Heat transfer in phase change materials for thermal management of electric vehicle battery modules

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1. Introduction

Phase change materials (PCMs) for passive thermal management have useful applications to cooling of microelectronics assemblies, battery modules for electric vehicles (EVs), among many others. This paper examines the heat transfer characteristics of PCMs for EV applications. The performance, lifespan, durability and cost of electric vehicles are highly dependent on the battery packs. Battery temperature is a crucial parameter for the battery performance. Most batteries can only charge or discharge efficiently and safely in a certain temperature range [1]. High temperatures above the defined operating range can significantly reduce the lifetime and even damage the battery [2]. Battery temperatures below the defined operating temperature range (especially below 0 °C) lead to a decrease in voltage and charge of the battery [3]. In both cases, the performance and lifetime of the battery are reduced, resulting in higher costs and decreased reliability of the electric vehicles. It is therefore crucial to keep the battery modules within a defined temperature range. This requires an effective thermal management system.

A good thermal management system must maintain the batteries in a defined temperature range, when the vehicles operate in both hot and cold climates. Most batteries generate a significant amount of heat during discharge, which must be dissipated by adequate cooling from the thermal management system. Also, heating is necessary when the vehicles operate in cold winter climates. The thermal management system should be able to maintain a uniform temperature among all battery cells in the entire battery pack. Previous studies have found that temperature gradients between modules reduce the overall battery pack capacity [4]. Temperature uniformity within a battery pack is important to ensure all battery cells operate as close as possible within the defined temperature range, to maintain high performance and lifetime of the whole pack. Thus, good thermal management is crucial for reducing the life-cycle costs of EVs. In this paper, PCM configurations are examined with an objective to provide (1) the desired operating temperature range for all modules, (2) minimal temperature variations within a module, and (3) minimal temperature variations among various modules.

Several past studies have been conducted on thermal analysis and modeling of battery packs. Chen and Evans [5] examined the heat transfer within batteries using two-dimensional transient heat conduction analysis of the battery stack, with convective heat transfer at the battery boundaries. Thermal characterization of several EV batteries was studied by Pesaran [6]. Lithium-ion batteries, with their high energy density and other favourable properties, have found many applications in recent years. Al-Hallaj and co-workers [7] developed an unsteady one-dimensional model of heat transfer in lithium-ion batteries. Sato [8] reported the thermal behaviour of lithium-ion batteries for EVs through thermodynamic analyses, and examined the heat absorption and generation processes during charging and discharging. Pesaran [9] used an advanced vehicle simulator (ADVISOR), developed at the US National Renewable Energy Laboratory, which involves several...
battery models and finite element analysis. Chen and co-authors [10] developed a three-dimensional model for thermal analysis of lithium-ion batteries using a finite-difference technique.

Different thermal management techniques and devices have also been developed for battery packs in electric vehicles. McKinney et al. [11] examined thermal management of lead-acid batteries for an EV with electrolyte circulation pumps, cooled by both forced air and natural convection. Pesaran [1] provided a review of battery thermal management in EVs. The review compared different active and passive cooling and heating methods, using air or liquid. He concluded that hybrid electric vehicles (HEVs) and EVs operating over a wide temperature range (−30 to 60 °C) need both active heating and cooling. Jung et al. [12] developed a comprehensive battery management system for nickel-metal hydride batteries in electric vehicle applications. The system controlled the charging and discharging periods, with overcharge and over-discharge protection.

Many early models of electric vehicles used air for battery pack cooling and heating (such as the General Motors EV1, Ford Ranger EV, Chrysler EPIC minivan, and the Toyota RAV4 electric). But studies have shown that conventional heat dissipation methods with air cooling are insufficient, particularly in larger battery modules [2]. On the other hand, thermal management studies by Nelson et al. [13] suggested that rapid heating of the battery from a very low start-up temperature is more difficult than cooling during driving. Electric heaters with resistive elements have been used to heat batteries subjected to adversely cold temperatures. Neslon et al. [13] also found that a dielectric transformer fluid is superior to air for both heating and cooling the battery. A dedicated refrigeration system for cooling the battery coolant is helpful in maintaining low temperatures during driving. However, forced liquid circulation, evaporators, and other refrigeration equipment make the overall system bulky, complex and costly. The thermal management system should be compact, lightweight, easily packaged in the vehicle, reliable, and low-cost.

