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Application of Phase Change Energy Storage Materials in BTMS Based on Element Analysis

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In this paper, the author researches on the application of phase change energy storage materials in battery thermal management system based on element analysis. With low weight, good compactness and excellent temperature control, passive battery thermal management (BTM) using phase change materials (PCM) of electric vehicles shows great business prospect. Based on the advantages and disadvantages of BTM employing air and liquid cooling system, this paper introduces the working principle parameters of battery pack and PCM for BTM design, as well as the research progress and development in this area. It also points out that the application of PCM-based BTM to high performance battery, such as lithium ion power battery, will become the mainstream trend in the future which deserves more attention.

1. Introduction

With the continuous progress of society and economy, energy and environmental problems have become increasingly prominent. Energy saving and emission reduction correspondently have become more urgent. There are two promising directions: the storage and utilization of thermal energy and the development of new energy vehicles. The former can further improve energy efficiency while the latter can reduce fossil energy use and promote the development of new energy, thereby reducing pollutant emissions. Being one of the four core technologies in electric vehicle area, battery thermal management (BTM) have become the focus and hotspot in recent years. The potential of phase change materials (PCM) used in thermal management and thermal energy storage is tremendous (Xu et al., 2015; Ling et al., 2015). As a kind of good heat transfer media, oscillation heat pipe (OHP) can compensate the disadvantage of PCM's low thermal conductivity and connect PCM with outside (Wang et al., 2015; Lin et al., 2015; Zhou et al., 2015).

Good battery thermal management systems (BTMSs) are essential to the safety, reliability and efficiency of the batteries. A BTMS needs to ensure not only that the temperature of all battery cells is within a safe range, but also that the maximum temperature difference between different cells within battery pack is below 5°C. Conventional BTMSs such as active air cooling and liquid cooling system require extra power and fail to cope with high density of heat generation. Passive BTMSs making use of latent heat of phase change materials (PCMs) to absorb the heat generated by batteries are proved to be an effective way to maintain the battery temperature within their safety range without using extra energy (Browne et al., 2015; Jocob and Bruno, 2015). If combined with expanded graphite or metal foams, the thermal conductivity of PCMs could be improved significantly. This can minimize the battery pack temperature difference and achieve a uniform temperature difference between different cells. As it is relatively easy to make PCMs into different shapes, they can be applied to batteries of different shapes and battery systems with a variety of configurations.

The latent heat and sensible heat of PCM is utilized to store and transfer the heat from the batteries: when operating temperature rises, the heat is stored and transferred by PCM in solid state in order to control the temperature, and the temperature of PCM rises at the same time. When the temperature of PCM reaches the melting point, PCM begins to melt and the heat is absorbed as latent heat, which is usually abundant; in turn, as the operating temperature of batteries is too low, the latent heat of PCM in liquid state can be released to heat up the batteries and can ensure that they work in an optimal temperature range.

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2. Paraffin wax and its heat transfer enhancement

2.1 Paraffin wax

Apart from high latent heat of phase change, negligible super-cooling, non-toxic and non-corrosiveness quality, wide source and low cost, Paraffin wax is an ideal PCM for BTMS also because its melting point is near the optimal operating temperature,. However, its thermal conductivity coefficient is as low as 0.15W/m·°C, which is in the same order of magnitude as ordinary thermal insulation materials, meaning that its heat-transfer capability is weak. That's the reason why a great many of latest studies all focus on heat transfer reinforcement of paraffin wax.

2.2 The heat transfer enhancement of paraffin wax

Weak heat transfer capability will result in non-uniformity of temperature inside the paraffin wax and bad heat dissipation, so it is necessary to reinforce the heat transfer capability of paraffin wax. The latest studies mainly focus on modifying the structure of its heat storage equipment such as adopting fins, honeycomb, porous media and adding materials with high conductivity such as metal powder and graphite.

