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Experimental investigation of a passive thermal management system for high-powered lithium ion batteries using nickel foam-paraffin composite

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ABSTRACT

It is necessary for electric vehicles (EVs) and hybrid electric vehicles (HEVs) to have a highly efficient thermal management system to maintain high powered lithium ion batteries within permissible temperature limits. In this study, an efficient thermal management system for high powered lithium ion batteries using a novel composite (nickel foam-paraffin wax) is designed and investigated experimentally. The results have been compared with two other cases: a natural air cooling mode and a cooling mode with pure phase change materials (PCM). The results indicate that the safety demands of lithium ion batteries cannot be fulfilled using natural air convection as the thermal management mode. The use of PCM can dramatically reduce the surface temperature within the permissible range due to heat absorption by the PCM undergoing phase change. This effect can be further enlarged by using the nickel foam-paraffin composite, showing a temperature reduction of 31% and 24% compared to natural air convection and pure PCM, respectively under 2 C discharge rate. The effect of the geometric parameters of the foam on the battery surface temperature has also been studied. The battery surface temperature decreases with the decrease of porosity and the pore density of the metal foam. On the other hand, the discharge capacity increases with the increase in porosity, but decreases with pore density.

1. Introduction

Lithium-ion batteries have turned into a key component of mobiles, hybrid electric vehicles (HEVs) and electric vehicles (EVs) owing to their high energy and power densities, extended life span and low weight to volume proportion [1]. These properties connected with lithium-ion batteries do, however, cause a rapid rise in temperature beyond the permissible operating range during operation. This expeditious temperature rise not only affects the battery performance and life span, but also causes localized deterioration within the battery pack. Managing this excessive temperature remains a challenge. Depending on the mode of cooling, thermal management of the battery could be active (i.e. pump, fan, heat sink, etc.) [2,3] or passive (i.e. phase change material) [4,5]. Due to the addition of components such as a fan, pump or heat sink, the active cooling approach is not only expensive but also cumbersome, increasing the overall weight and cost of the battery pack. Passive thermal management employing PCMs differs from traditional thermal control systems, being light, compact and highly efficient. Owing to this, passive thermal systems have attracted increasing interest in recent years.

PCMs used in thermal management systems should possess large latent heat, low volume expansion, be non-poisonous, non-corrosive, non-explosive and low cost [6]. Although PCMs have advantages over other heat storage materials (water, oil, glycol, acetone, refrigerants etc.) owing to the above mentioned characteristics, their low thermal conductivity (~0.1 W/m K) [6] is likely to hamper their efficiency and cause failure in electronic devices. A variety of heat transfer enhancement techniques have been reported previously in literature to address this problem. These enhancement techniques are summarized in the following ways (1) utilizing metal fins or adding metal screens/spheres [7–13]; (2) utilizing thermally conductive additives like aluminum powder, carbon-fiber chips or nano-materials with the PCM [14–25]. Wang et al. carried out a simulation to study three dimensional transient heat transfer of hybrid PCM based multi-fin sink. They found that

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Nomenclature

a	Interfacial surface area [1/m]
d	diameter [m]
K	thermal conductivity [W/(mK)]
T	temperature [°C]
t	time [s]

Greek symbols

ε	Porosity [−]
ω	Pore density [PPI]

Subscripts

f	fiber
p	pore
sf	solid-fluid

Abbreviations

A	ampere
Ah	ampere-hour
C	charge/discharge rate
DAQ	data acquisition system
DC	direct current
EV	electric vehicle
HEV	hybrid electric vehicle
P	parallel
PPI	pore per inch
PCM	phase change material
RT	Rubitherm
S	series

