International Journal of Thermal Sciences 102 (2016) 9–16

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Thermal performance of phase change material/oscillating heat pipe-based battery thermal management system

Qingchao Wang [a], Zhonghao Rao [a, b, *], Yutao Huo [a], Shuangfeng Wang [b]

[a] School of Electric Power Engineering, China University of Mining and Technology, Xuzhou 221116, China
[b] Key Laboratory of Enhanced Heat Transfer and Energy Conservation of the Ministry of Education, South China University of Technology, Guangzhou 510640, China

A R T I C L E I N F O

Article history:
Received 28 December 2014
Received in revised form
10 November 2015
Accepted 10 November 2015
Available online 12 December 2015

Keywords:
Battery thermal management
Electric vehicle
Phase change material
Oscillating heat pipe

A B S T R A C T

To understand the cooling effect of power battery system within electric vehicle, this paper experimentally studied a phase change material/oscillating heat pipe (PCM/OHP)-based battery thermal management (BTM) system. The influencing factors, including temperature variations under different heating powers, battery surrogate terminal direction and OHP placement, were discussed. In this study, the cooling effects of OHP-cooled and PCM/OHP-based BTM system were also compared. The results showed that: (1) in order to obtain evenly distributed temperature, the start-up temperature of OHP, which was decided by the target temperature and maximum temperature difference (ΔT), should be below the phase change temperature of PCM; (2) the battery surrogate terminals should be away from the adiabatic section of OHP; (3) the PCM/OHP-based BTM system designed in this study was more efficient in cooling than the OHP-cooled system. The results of this experiment may contribute to designing of the PCM/OHP coupled battery cooling system.

1. Introduction

With the continuous development of economy, the issues of the energy use on power batteries have received great attention in many countries. Nickel–metal hydride (Ni–MH) and lithium-ion (Li-ion) batteries have displayed superior properties than lead–acid batteries that can meet the operational requirements of electric vehicles [1]. Nevertheless, the heat generated during rapid charging and discharging cycles will affect the lifetime of power battery [2]. Therefore, both temperature distribution and uniformity play important roles in battery thermal management (BTM) [3]. Noboru Sato [4] conducted a thermodynamics experiment for the Li-ion batteries, and analyzed the thermal behavior factors: reaction heat value, polarization heat value and Joule heat value. The thermal performance of the battery was influenced by the tab placement. For example, double-side tab can uniform the temperature distribution of the battery and a widened tab can decrease the maximum temperature of the battery [5]. In order to overcome the thermal stability problems of Li-ion battery, Giuliano et al. [6] designed an air-cooled thermal management system to investigate the performance of high capacity lithium–titanate batteries using metal-foam based heat exchanger plates, and they analyzed the heat yield under charge–discharge cycling when electric current was 100 A and 200 A respectively. The results show that the air-cooled systems can be a valid way for the BTM system. However, the air- and liquid-cooled methods became a dilemma: on the one hand a complex cooling system true offers a better performance and life span of battery, while on the other hand, both of them always need extra energy provided by battery, since power consumption also reduces battery service life. It is necessary to design a valid BTM system to increase the cycle lifetime of the battery for the purpose of optimizing the cooling performance of the power battery.

On account of the excellent cooling performance of heat pipe, it is a good element for BTM system. A large amount of experiments have been conducted to study the properties and applications of OHP [7–11]. Studies have shown that heat pipes can be used to achieve effective thermal management for a battery pack [12–14]. A higher surface contact of heat pipes shows a better cooling effect compared with forced convection cooling [12]. The thermal performance of OHP was influenced by its thermal resistance that

---

* Corresponding author. School of Electric Power Engineering, China University of Mining and Technology, Xuzhou 221116, China. Tel.: +86 516 83592000.