Phase change materials (PCMs) have shown excellent performance for thermal management of electronic devices [14,15]. Phase change heat transfer has been investigated by the authors previously, both numerically and experimentally [16–18]. With its latent energy storage capacity and controllable temperature stability, PCMs have great potential for thermal management in EVs, particularly for reducing peak temperatures during intermittent discharge. Thermal energy storage in PCMs can overcome performance losses of the battery at cold temperatures. PCMs have the advantage of maintaining better temperature uniformity and reduced system volume. Most commercially available Li-ion batteries exhibit a net cooling effect during charge, and they are highly exothermic during discharge. Therefore, a thermal management system based on phase change heat transfer can be particularly effective for these batteries. Recent studies have examined the feasibility of thermal management of EV battery packs using PCMs. Examples include past experimental and numerical studies conducted by Al-Hallaj and Selman [19], Khateeb et al. [20], and Kim et al. [21]. The former study found that PCMs can effectively keep battery packs within a predetermined temperature range. But Kim et al. [21] found that the overall battery thermal management must still rely on active cooling and/or limiting the battery power output.

In this paper, thermal management of batteries with PCMs are examined experimentally. A battery cell is simulated by an electric heater in a test cell. Two different thermal management configurations with PCMs are investigated. In the first case, the heater is placed in a cylindrical container filled with PCM. In the second case, the heater is wrapped by a jacket of PCM sheet. Temperatures of the heater are measured during heating rates and ambient temperature conditions. The effectiveness of both thermal management schemes is evaluated by comparisons between measured temperatures, with and without the PCMs. This study provides new experimental data for the effective thermal design of PCM thermal management of battery modules in electric vehicles.

2. Heat transfer formulation of phase change with a line heat source

In this section, an analytical model is presented for melting processes of a phase change material, with a line heat source in the centerline of cylindrical coordinates, based on past models discussed in Refs. [22,23]. This corresponds to the case where a battery cell or heater is surrounded by phase change materials, which are initially at a solid state, and then start to melt when the battery cell/heater is generating heat, as shown in Fig. 1.

In Fig. 1, a line heat source of strength \( q \) (W/m) is located at \( r = 0 \) in an infinite solid at a uniform temperature, \( T_0 \), lower than the melting temperature, \( T_m \) of the PCM. The heat source is activated at time \( t = 0 \) to release heat continuously for time \( t > 0 \). Consequently, the melting commences at the origin, \( r = 0 \), and the solid–liquid interface, at radius \( X(t) \), moves outwards in the positive \( r \) direction. The liquid and solid regions are indicated by \( r < X(t) \) and \( r > X(t) \), respectively. It is assumed that both phases have constant thermophysical properties. The energy balance around the line heat source is expressed as

\[
\lim_{r \to 0} \left( -2\pi r k \frac{dT}{dr} \right) = q
\]

It can be shown that the temperatures in the solid and liquid phase can be written as

\[ T(r, t) = T_0 + \frac{q}{2\pi k} \ln \frac{r}{r_0} \]
Two thermal management schemes with different phase change materials were investigated. In the first case, the heater is installed in the center of a cylindrical container filled with PCM 1 (details to follow). The container is made of aluminum, with a thickness of 0.2 mm, a diameter of 52 mm, and a height of 125 mm. The aluminum container is installed in a bath (Neslab RTE 140) where the temperature of bath fluid is controlled by a computer program. The thermal resistance through the thin aluminum is negligible, so that the phase change material is assumed to be exposed to the controlled ambient temperature in the bath. PCM 1 is a product named RPCM, provided by the Glacier Tek Inc. It has a phase change temperature of 18 °C, a specific heat of 2.1 kJ/kg K, a latent heat of 195 kJ/kg, and a thermal conductivity of 0.55 W/m K. The phase change material is a liquid at room temperature.

