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# Experimental and numerical investigation on integrated thermal management for lithium-ion battery pack with composite phase change materials

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## ABSTRACT

In this article, a novel composite phase change materials based thermal management system coupled with air cooling was proposed in order to sustain the temperature rise and distribution within desirable ranges of the lithium-ion battery utilized in a hybrid power train. A combined experimental and numerical study was conducted to investigate the effects of air flow rate and phase change material liquid fraction on the thermal behavior of the integrated thermal management system. Comparisons between the integrated system and an air cooling system were implemented under different air flow rates and ambient temperatures. Furthermore, thermal characteristics of both systems during charge-discharge cycles were numerically simulated. The results showed that the cooling effect of the integrated system was obviously better than that of the air cooling system. The variation of the air flow rate and ambient temperature had negligible impact on the heat dissipation of the phase change cooling. After the fully melt of phase change material, the battery temperature did not rise rapidly due to the auxiliary cooling of the cooling air. During 4 C charge-discharge cycles, the temperature rise of the battery pack could be effectively restrained by the air cooling at a flow rate exceeding 300 $m^3$/h. While for the integrated system, good thermal management could be achieved with only 100 $m^3$/h of air flow rate. Especially for the operation mode, i.e., phase change material cooling during the discharge and coupled phase change material and air cooling during the charge, the integrated system could control the maximum temperature of the battery pack below 49.2 °C and reach up to six charge-discharge cycles under no additional battery power consumption.

## 1. Introduction

In recent years, as the most suitable candidate for the hybrid electric vehicles and electric vehicles, the lithium-ion power batteries have attracted wide increased attentions due to their high specific energy density and long cycle life [1]. However, the performance of the lithium-ion batteries is significantly affected by the operating temperature. High operation temperature more than 55 °C can accelerate the battery ageing and shorten the lifespan [2]. It is recognized that the heat accumulation inside the battery will lead to a rapid temperature rise and even thermal runaway. The heat dissipation technology is limiting the commercial development of the large-scale battery pack [3]. It is therefore imperative to seek an effective thermal management system (TMS) in order to guarantee the battery can operate in the desired temperature range and keep as little temperature difference from cell to cell as possible [4].

Over the past two decades, many thermal management approaches have been studied, which mainly consist of air cooling system (ACS) [5], liquid cooling system [6], phase change material (PCM) cooling system [7] and heat pipe cooling system [8]. Due to the simple structure and low cost, ACS could be the earliest cooling technique that used for the battery thermal management. The experimental and numerical results investigated by Wu et al. [9] revealed that natural convection cooling could not effectively remove the heat from the battery pack

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**Nomenclature**

| | |
|---|---|
| $A$ | heat exchange area, $m^2$ |
| $c$ | specific heat, J/(kg K) |
| $h$ | convective heat transfer coefficient, $W/(m^2\,K)$ |
| $H$ | enthalpy, J/kg |
| $k$ | thermal conductivity, W/(m K) |
| $L$ | latent heat, J/(kg K) |
| $p$ | static pressure, Pa |
| $q$ | heat generation rate of battery, W |
| $Q$ | volume flow rate, $m^3/s$ |
| $t$ | time, s |
| $T$ | temperature, K |
| $u$ | velocity, m/s |
| V | volume, $m^3$ |
| $\Delta P$ | pressure difference, Pa |
| $\Delta T$ | temperature difference, K |
| $\beta$ | liquid fraction |
| ρ | density, $kg/m^3$ |
| $\mu$ | dynamic viscosity, kg/(m s) |

*Subscripts*

| | |
|---|---|
| amb | ambient |
| b | battery |
| dot | per unit volume |
| f | fluid |
| l | liquid |
| max | maximum |
| min | minimum |
| p | phase change material |
| ref | reference |
| s | solid |

*Acronyms*

| | |
|---|---|
| ACS | air cooling system |
| CAD | computer aided design |
| ITMS | integrated thermal management system |
| PCM | phase change material |
| PCSEU | phase change storage energy unit |
| SOC | state of charge |
| TMS | thermal management system |

whereas the forced convection cooling attained satisfactory the temperature rise of the battery. Park and Jung [10] numerically studied the effect of the battery cell arrangement on the thermal performance of the ACS and the parasitic power consumption. It was found that a wide battery module with a small cell to cell gap was desirable for the ACS. Under large heat load conditions, the consumed power of the ACS was much more than that of the liquid based TMS. Although a better cooling performance of the ACS could be achieved by means of the structure optimized design, the temperature difference in the battery pack was inevitable. Especially for large capacity and high discharge rate, the ACS could not effectively control the temperature rise and suppress the temperature difference of the battery [11].