E-mail address: raozhonghao@cumt.edu.cn (Z. Rao).

http://dx.doi.org/10.1016/j.ijthermalsci.2015.11.005
1290-0729/

Nomenclature

C	specific heat capacity ($J\ kg^{-1}\ K^{-1}$)
T	temperature (K)
N	nature air cooling
H	horizontally
D	downward terminal
R	thermal resistance
Q	heat of the battery surrogate
L	battery length
ID	inner diameter of OHP
TH	battery thickness
cl	condensation section length (cm)
K	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
V	vertically
UP	upward terminal
g	gravity acceleration ($m\ s^{-2}$)
ΔT	temperature difference (K)
W	battery width
OD	outer diameter of OHP
el	evaporation section length (cm)
T_{Max}	maximum temperature (K)

Greek symbols

ρ	density ($kg\ m^{-3}$)
ρ_v	density of vapor
ρ_l	density of liquid
μ_l	volume flow rate of water
σ	surface tension
ν	viscosity ($kg\ m^{-1}\ s^{-1}$)

Subscripts

e	evaporation section of OHP
c	condensation section of OHP
max	maximum
l	liquid
s	solid
a	aluminum
M	melting

Acronyms

Ni–MH	nickel–metal hydride
PCM	phase change material
OHP	oscillating heat pipe
BTM	battery thermal management

decreased with the rise of the heating power. The OHP thermal resistance (R_{OHP}) can be obtained by the following equation [15]:

$$R_{OHP} = \frac{(T_e - T_c)}{Q}$$

T_e and T_c are the temperature of OHP in this study, namely average temperatures of the evaporation and the condensation section, respectively. Qu et al. [16] have experimentally investigated the thermodynamic performances of two same OHPs which were filled with SiO_2/water and Al_2O_3/water nano-fluids, respectively. They also experimentally studied the thermal properties and flow characteristics of a silicon-based micro-pulsating heat pipe which was embedded in a semiconductor chip. Finally, the experimental results showed that the maximum localized temperature was remarkably decreased [17].

On the other hand, latent heat storage is a more efficient method to store thermal energy than other heat storage methods. PCM is selected based on their melting temperature [18]. PCM has been broadly utilized in some latent heat thermal storage systems such as heat pumps [19,20], solar engineering [21–23] and BTM [1,24,25]. Various experiments have been conducted to study the properties and applications of PCM [26–28]. Qu et al. [29] developed a two-dimensional transient model to study the performance of battery by using the paraffin which was saturated in metallic copper foam. Finally, they concluded that the predicted surface temperature of battery was consistent with experimental data when the discharge rates were 1 C and 3 C respectively. However, the main drawback of PCM is its low thermal conductivity that limited its applications. For this reason, some metallic particles were applied to the PCM such as copper particles [30]. More recently, Greco et al. [31] studied a PCM/compressed expanded natural graphite (CENG) BTM system, in which the transient thermal behavior of both the battery and PCM/CENG was described detailedly. Finally, they concluded that the cooling system performed superior to forced convection cooling and the graphite-matrix bulk density was a significant factor in this cooling system. Ramandi et al. [32] designed a passive thermal management system for power batteries which were encapsulated in PCM. The exergy efficiencies of three PCM shells, including double PCM shell system with insulated walls, single PCM shell system with insulated walls and single PCM shell system with non-insulated walls, were comparably studied. Duan et al. [33] investigated two different thermal management schemes. The first design was that the heater was surrounded by a PCM cylinder, and the other with PCM jackets wrapping the heater. Finally, they concluded that both designs were efficient enough for making the heater temperature change over a defined range. In previous work, the thermal energy management property of aging rectangular $LiFePO_4$ power battery packs which were submerged in PCM was investigated [34]. In order to have a better understanding of the effects on PCM applied in BTM, a review of BTM was also done in our previous work Ref. [35]. PCM for BTM which is a novel method with well designed OHP may be more effective than other methods.

In our previous work, an experiment on thermal management of power battery with heat pipe was designed [13,14] and the results showed that power battery thermal management with heat pipes was a valid way for energy saving. In order to further reduce the temperature of the battery and optimize the thermal performance of BTM system for electric vehicle, the phase change material/oscillating heat pipe (PCM/OHP) coupled battery cooling system was designed. The effects of different heating powers, battery surrogate terminal direction and OHP placement on the thermal behavior of battery were discussed.

2. Experiment setup

A battery surrogate, which was manufactured by aluminum block, was selected to experimentally simulate a battery cell. The length and width of the battery surrogate were 115 mm and 90 mm, respectively. Battery surrogates were used instead of real batteries for safety reasons. The heating rods, as shown in Fig. 1, were embedded into the battery surrogate. In this experiment, system uncertainty (equipments and thermocouples) may have influence on the experiment results. The heating rods, which were connected with a direct-current (DC) power supply (the uncertainty was ±0.5 W), can be seen as the battery surrogate positive and negative