In the second experimental case (shown in Fig. 2), the electric heater is wrapped by jackets of another phase change material (PCM 2). The jackets are made with PCM flexible sheets (T-PCM 920 manufactured by Laird Technologies). The material has a phase change temperature of 50 °C, and it is a solid at room temperatures. The other parameters of the PCM are given as follows: thickness = 0.51 mm, density = 1390 kg/m³, latent heat of 195 kJ/kg, and a thermal conductivity = 2.23 W/m K. The heater, wrapped with the PCM jacket, was installed into the Neslab bath and exposed to different simulated ambient temperature conditions.

In both cases, the PCM absorbs heat when the heater has a surface temperature that is higher than the temperature of the PCM. The PCM also absorbs heat from the bath (or air during tests in air) when the ambient temperature is higher than its temperature. When the ambient temperature drops below the temperature of the PCM, it releases heat but can remain at its phase change temperature for a significant period of time, thereby keeping the temperature of the heater within a defined range.

The Neslab bath is filled with a temperature controlled mixture of water and ethylene glycol, so it does not freeze and stop working under cold temperatures below 0 °C. The Neslab RTE 140 bath can provide a temperature range of −40 °C to +150 °C, with a stability
A container is 24 mm deep, and the PCM was placed in different locations. The initial temperature in the container was measured at various times. The initial temperature in the container is approximately 22 °C, and the Neslab bath temperature is maintained at 2 °C. The temperature of the PCM starts to freeze from the outer layer. When all of the PCM in the container freezes, the temperature at the container bottom (T 2) quickly drops to temperatures lower than 18 °C (phase change temperature). Since this location has approximately direct contact with the ambient bath, it is not protected by the PCM. At T 4, a short flat portion of the temperature profile (around 18 °C) can be observed. At locations closer to the center of the container, the temperatures drop and remain at 18 °C for a significantly long period, due to the thermal effect of the thick PCM layer. This result indicates the usefulness of thermal management of EV batteries with PCMs, particularly in cold weather temperatures.

Fig. 7 shows melting processes of the RPCM around a heater in the PCM container. The initial temperature of the PCM and heater is 2 °C, and the Neslab bath temperature is also maintained at 2 °C. The heater has a heating rate of 1.36 W with a power supply of 14 V. In the experiment, it was found that one-dimensional melting cannot be achieved due to significant buoyancy effects within the melted phase change material. This effect led to a two-dimensional melting process, with more melting at the top.

The larger circle of the melted area occupies a relatively shallow layer in the container. The smaller melted area around the heater (darker spaces in Fig. 7) indicated the melted space that extends down to the bottom of the container. Fig. 8 shows the measured temperatures at different locations in the PCM container during this process. These results also confirm that in this experiment melting of the PCM occurs only in a limited space surrounding the heater, since temperatures at many locations in the PCM remain below the phase change temperature of 18 °C. The temperature at the heater surface increases continuously and tends to stabilize around 25 °C. In the following section, this temperature will be compared to the heater surface temperature in the air (without PCM protection) to investigate the thermal effectiveness of the PCM.

4. Effectiveness of thermal management with PCMs

4.2.1. Constant heating rate and ambient temperature

With a constant heat generation rate and ambient temperature, the temperature of a battery pack will rise and may reach a steady state. This was simulated in our experiments by a constant heating rate of the heater, and exposing it to a stable ambient temperature. Fig. 9 shows a comparison between the measured heater surface temperature, with air cooling under natural convection, and that with thermal protection in the PCM container. The voltage supply...
for the heater is 14 V, the air temperature is 25 °C, and the PCM in the container has an initial temperature of 2 °C. The results indicate that a PCM environment at low temperatures can greatly reduce the temperature of a battery cell.

In another case, the heater is wrapped with the 0.51 mm T-PCM 920 jacket and the heater surface temperatures are compared with temperature results without the PCM jacket. The results are shown in Fig. 10(a). In the experiments, the air temperature is 25 °C and the voltage supply for the heater is 14 V. The results show that the PCM jacket reduces the heater surface temperature by approximately 6 °C under air cooling with natural convection.