It is well known that the liquid cooling can provide higher cooling efficiency and better thermal uniformity than the air cooling. The liquid cooling based TMS could maintain the battery temperature within a desirable range and the temperature difference from cell to cell is within 2 °C [12]. Transient thermal performance of a lithium-ion battery pack was analyzed by De Vita et al. [13] through comparing air cooling with liquid cooling strategy. By employing a liquid cooling based TMS on the basis of mini-channel cold plate, Rao et al. [14] numerically investigated the effect of various control factors, such as the number of channel, flow direction, coolant mass flow rate and ambient temperature on the temperature rise and distribution of the rectangular lithium-ion battery. For a cylindrical lithium-ion battery, they further studied the thermal performance of the mini-channel liquid cooling based TMS and found that the maximum temperature could be controlled under 40 °C as the number of mini-channel was no less than four and the inlet mass flow rate was 0.001 kg/s [15]. Afterwards, a series of research from the same research group revealed that the similar TMS with five mini-channels cold plate could achieve high cooling efficiency for the battery at 5C discharge [16]. Still liquid cooling based TMS has several disadvantages such as complex design, likelihood of leakage, high cost and difficult sustainment.

More recently, due to the extensive application in solar energy storage fields [17], the PCM based TMS that used to cool the battery are receiving increased attentions. It has simple structure, high latent capacity and no power consumption [18]. Al-Hallaj and Selman [19] took the lead in conducting the research on a battery module with a PCM based TMS. It was found that the temperature profile of the cells was substantially more uniform at different rates discharge than those without PCM. In the next study on a scaled-up battery pack, they [20] also presented that the PCM placed between the cells was able to be effectively used as a passive battery TMS without introducing moving components. However, the pure PCMs, such as paraffin, are not capable of meeting the demands of rapid heat storage owing to the low thermal conductivity. Therefore, many studies have been carried out to enhance the thermal conductivity through adding metal foam, metal fins, or expanded graphite into paraffin [21]. The numerical investigations on the lithium-ion battery TMS made from pure octadecane, gallium and octadecane-Aluminum foam composite materials were carried out by Alipanah and Li [22]. It was stated that in comparison with the pure octadecane, adding Aluminum foam of 0.88 porosity to the octadecane led to 7.3 times longer discharge time and remarkably improved the uniformity of the battery surface temperature. Wilke et al. [23] conducted the nail penetration on a lithium-ion pack and studied the effectiveness of the TMS with and without phase change composite material. Their results showed that as a single cell entered thermal runaway, the TMS with PCM could prevent the propagation while the TMS without PCM could not. Compared to the TMS without a composite of PCMs and aluminum wire mesh plates, the thermal behavior of the LiFePO4 pack with the TMS was experimentally studied by Azizi and Sadrameli [24]. It was recognized that the maximum cell surface temperatures under ambient temperature condition were reduced by 19%, 21% and 26% at the rate of 1C, 2C and 3C, respectively.

With the increasing power and heat generation of the battery pack, single thermal management approach is not competent to meet the demand of the heat dissipation of the battery. As a consequence, the integrated thermal management system (ITMS) has become an important way to solve the problem of the battery thermal safety. So far, there are mainly several types of the ITMS, for instance, air cooling/PCM TMS, liquid cooling/heat pipe TMS and PCM/heat pipe TMS. Wu et al. [25] designed a heat pipe-assisted PCM based TMS and experimentally studied the thermal performance. Experimental results showed that the highest temperature of the battery could be kept below 50 °C even at 5 C discharge and a more stable and lower temperature fluctuation was achieved at different cycling conditions. For a tube-shell lithium-ion battery pack with expanded graphite/paraffin composite, the thermal characteristics of the TMS coupled with forced air cooling were investigated experimentally and numerically by Jiang et al. [26]. It was found that the ITMS obviously reduced the cell temperature rise and kept the maximum temperature difference within a low value of 1–2 °C. Zou et al. [27] proposed an ITMS with heat pipe