The addition of fins can efficiently improve the heat transfer capability of the whole equipment by enlarging the heat dissipation area, yet without changing the heat conductivity of PCM itself. The use of finned tubes with different configurations has been proposed by various researchers. The investigation showed that the addition of Eros can enhance the heat transfer capability of tubes. By adding fiber with high heat conductivity, the composite PCM can achieve much higher heat conductivity. But this also brings bad influence on the latent heat storage of paraffin wax. Thus, proper mixing ratio becomes significant to improve the heat conductivity without weakening the heat storage capability too much. Porous media with high heat conductivity, especially those made through sintering process, has often been used because of the advantage of low weight, high surface volume ratio, strong structure and low processing cost. Carbon fibers, with strong resistance to erosion and relatively high heat conductivity, have less density for heat transfer enhancement than common metal. Being compatible with paraffin wax, carbon fibers show great advantages in heat transfer enhancement. The features of this method include that the volume fraction of fibers is accurately and can be easily controlled and that fibers with low volume fraction would be entirely dispersed in the PCM. Carbon fibers can raise the heat conductivity coefficient by 10 times. Samimi et al. proposed a graphite-compound material, where the PCM is embedded inside a graphite matrix as shown in Fig. 1. The main advantage of such a material is the increase in heat conductivity in the PCM without much energy storage reduction (Samimi et al., 2016; Wu et al., 2016; Wilke et al., 2017).

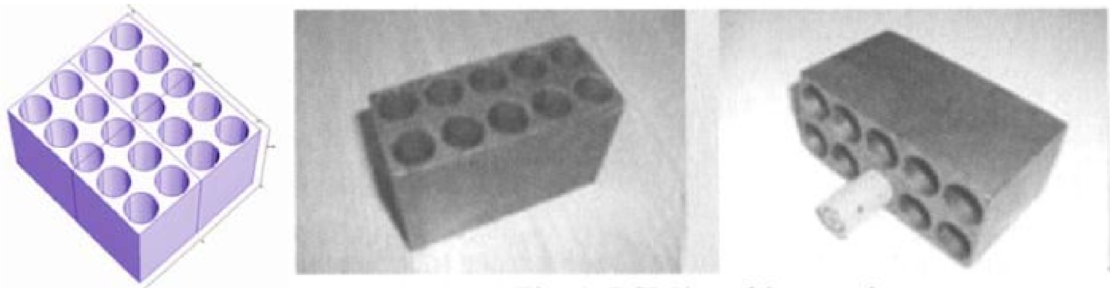

Figure 1: PCM/Graphite Matrix

2.3 The element analysis and algorithm

Thermal conductivity was one of the most important parameters of phase change materials. In this section, the effects of thermal conductivity have been investigated. Figure 2 shows the variations of paraffin liquid fraction with different thermal conductivity. Figure 2a shows that the effects of thermal conductivity on phase change phenomenon were inconspicuous at the beginning of the melting process when the heat flux was applied to the left wall. About 600s later, it turned to be obvious that with the increase in thermal conductivity, the rate of melting process increased. However, when the heating wall was located at the bottom side at the same moment, the greater thermal conductivity led to a smaller liquid fraction, which is quite different from the results shown in Fig. 2a. With the increase in thermal conductivity, the gradient of liquid fraction was increased, and finally the process of phase change was almost completed as well. Similar results could be concluded from Fig. 2c. To sum up, thermal conductivity had great effects on the gradient of liquid fraction.

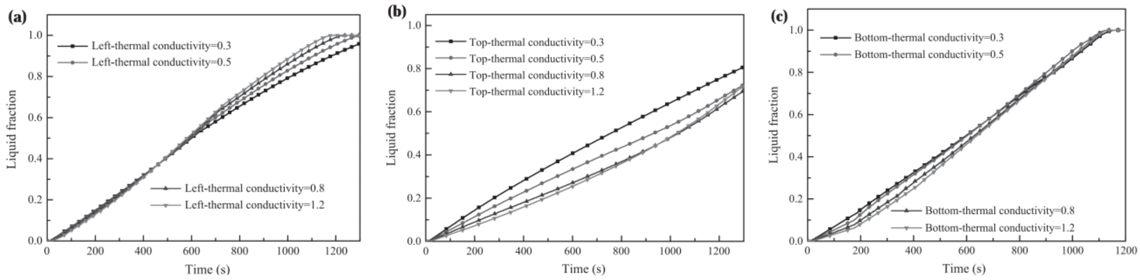

Figure 2: Effects of the Thermal Conductivity of PCM on the Phase Change Process. Heat flux was Applied to the Left Wall (a), the Top Wall (b) and the Bottom Wall (c)