the use of PCM in the aluminum heat sink would give electronic packages a more stable operation temperature. Besides, a longer melting time can be conducted by using a multi-fin hybrid heat sink [7]. Aadmi et al. numerically and experimentally studied the storage and release of thermal heat during melting and solidification of a composite PCM that is based on epoxy resin loaded with metal hollow tubes filled with paraffin wax. They observed an increase in thermal conductivity of pure paraffin by 3–4 times. Their results also indicated that the heat storage capacity of the composite is increased with the PCM content [8]. Zhang et al. have successfully synthesized a novel type of multi-functional microencapsulated PCMs with a silver/silica double-layered shell. They found that a good latent heat storage capability for thermal regulation and temperature retention can be achieved. Most importantly, the multi-functional microcapsules exhibited a considerable electrically conductive capability [10]. Regarding the second technique, Xu et al. prepared a composite PCM based on paraffin/diatomite/multi-wall carbon nanotubes. They discovered that the thermal conductivity of the paraffin-diatomite composite is enhanced by about 42% after using 0.26% multi-wall carbon nanotubes [14]. Zhang and his co-workers carried out a study to investigate the thermal and electrical conductivity of graphite nanoplatelets (GnPs) on form-stable phase change materials. The results showed that the GnPs additives were able to effectively enhance the thermal and electrical conductivity of the organic form-stable phase change materials. When the mass ratio of GnP was 8%, the thermal and electrical conductivity are enhanced by 9 times and 8 orders of magnitude over that of polyethylene glycol/polymethyl methacrylate matrix, respectively [16]. Last, Li. et al. experimentally studied the heat transfer performance of a porous stainless-steel fiber felt saturated with paraffin. The effects of the porosity and the fiber diameter on the surface temperature and the solid/liquid interface evolutions were investigated. They observed a drop of 100 °C in fluid surface temperature during the melting region of the composite [19].

In addition to those methods, one attractive means to enhance thermal conductivity is by inserting PCM into porous media. Porous metal foam possesses properties like high porosity, high specific strength, stiffness and good mechanical and thermo-physical properties. Aluminum foam-paraffin composite has been explored by Lafdi et al. [26], Khateeb et al. [27] and Wang et al. [28]. In detail, Lafdi found that steady state temperature can be rapidly attained by using foam of higher porosity as there is a large convection effect in higher porosity foam. However, the battery/heater temperature will be relatively high due to low heat conduction [26]. Thus, a compromise is required between porosity and pore density in aluminum foam to utilize the advantage of both the conduction and convection of an aluminum foam-paraffin composite. Khateeb et al. [27] experimentally proved a drop of 5 °C in temperature by use of an aluminum foam-PCM composite for a 13.2 A h battery pack as compared to pure PCM, while Wang et al. experimentally proved that the use of aluminum foam increased the thermal conductivity of composite paraffin by 218 times that of pure paraffin wax. The battery surface temperature was reduced by 11.7 °C under 2 C discharge rate after using aluminum foam-paraffin composite [28]. It should be noted that Wang et al. utilized rectangular lithium ion batteries. The battery surface temperature drop after using aluminum foam-paraffin composite is different in various studies due to the difference in the melting range of the paraffin utilized, battery capacity, discharge rate, ambient conditions and geometric features of aluminum foam. In addition, copper foam-paraffin composites have also been widely studied [29–32]. Li et al. conducted a numerical study regarding enhancement of the thermal conductivity by incorporating PCM into copper metal foam [29]. They found that temperature uniformity inside copper foam-PCM composite can be achieved by using a foam with a lower porosity and pore density. A lower value of pore density aids in improving the effective thermal conductivity of the composite, while the lower value of porosity assists in accelerating the natural convection performance. Li et al. [30] experimentally investigated the surface temperature of 10 A h batteries using copper foam-PCM composite. They observed a decrease of 29% and 12% in temperature as compared to the surface temperature of air convection and the pure PCM mode respectively at 1 C discharge rate. Qu et al. developed a 2D transient model to study a passive thermal management system for square lithium ion batteries. They also utilized copper foams to enhance the thermal conductivity of paraffin wax. Their result indicated that the battery surface temperature was reduced by 17 °C and 30 °C after employing copper foam-PCM under 1 C and 3 C discharge rates respectively [31]. A group led by Wang found that the copper foam enhanced the thermal conductivity of paraffin wax by 6 times, but the heat storage capacity of pure paraffin was reduced by 33% after the formation of copper foam-PCM composite [32]. Moreover, expanded graphite-paraffin wax composites have also been investigated by many different research groups [5,33–35]. Somasundaram et al. developed a 2D transient thermo-electrochemical model to study a passive thermal management system for lithium ion batteries. Their model contained the geometry and edge effects to analyze the effect of discharge rate on passive thermal