Further experiments were conducted to study the effectiveness of this PCM jacket under relatively cold ambient temperatures. In this case, the temperature of the heater surface was measured during heating processes in a ambient temperature of 6 °C, provided by the Neslab bath. A higher voltage supply of 24 V was provided for the heater surface. Fig. 10(b) shows a comparison of measured heater temperatures, with and without the PCM jacket. The results show that the PCM jacket shows a good cooling effect, reducing the steady state heater surface temperature by 7 °C.

**4.2.2. Variable heating rates and constant ambient temperature**

Effectiveness of the PCMs was also studied for variable heat generation rates of a battery cell. In this case, variable heating rates were achieved with controlled power supply to the heater. As shown by the dashed curve in Fig. 11(a), the voltage supply to the heater is maintained at 1.5 V, 4.5 V, 7.5 V, 12 V, 7.5 V, 4.5 V, and 1.5 V, each step lasting 5 min. With only air cooling under natural convection, the heater surface temperature continues to increase with higher heating power, showing no trend of a steady state. A peak temperature of 68 °C was reached. Fig. 11(b) shows the heater surface temperature with the same variable heating powers. The heater is placed into the RPCM container where the initial temperature of the PCM is 18 °C. Compared to the results in Fig. 11(a), the heater surface temperature shows distinct steps.
with a nearly steady state temperature at the end of each step. More importantly, the peak temperature is reduced to 24°C.

4.2.3. Variable/cyclic ambient temperature conditions

In northern climates, the daily air temperature range can be very large. Battery packs in EVs are often subjected to sudden changes of ambient temperature, which reduces their safety, efficiency and lifetime. As shown in previous sections, the effectiveness of PCM thermal management is dependent on the ambient air conditions. In this section, the effects of variable (including cyclic) ambient temperature conditions are investigated. Again, two cases are considered: one with the heater in the RPCM container,
and the other with the T-PCM 920 jacket. In both cases, the variable ambient temperature is created by the Neslab bath, in which the electric heater is installed with different PCM protection methods. The power supply to the electric heater is 24 V for both cases. Fig. 12 shows measured results in the first case. With thermal protection effects of the RPCM in the container, the heater temperature experiences a much smaller amplitude of fluctuation (after the initial heating period), even under significant ambient temperature variations. This is achieved by keeping the inner layer of the PCM container at relatively stable temperatures (solid curve). The small peaks of the heater temperature are caused by the previously discussed buoyancy effects during melting of the PCM.

Fig. 13 shows the measured results in the second case, where the heater is wrapped with the 0.51 mm PCM jacket. Since the refrigeration function of the Neslab bath is disabled above 40 °C, continuous ambient temperature variations cannot be realized in the bath. In this case, a refrigerator–room–oven scheme was used. The heater (with and without the PCM jacket) is kept at room temperature for a certain period, then it is moved to a refrigerator, then to an oven, and so on. In this way, variable ambient temperatures of a large range are achieved. Examination of the heater surface temperatureprofiles with and without the PCM jacket shows that the PCM jacket makes the heater temperature higher (relative to that without the PCM jacket) when the ambient temperature drops, while it makes the heater temperature lower when the ambient temperature increases. The largest difference is about 8 °C. The PCM jacket keeps a battery within a relatively stable temperature range. This effect would be more significant with a thicker PCM jacket. Better demonstration of this effect can be expected in experiments with an improved chamber that provides better controlled ambient temperatures.

5. Conclusions

In this paper, thermal management with phase change materials was investigated for their feasibility and effectiveness for electric vehicle battery modules. Detailed solidification and melting processes were examined and new measured PCM data was reported. In the experiments, a heater was used to simulate a battery cell. Two different PCM designs for the heater temperature management were investigated: one with a PCM container surrounding the heater, and another with a PCM jacket wrapping the heater. It was shown that both designs are effective in maintaining the heater temperature within a defined range. The effects of variable heating rates and ambient temperature conditions were also reported.

References