A square cavity filled with paraffin was designed in this research. The size of the cavity was 20 mm x 20 mm. Heat was applied to a wall at constant heat flux, and the others were thermally insulated. The heat flux was obtained by the heat generation model of battery. In the following analysis, several assumptions have been adopted. Firstly, paraffin was assumed to be pure, and the density, melting point and thermal conductivity be constant. Secondly, it was assumed that liquid paraffin was Newtonian incompressible, and the flow in the cavity was laminar. The approximation has been applied, which meant that the density of paraffin only changed in buoyancy items as follows:

$$\begin{aligned}\hat{f}_H^{\alpha}(x) &= \frac{1}{\Gamma(1+\alpha)}\int_{-\infty}^{\infty}\frac{f(t)}{(t-x)^{\alpha}}(dt)^{\alpha} \\ &= \frac{1}{\Gamma(1+\alpha)}\int_{-\infty}^{\infty} f(t)g(x-t)(dt)^{\alpha} \\ &= f(x)*g(x),\end{aligned} \tag{1}$$

$$\partial_j(C_{ijkl}\partial_k u_l + e_{kij}\partial_k\varphi) - \rho\ddot{u}_i = 0 \tag{2}$$

$$\partial_j(e_{ijkl}\partial_k u_l - \eta_{kij}\partial_k\varphi) = 0 \tag{3}$$

The linear equation can be expressed into the following simplified forms:

$$L(\nabla,\omega)f(x,\omega) = 0 \tag{4}$$

$$L(\nabla,\omega) = T(\nabla) + \omega^2\rho \mathrm{J} \tag{5}$$

So we get the PR value as the following:

$$PR(u) = \sum\frac{PR(V)}{L(V)} \tag{6}$$

$$L_k = \frac{d_e}{\sum_{e=1}^{n} d_e} \tag{7}$$

To calculate the parameters in above equations, then we have:

$$\Lambda_{ik}(k,\omega) = k_j C_{ijkl}^0 k_k - \rho_0\omega^2\delta_{il},\ h_i(k) = e_{kil}^0 k_k k_l,\ h_l^T = e_{ikl}^{0T} k_i k_k,\ \lambda(k) = \eta_{ik}^0 k_i k_k \tag{8}$$

$$\frac{1}{2\pi}\int_{-\infty}^{\infty} e^{-ik_3x_3'}dx_3' = \delta(k_3) \tag{9}$$

$$s(X \to Y) = \frac{\sigma(X \cup Y)}{N} \tag{10}$$

$$c(X \to Y) = \frac{\sigma(X \cup Y)}{\sigma(X)} \tag{11}$$

Its local fractional Hilbert transform, denoted by $f_x^{H,\alpha}(x)$ is defined by

$$\begin{aligned} H_\alpha\{f(t)\} &= \hat{f}_H^\alpha(x) \\ &= \frac{1}{\Gamma(1+\alpha)} \oint_R \frac{f(t)}{(t - x)^\alpha}(dt)^\alpha \end{aligned} \tag{12}$$

Where x is real and the integral is treated as a Canchy principal value, that is,

$$\begin{aligned} &\frac{1}{\Gamma(1+\alpha)} \oint_R \frac{f(t)}{(t - x)^\alpha}(dt)^\alpha \\ &= \lim_{\varepsilon \to 0}[\frac{1}{\Gamma(1+\alpha)} \int_{-\infty}^{x-\varepsilon} \frac{f(t)}{(t - x)^\alpha}(dt)^\alpha + \\ &\frac{1}{\Gamma(1+\alpha)} \int_{x+\varepsilon}^{\infty} \frac{f(t)}{(t - x)^\alpha}(dt)^\alpha] \end{aligned} \tag{13}$$

3. Application of paraffin wax in thermal management of lotteries in electric vehicles

To achieve the optimum performance of a battery, it is necessary for BTMS to:
(1) Regulate batteries to operate in the desired temperature range; and (2) to reduce uneven temperature distribution. There has been increasing number of studies on paraffin management of batteries. The batteries for the scooter consist of two modules and each contains 18 cells as is displayed in Figure 3. Each module consists of six strings with three cells in series while the six strings of cells are connected in parallel as is shown in Figure 1. The nominal voltage and capacity of each module is 11.1 V and 12Ah respectively. The current and voltage requirement for the electric scooter is 20--24A and I2V respectively, under the normal operating conditions on a flat ground. Hence, two modules have to be connected in parallel to meet the current requirements. During the start-up of the vehicle, the current requirement is 55A for 300ms and each string of the module would discharge at 2.4C rate for 300ms.

