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Experimental investigation on the thermal performance of heat pipe-assisted phase change material based battery thermal management system

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ABSTRACT

In this paper, a heat pipe-assisted phase change material (PCM) based battery thermal management (BTM) system is designed to fulfill the comprehensive energy utilization for electric vehicles and hybrid electric vehicles. Combining the large heat storage capacity of the PCM with the excellent cooling effect of heat pipe, the as-constructed heat pipe-assisted PCM based BTM is feasible and effective with a relatively longer operation time and more suitable temperature. The experimental results show that the temperature maldistribution of battery module can be influenced by heat pipes when they are activated under high discharge rates of the batteries. Moreover, with forced air convection, the highest temperature could be controlled below 50 °C even under the highest discharge rate of 5C and a more stable and lower temperature fluctuation is obtained under cycling conditions. Meanwhile, the effectiveness of further increasing air velocity (i.e., more fan power consumption) is limited when the highest temperature continues to reduce at a lower rate due to the phase transition process of PCM. These results are expected to provide insights into the design and optimization of BTM systems.

1. Introduction

Under the mounting pressure of emissions legislation and energy shortage, pure electric vehicles (EVs) and hybrid electric vehicles (HEVs) with highly efficient drive systems and green energy power are viable alternatives to conventional vehicles with combustion engines. Secondary Li-ion batteries are normally used as the power source for EVs and HEVs because of their good stability, high voltage, low self-discharge rate and high energy density [1,2]. Nevertheless, both extreme environmental and operating temperatures will affect the reliability, lifespan and safety of the batteries. The temperatures of all cells must be maintained within an operating range between 20 °C and 50 °C for the tolerable operation [3]. Cells are vulnerable to overheating from rapid discharging, overcharging or excessive ambient heating. Such issues can lead to rapid cell degradation and shorten battery life. Thus, an efficient and feasible battery thermal management (BTM) system for EVs and HEVs is essential to control the operating temperature of batteries within an appropriate range.

Consequent to these requirements, considerable research efforts have been invested to develop an advanced BTM system which can be summarized as several types based on the employment of different heat transfer medium such as air [4], liquid [5,6] and phase change material based systems and combination of them [7]. As an innovative solution for thermal management applications, PCM can absorb/release abundant latent heat during the melting/solidifying process, giving rise to a relatively constant temperature for the PCM based system, which make this type of BTM system receive extensive attention and exploration in recent years [8]. The thermal management solution using PCM as heat transfer medium was first proposed by Al-Hallaj and Selman [9] in 2000, in which the paraffin mixture was used as the PCM and filled in the gap between batteries. The as-designed PCM based BTM system actually showed a much better thermal performance than conventional systems.

Currently, paraffin wax is the most widely researched PCM for BTM because of its low cost, hard-to-decompose character and a broad range of suitable phase-change temperature varying with the number of main chain carbon atoms [7]. Unfortunately, one of the main bottlenecks that limits the application of PCM is its low thermal conductivity. In regard to this weakness, many different approaches have been developed to enhance the thermal

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Nomenclature

T	temperature (°C)
ΔT	temperature difference (°C)
Acronyms	
PCM	phase change material
EG	expanded graphite
EVs	pure electric vehicles
HEVs	hybrid electric vehicles
BTM	battery thermal management
HP	heat pipe
OHP	oscillating heat pipe
PCMP	phase change material plate

conductivity of PCM by introducing a second component made of high conductive materials such as metallic particle [10], metal foam/mesh [11,12], carbon fiber [13], graphene [14,15] and carbon nanotubes [16]. Al-Hallaj et al. [17] designed different modes of heat dissipation for Li-ion battery modules and tested at various constant C-rates, the results showed that the distribution of PCM in the pores of aluminum foam resulted in a minor temperature drop when compared to PCM alone and a significant drop of about 50% compared to natural convection cooling. Under the road operating state, that is, the fluctuations of discharge current, such paraffin/metal foam technology is also efficient for BTM within EVs [18]. However, closed tanks or containers are necessary to prevent leakage of liquid-phase PCM when the temperature of the PCM is over the melting point, giving rise to a relatively complex structure in practical applications.

