Energy Conversion and Management 138 (2017) 84–96

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Non-steady experimental investigation on an integrated thermal management system for power battery with phase change materials

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ARTICLE INFO

Article history:
Received 12 September 2016
Received in revised form 20 January 2017
Accepted 28 January 2017

Keywords:
Integrated thermal management system
Power battery
Phase change material
Air cooling
Heat power

ABSTRACT

A large amount of heat inside the power battery must be dissipated to maintain the temperature in a safe range for the hybrid power train during high-current charging/discharging processes. In this article, a combined experimental and theoretical study has been conducted to investigate a newly designed thermal management system integrating phase change material with air cooling. An unsteady mathematical model was developed for the battery with the integrated thermal management system. Meanwhile, the heat generation power, thermal resistance, and time constant were calculated. The effect of several control parameters, such as thermal resistance, initial temperature, melting temperature and ambient temperature, on the performance of the integrated thermal management system were analyzed. The results indicated that: (1) the calculated temperature rise of the battery was in good agreement with the experimental data. The appropriate operation temperature of the battery was attained by the action of the phase change storage energy unit which is composed of copper foam and *n*-Eicosane, (2) the remarkable decrease of the battery temperature can be achieved by reducing the convection thermal resistance or increasing the conductivity of the phase change storage energy unit, where the latter could be the better option due to no additional energy consumption. When convective resistance and thermal resistance between the battery surface and the phase change storage energy unit are less than 2.03 K/W and 1.85 K/W, respectively, the battery will not exceed the safety temperature under extreme condition, (3) the temperature rise declines with the decrease of the melting temperature or with the increase of the ambient temperature. It could be possible that the battery temperature exceeds the safety temperature for the high ambient temperature, (4) even if the phase change material is completely melted, the integrated thermal management system can still maintain the battery temperature within the safe range because of the air cooling.

1. Introduction

Compared to the traditional batteries such as lead-acid and nickel metal hydride, lithium-ion battery has attracted much attention due to its characteristics of stable charge/discharge cycle, high power density, long lifespan, wide working temperature range, environment friendly [1]. The lithium-ion battery has been widely used in hybrid electric vehicles and electric vehicles [2]. However, during the process of charge/discharge especially at large current, a large amount of heat will be generated due to various electrochemical and physical changes inside the battery. If the heat cannot be removed timely then it will accumulate inside the cells, which results in a sharp increase of the operating temperature inside the battery [3]. This will further lead to an overheating, fire, even explosion. The previous research revealed that the performance and lifetime of the battery are strongly impacted by the operating temperature [4]. There should be an optimum operating temperature range and a maximum temperature difference in the battery pack [5]. In this case, an efficient thermal management system would be highly needed to dissipate the generated heat in order to obtain an ideal operating temperature and temperature uniformity.

A variety of thermal management system (TMS) have been reported in the open published literatures and many studies have been devoted to this area over the past decades. Zolot et al. [6] evaluated the thermal performance of the Prius NiMH battery pack which used the forced air cooling system. It was found that both

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http://dx.doi.org/10.1016/j.enconman.2017.01.069
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Nomenclature

A	heat exchange area (m^2)
B	time constant (s)
Bi	Biot number
C	specific heat (J/(kg·°C))
E	open-circuit (V)
h	convective heat transfer coefficient (W/(m^2·K))
I	current (A)
L	battery thickness (m)
q	heat generation power of battery (W)
R	thermal resistance (K/W)
T	temperature (K)
T_D	phase transition temperature (K)
T_∞	ambient temperature (K)
t	time (s)
U	terminal voltage (V)
V	volume (m^3)

Greek letters

ε	emissivity
θ	excess temperature (°C)
θ_0	initial excess temperature (°C)
θ_D	excess phase transition temperature (°C)
λ	thermal conductivity (W/(m·K))
μ	heat dissipation ratio of PCM and air cooling
ξ	the ratio of thermal resistance of air cooling and PCM
ρ	density (kg/m^3)
σ	Stefan-Boltzmann constant
τ	time step (s)
Φ	heat transfer quantity (J)