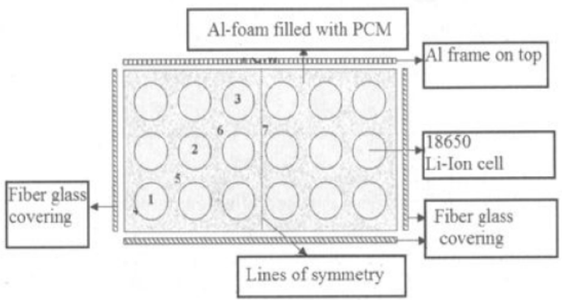

Figure 3: Battery Module of the Scooter

First the effect of the module during the battery operation with air-cooling is simulated. The temperature at center location of the cell rises by 450C under natural convection with the heat transfer coefficient, whereas the cell exposed to forced air-coating during discharge at location (1) rises by 35C, with a temperature gradient of 10°C between the cells. The cell in this case is prone to a thermal runaway, risking the safety of the battery and vehicle. The serial airflow scheme and the parallel airflow scheme are shown in Figure 4.

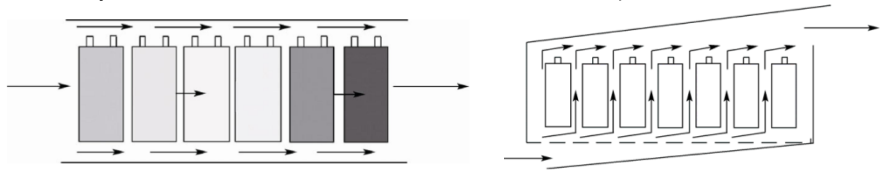

Figure 4: Serial Airflow Scheme and Parallel Airflow Scheme

PCM alone was then used as the spacing material with melting point of 40-44°C and specific heat of 1.77kJ/kg, while the conductivity coefficients under solid and liquid condition was 0.21 and 0.29W/m·k respectively. It reduced the temperature rise and got results with obvious non-uniformity. Then the poor thermal conductivity of PCM was overcome by using aluminium foam with a density of 8-l0% and 40ppi (pores per inch). The effective thermal conductivity, filling up the voids by accounting for the combined conduction of aluminium foam material and PCM, was raised to be approximately 3W/(m^{2}·K), which modified the uniformity significantly. Finally Aluminium fins were added to the existing battery module and numerous simulations were conducted to obtain a stable temperature profile of the battery module by optimizing the length and the number of fins. The aluminium fins were proved to be very effective in maintaining the temperature uniformity and suppressing the temperature rise during the three cycles of scooter operation. It not only validated the feasibility of PCM used in BTMS under normal temperature by experiments, but also showed that PCM presents excellent heat storage capability under high temperature and the heat conductivity is better in liquid state than that in solid state, in which it is found that PCM foam composite materials can be effective to keep the temperature uniformity and to control the temperature rise. A passive BTMS using PCM is tested under extreme conditions, such as ambient temperature of 45°C and discharge rate of 2.08C-rate (10A). Contrary to the packs without thermal management system, high energy packs with PCM are discharged safely at high currents, and the degrading rate of capacity of the packs lowered by half. This means that it's passive to apply PCM in electric vehicles under extreme conditions. Figure 5 shows the air cooling system schematic diagram and Figure 6 shows the liquid cooling system schematic diagram.

