that the heat transfer area can be employed more sufficiently. Heat pipe-based BTMS (HP-BTMS) may achieve the trade-off between high heat transfer rate and compactness of battery pack. Wu et al. [20] verified the feasibility of HP-BTMS by attaching two heat pipes with fins to the battery wall. Tran et al. [21] put 14 cylinder batteries inside a resine matrix on which the heat pipe was attached. The result shows

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Nomenclature

A	area of battery surface (m^2)
c_p	specific capacity (J/(kg K))
d	the outer diameter of heat pipe (m)
Gr	Grashof number
g	gravity acceleration (m/s^2)
h	convective heat transfer coefficient ($W/(m^2 K)$)
h_n	natural convective heat transfer coefficient ($W/(m^2 K)$)
k	thermal conductivity (W/(m K))
L	the width of battery (m)
m	mass of battery (kg)
Nu	Nusselt number
Pr	Prandtl number
Q_b	heat generation rate of a battery (W)
Q_s	heat leakage to the surroundings (W)
q	heat flux (W/m^2)
q_v	coolant flow rate (*L*/min)
T	temperature (°C)
T_0	initial temperature of battery (°C)
T_{ab}	ambient temperature (°C)
T_{air}	air temperature (°C)
T_{ave}	average temperature of battery (°C)
T_{bf}	temperature difference between inlet coolant and maximum temperature of battery (°C)
T_i	temperature at measuring points on the battery surface (°C), i = 1, 2, …, 6
T_{in}	inlet coolant temperature (°C)
T_{max}	maximum temperature of battery (°C)
T_{min}	minimum temperature of battery (°C)
T_{out}	outlet coolant temperature (°C)
$\triangle T$	temperature difference of battery (°C)
$\triangle t$	temperature difference between the wall of heat pipe condenser section and the surrounding fluid (°C)
U	indirectly measured parameter

Geek letters

a	thermal diffusivity (m^2/s)
α_V	volume expansion coefficient (K^{-1})
ε	emissivity
σ	Stefan–Boltzmann constant ($W/(m^2 K^4)$)
τ	time (s)
ν	kinematic viscosity (m^2/s)
w_i	directly measured parameter

that HP-BTMS is promising by coupling with adequate ventilation configuration. The thermal conductivity and the specific capacity of water are higher than those of air. The HP-BTMS coupled with liquid cooling was also investigated [22]. The result shows that the battery temperature can be controlled within the desired range during operation if less than 30 W/cell is generated, with adiabatic test condition and coolant temperature of 25 °C. Wang et al. [23] further studied the thermal performance of HP-BTMS in “off normal” conditions, with coolant temperature of 20 °C and ambient temperature of 35 °C. The temperature of battery can be maintained under 40 °C if less than 10 W/cell is generated. Based on the design used by Rao [22], the structure of HP-BTMS was numerically optimized by adding heat pipes, fins and copper plates [24], aiming to cope with the high amount of heat in fast charging application. Recently, core cooling (or internal cooling) was also investigated by inserting the heat pipe into the core of cylinder battery [25,26]. This seems to be complicated and requires further research when applying in battery pack.

However, these researches either focus on the thermal performance of HP-BTMS in a certain environment or improve the thermal performance by changing structure. The effects of coolant temperature and ambient temperature on the thermal performance of HP-BTMS should be further evaluated. Improving the thermal performance of HP-BTMS in some severe working conditions simply by changing structure of HP-BTMS may lead to high pressure drop of flow and low energy density of battery pack. It is undesired in most normal working conditions. Actually, the thermal performance can be enhanced and the power consumption can be reduced through cooling strategies. Mahamud et al. [27] enhanced the temperature uniformity of battery in air-based BTMS through reciprocating flow, where the flow direction is changed once the downstream battery temperature reaches to a certain value. The temperature responses of battery under synchronized cooling and unsynchronized cooling were compared in liquid based BTMS [28]. These studies have verified the effectiveness of cooling strategy, but the relevant studies about HP-BTMS are rare.

The coolant temperature, coolant flow rate and ambient temperature are the important parameters for the cooling strategy of HP-BTMS. The thermal performance of HP-BTMS should be further evaluated covering these parameters. Ye et al. [29] studied the effects of coolant flow rate and relatively low coolant temperature (15 °C, 20 °C, 25 °C) by attaching a uniform surface heat source on a heat pipe cooling plate, without consideration of ambient temperature. The unsynchronized cooling with a lag time of 100 s was also verified in case of 8 C charging. But the detail adjustment of such lag time should be further studied based on the heat generation rate. Therefore, in the present study the temperature response of battery is experimentally investigated under different ambient temperatures with different coolant flow rates, coolant temperatures and heat generation rates. The thermal performance of HP-BTMS is discussed by taking the effect of ambient temperature and coolant temperature into account. The unsynchronized cooling is extensively discussed by varying the start-up time of HP-BTMS and then the intermittent cooling is proposed to reduce power consumption. The present study would be helpful to the development of cooling strategy for HP-BTMS.

2. Experimental setup

Fig. 1 shows the experimental setup in the present study. The experimental setup includes a refrigerated/heated circulating bath, a DC power supply, a pump, a gate valve, a ball value, a flow meter and data acquisition system. The water is used as coolant and its temperature can be maintained at the desired value in the refrigerated/heated circulating bath with uncertainty of ± 0.5 °C. The coolant flow rate is controlled by the combination of ball valve and flow meter with uncertainty of ± 0.01 L/min. The heat generation of battery is simulated by using the DC power supply with uncertainty of ± 0.5 W. The ambient temperature is controlled by the air conditioner. Several K-type thermal couples and data acquisition devices (Agilent 34970A acquisition/switch unit) are used to measure and record the battery temperature response and the ambient temperature. The uncertainty in the measurement of temperature is ± 0.3%.

The test section is shown in Fig. 2(a). Two simulated batteries made up of aluminum is used in the present study. They have the same size as the commercially available power battery, namely 118 mm in length, 63 mm in width and 13 mm in thickness. Each simulated battery contains two heating rods acting as anode and cathode, through which the heat generation can be adjusted easily using the DC power supply. In order to reduce the time consumption and the waste of battery, this method had been widely adopted in the studies focusing on the thermal performance of BTMS [22,23,30,31]. Fig. 2(b) shows the shape of heat pipe (sintered copper-water) used in present study. Based on our