Subscripts

h	convection heat transfer
max	maximum
p	phase change
r	radiation heat transfer
s	the heat absorbed by the battery

Acronyms

DOD	depth of discharge
ITMS	integrated thermal management system
PCM	phase change material
PCSEU	phase change storage energy unit
SOC	state of charge
TMS	thermal management system

the battery temperature and the temperature uniformity were maintained at an appropriate temperature range. Wu et al. [7] carried out a combined experimental and numerical study to investigate the temperature distribution in lithium-ion batteries. Their results showed that cooling by natural convection was not an effective means for removing heat from the battery system. It was also found that the forced convection cooling could mitigate temperature rise in the battery. Huo et al. [8] employed a mini-channel cold plate to cool the rectangular lithium-ion power batteries and the effects of the number of channels, flow direction, inlet mass flow rate and ambient temperature on the battery temperature rise were investigated. Zhao et al. [9] proposed a new kind of cooling method for cylindrical batteries based on mini-channel liquid cooled cylinder. It was found that the capacity of reducing the maximum temperature was limited through increasing the mass flow rate. The capacity of heat dissipation was enhanced first and then weakened along with the rising of entrance size. Khateeb et al. [10] designed a lithium-ion battery TMS with a novel phase change material (PCM). It was stated that the successful use of the PCM could be a potential candidate for the thermal management solution in electric scooter applications and for other electric vehicle applications. Rao et al. [11] experimentally and numerically discussed the thermal energy management performance of ageing commercial rectangular $LiFePO_4$ power batteries using PCM and thermal behavior related to the thermal conductivity between the PCM and the cell. It was pointed out that it is necessary to improve the thermal conductivity and to reduce the melting point of the PCM for heat transfer enhancement.

In general, thermal management strategies of the battery can be divided into passive system and active system. The active TMS based on the forced air convection or liquid cooling with heat exchanger is always a routine solution [12]. However, the drawback of the system is that it induces non-uniform temperature distribution in the battery pack with additional energy consumption. It has been reported that it consumed about 40% of the energy of the battery for the air TMS [13]. Whereas passive TMS using PCMs can decrease both the maximum temperature and the temperature difference within the battery pack [14]. Meanwhile, there is no added energy consumption, which can significantly increase the available energy of vehicles. However, the traditional PCMs, such as paraffin, have low thermal conductivity which is in conflict with rapid heat storage. In order to overcome it, composite PCM is developed by adding high thermal conductivity materials, i.e. porous metal, metal fins, or expanded graphite into paraffin. Li et al. [15] designed a sandwiched cooling structure using copper metal foam saturated with phase change materials for battery TMS. Although pure PCM could dramatically reduce the surface temperature, the foam-paraffin composite further reduced the battery's surface temperature and improved the uniformity of the temperature distribution caused by the improvement of the effective thermal conductivity. Alipanah et al. [16] numerically investigated the TMS of the battery made from octadecane–aluminum foam composite materials. It was found that adding metal matrix of 0.88 porosity to the octadecane led to 7.3 times longer discharge time compared to the pure octadecane and increased the uniformity of the battery surface temperature. Wu et al. [17] developed a copper mesh composite as a composite PCM for battery thermal management. Copper mesh acted as a skeleton could further enhance both the thermal conductivity and strength of the whole module. Lin et al. [18] developed a passive TMS and applied the expanded graphite matrix and graphite sheets to compensate low thermal conductivity of PCM. Recently, with the increasing power of the battery module, single passive or active TMS is not competent to meet the requirements of battery temperature control. As a consequence, the combination of both active and passive systems has been developed as an effective measure. Zou et al. [19] presented an integrated thermal management system (ITMS) combining a heat pipe battery cooling/preheating system with a heat pump air conditioning system to fulfill the comprehensive energy utilization for electric vehicles. It was found that around 20% of the cooling capacity was supplied without increasing the input power. Tiari et al. [20] developed the discharging process of the thermal energy storage system which consisted of a square container, finned heat pipes, and potassium nitrate (KNO_3) as the phase change material. Charles-Victor et al. [21] developed a battery TMS coupling PCM (Rubitherm RT28 HC) with an active liquid