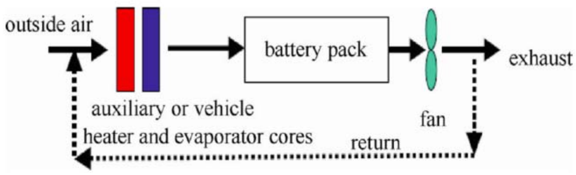

Figure 5: Air Cooling System Schematic Diagram

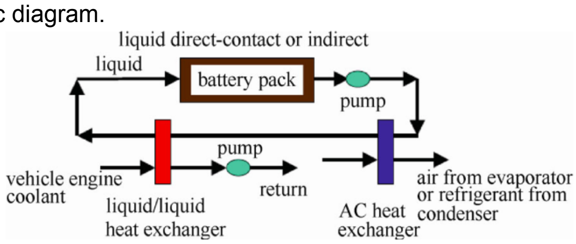

Figure 6: Liquid Cooling System Schematic Diagram

It compared the effectiveness of passive cooling by PCM with that of active (forced air) cooling at different discharge rates, operating temperatures and ambient temperatures of a compact battery pack suitable for plug-in hybrid electric vehicle (Pl-IEV) propulsion. The PCM cooling mode used a micro-composite graphite-PCM matrix surrounding the array of cells, while the active cooling mode used air blown through the gaps between the cells in the same array. The results showed that under stressful conditions, i.e. at high discharge rates and high operating or ambient temperatures, for example 40-45°C, air-cooling is not a proper thermal management system for keeping the temperature of the cell in the desirable operating range without expanding significant fan power, whereas the passive cooling system is able to meet the operating range requirements under the same stressful conditions without the need for additional fan power. It compared the effects of thermal runaway to surrounding cells inside the battery modules by air cooling with that by PCM and the influence of cell spacing on the heat transfer among the cells.

Under extreme conditions, i.e. when the temperature is high enough to get PCM completely melt, additional cooling is needed. It proposed a combination of two cooling systems (Air & PCM), which is an effective thermal management method. The proposed system keeps the cells' temperature uniform and within safety limits. It also requires less complex designs for uniform air distribution as well as less fan power.

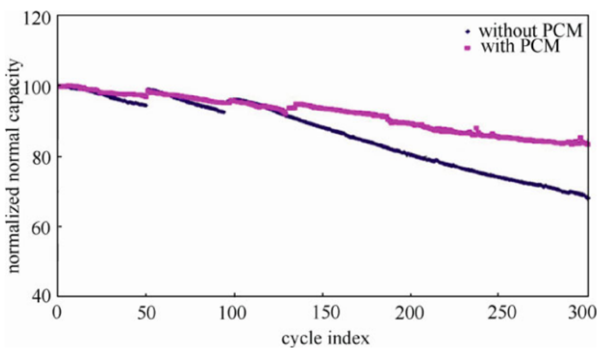

Figure 7: The Capacity Fade Testing of Battery Modules with/without PCM.

The PCM acts as a thermal capacitor to buffer short-term thermal events and absorb heat at a high rate during discharge and release the heat to an air cooling system at a steadier rate. The capacitor effect allows the air cooling system to be minimized and makes it possible, by a practical air or liquid cooling system, to achieve a lower and more uniform pack temperature thaw. Combining PCM method would allow smaller air cooling system and less need to limit battery power output under high-temperature conditions. So the combination of PCM and an active cooling system will be a significant research direction except for air-cooling system, and water cooling with tiny tube in PCM is also a good alternative.
Combining PCM method also designs a battery module based on Air &PCM cooling, using an all-electric bus. Figure 7 shows the capacity fade testing of battery modules with/without PCM.

4. Conclusion

In this paper, the author researches on the application of phase change energy storage materials in BTMS based on element analysis. With its low weight, good compactness and excellent temperature control mentioned above, passive BTM using PCM for electric vehicles shows great business prospect. But as the related studies are still in the initial stage so far, there are many problems to be solved:
1) Further studies are needed to modify the structure of battery module, such as the overall arrangement of cells.
2) The heat transfer enhancement needs to be improved to meet the demands of heat dissipation and temperature uniformity. Additional cooling is necessary under extreme conditions when FCM completely melts and heating is needed for keeping the battery at optimal temperature during the start-up under low temperatures. All requires the combination of passive thermal management by PCM and active thermal management.

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