Expanded graphite (EG) material as a porous matrix is often inserted into PCMs due to its high thermal conductivity (about 200 $W m^{-1} K^{-1}$) and high porosity for increasing absorbability, which is favorable for the creation of thermal conductive networks within the composite PCM and shape-stabilized during the solid-liquid phase change [19,20]. With EG impregnated in the PCM, the total thermal conductivity of composite PCM was increased by two orders of magnitude and the performance of the BTM system was significantly improved in comparison to the original battery packs [21,22]. The thermo mechanical properties of PCM/EG composites such as tensile strength, burst strength, compression strength and bending strength were also studied in Refs. [23,24]. Wu et al. [25] proposed a copper mesh-enhanced PCM/EG composite BTM for prismatic batteries, in which the as-constructed system presented much better heat dissipation performance and temperature uniformity compared to PCM/EG based system. In spite of the high efficiency, the PCM/EG based system without any other cooling methods still encountered the problem that single PCM-based cooling technology usually presents low surface heat transfer coefficient between PCM and air, which may lead to the running out of the available latent heat under extreme conditions [25,26].

Heat Pipe (HP), as a high efficient heat transfer device with excellent characteristics such as compact structure, flexible geometry and long service life, has been widely used in thermal energy storage system [27,28] and electronic thermal management [29]. In the latent heat storage system, the assisted HP can amplify the charging/discharging process rate of PCM and thus improve the overall thermal performance [30–32]. For the usage on battery, HP based BTM systems were fully studied experimentally [33–39] and theoretically/numerically [40–42]. Wu et al. [43] proposed a method by applying HP with aluminum fins in a Li-ion battery pack and it was found that HP cooling is an effective method which can reduce the temperature rise and maintain a uniform temperature distribution over the battery surface. On account of the excellent advantages in simple design and cooling performance of oscillating heat pipe (OHP), an OHP-cooled simulative batteries system was designed and experimentally studied by Rao [44]. Further, considering the large heat storage capacity of the PCM, some changes were made and paraffin as PCM was added into the simulative OHP cooling system [45]. They concluded that some methods should be taken to increase the thermal conductivity of paraffin for the purpose of further improving the thermal performance of the BTM systems. Moreover, by taking into account the literature survey, it can be noted that the performance of HP/PCM coupled system has not been experimentally studied for real batteries, especially based on module level. In addition, a feasible and effective system with the feature of easy package is essential and should be further explored due to the potential for practical application.

In our previous work [46], a kind of shape-stabilized PCM/EG composite plate with enhanced thermal conductivity was prepared for use in the field of thermal management and this method can be also used in various practical applications. In order to further optimize the thermal performance of BTM system, a HP-assisted PCM/EG composite plate based BTM system was designed for EVs and HEVs in this study. Sub-modules were fabricated and then investigated experimentally under different operating conditions. As highlighted here, paraffin with large latent heat serves as the thermal buffer. Porous EG with high thermal conductivity can create thermal conductive networks and absorb liquid phase paraffin to address the leakage problem. HP acts as a heat conductor to further increase the heat absorption rate of PCM/EG composite, and also extract the heat from battery module to the external air environment. The as-designed battery pack with the feature of easy package is expected to be enclosed, leaving only a channel for heat exchange at side of the battery box, to meet the compact and water/moisture-seal requirements for practical applications.

2. Concept description

For EVs and HEVs applications, a compact and well designed battery pack is necessary because of the limited space in EVs and HEVs. Fig. 1 shows a generic design of pack-scale BTM system, in which there are several sub-modules in series/parallel arrangement. In the design, the battery pack consists of PCM composites surrounding the array of battery monomers. The evaporating section of HP is integrated within PCM with the condenser end extending outside of the battery box. An air flow channel on the side of the battery pack serves as the heat exchanger, where air could be blown through the finned condenser using fans. Such a novel thermal management system is designed to be compact and efficient.

Before constructing a commercial scale battery pack, a lab-scale battery module is usually used firstly to confirm the feasibility of a new thermal management strategy. A sub-module consisted of five commercially prismatic batteries (3.2 V/12 A h) in series connection rated at 16 V/12 A h was used as the research object in this work. In this module, six phase change material plates (PCMPs) with a thickness of 5 mm and five batteries were stacked alternately to form a compact sandwich structure. Two HP-assisted PCMPs were in contact with both long sides of this module. A typical HP-assisted PCMP (HP-PCMP) can be also seen in Fig. 1.