Experimental study of two organic phase change materials in cylindrical containers for battery module thermal management: a comparative analysis

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Abstract. Thermal runaway in battery Electric Vehicles (EV) is one of the most significant threats to their safety and overall performance. In this study, the use of saturated fatty acid and paraffin wax as phase change materials stored separately in a battery-like container, which acts as a thermal absorber for heat dissipation management, is analyzed. The melting characteristics between these two materials are relatively different, as shown from the Differential Scanning Calorimetry results. The fatty acid used in this study has a narrow melting point with its peak at 56°C, while the paraffin mixture has a wide range starting from as low as 37°C. The effect of such different profiles is translated to the difference in the measured temperature profiles. In passive thermal management based on PCM alone, the latent heat capacity is more important than having a melting range when the amount of PCM as heat absorber is strictly limited. However, when the PCM is evenly distributed, the paraffin tubes would have a better thermal profile than the fatty acid ones. Meanwhile, when the air blower is operated hence forming a hybrid thermal management system, there is almost no significant difference between the two PCM under investigation.

1. Introduction
Sustainable transportation and clean, renewable energy have become popular global issues in recent years. Electric Vehicles (EVs) have been sought as one of the potential solutions in transportation sectors, especially in order to reduce fossil fuel dependency and emissions [1,2]. Various types of EV have been developed rapidly, starting from hybrid EV, battery EV, as well as solar and Fuel Cells EV. Among all of the possible EV power sources at this moment, a rechargeable Lithium-ion (Li-ion) battery is at the top due to its exceptional energy capacity and lifecycle per unit of weight. However, the Li-ion cell is also known for its high sensitivity to temperature. It has been widely reported that its performance would drop quite significantly as its operating temperature increases [3–5]. Although temperature stability could be achieved by carrying more battery cells, it is actually not feasible since the overall weight, charging time, and price would also increase. As such, having the correct number of battery cells in a single EV is always desired in designing a vehicle, which requires a balance between weight and mileage covered [6,7].

Thermal management is a battery-based EV key technology that deals explicitly with heat dissipation and control from the operating components. Considering the nature of the Li-ion battery,
such a system is required to prevent the so-called thermal runaway. It is a severe problem that occurred when the battery cell is experiencing an uncontrolled temperature rise that could lead to operational failures, leaks, or fire [8,9]. One of the most recent accidents related to a thermal runaway involves a Boeing 787 Dreamliner jet which happened at least twice in the last decade [10,11].

To ensure that each battery cell could perform efficiently, the battery module should only be operated in a specific temperature range. Li-ion battery is known to have an upper-temperature limit of approximately 40°C for its optimum efficiency and 75°C in terms of safety [12]. Multiple thermal management options have been developed depends on the vehicle design and desired performance. At this moment, there is no single design that could be claimed as one size fits all. Each system would have different pros and cons on different vehicle sizes and purposes. The most commonly used thermal management relies on air or water as cooling fluids [13–15]. More advance and complex designs use a wide choice of cooling fluids/mixtures, phase change materials, or thermoelectric elements [16–18]. The contact mode between the cooling system and the heat source is often a distinguishing factor in determining the most efficient and safe thermal management [19].

In this manuscript, the use of Phase Change Materials (PCM) as a thermal wall inside a battery module is experimentally evaluated. The material is put into a thin cylindrical container made from carbon fiber and sealed to prevent leakage during the liquid phase. Comparison based on the measured temperature data is made between a saturated fatty acid and paraffin wax, a more commonly used PCM. Both fatty acid and paraffin are known for relatively low-cost materials with high latent heat capacity and reliability for an extended operation [20,21]. Various PCMs are extensively reviewed as in Ref. [21–23]. The difference in latent heat profiles between these two materials plays a role in the temperature profile of the EV battery module under different discharge rates.

2. Experimental methods
The battery module used in this study contains twenty 18650 Li-ion cells arranged in parallel, giving it a 50 Ah maximum capacity under 4.2 V nominal voltage when fully charged. The product specifications of the battery cell are tabulated in Table 1. The module is connected to a resistive dummy load which could operate in stable condition up to 200 A discharge current, as sketched in figure 1. Three battery arrangements inside the module are used: straight lines, scattered, and bulk at the sidewall, similar to Ref. [24]. Each cell is connected to a DS18B20 temperature sensor with an accuracy of ± 0.5°C at the cathode, which is expected to have the maximum surface temperature in a battery cell [25–27]. The temperature data logging process is performed using an Arduino microcontroller board connected to a PC with an optimum sampling rate of 4 seconds.

| Parameter                          | Value                          |
|------------------------------------|--------------------------------|
| Model/product code                 | INR18650-25R                   |
| Weight (g)                         | 45                             |
| Cell dimension (mm)                | 64.85 ± 0.15 (height); 18.33 ± 0.07 (diameter) |
| Nominal discharge capacity (mAh)   | 2500                           |
| Charge cut-off voltage (V)         | 4.20 ± 0.05 (CC-CV)            |
| Nominal voltage (V)               | 3.6                            |
| Max. continuous discharge          | 20A; 60% at 250 cycle          |
| Cut-off discharge voltage (V)      | 2.5                            |
| Max. internal impedance (mΩ)       | 18                             |

Table 1. Product specifications of the 18650 batteries used in this study.
A saturated fatty acid is selected as the PCM in this study. Based on the thermal profiles measured by means of Differential Scanning Calorimetry (DSC), it is found that it has different latent heat absorption characteristics than paraffin, as depicted in figure 2. The paraffin used in this study melts gradually as early as 32°C, while the fatty acid curve starts to increase rapidly at above 40°C. According to this profile, the saturated fatty acid shows a closer similarity with myristic (C-14) or palmitic acid (C-16) rather than lauric acid (C-12); all of them are commonly used fatty acids as PCM in EV or green buildings [22,28,29]. Both PCMs are local technical grade materials, hence the exact latent heat capacity and behavior might also be affected by impurities. The PCM is stored in a thin cylindrical container with similar dimensions to the 18650 battery. For each tube, the amount of PCM inserted is about 7 g, which is less than 16% of the additional weight to the module. The design offers simplicity to perform a change of configurations within the battery module and repair when needed.

The battery module is also connected to a fan blower with a maximum airspeed of 4.4 m/s, forming a hybrid cooling system to the module when operated. An INA219 voltage sensor is also connected to the experimental apparatus. Prior to every measurement, the battery module is fully charged to 4.2 V and 0.2 A (CC-CV) as specified by the battery manufacturer. The initial ambient temperature must lie within 24–26°C otherwise the scheduled run is retimed. For safety precautions, the cut-off temperature (maximum) and the minimum voltage are set at 75°C and 2.75 V, respectively.

3. Results and Discussion

The measurements were carried out for three different dummy load discharge current settings, that is, 50 A, 100 A, and 200 A. Figures 3 and 4 show the measured cathode temperature at the end of the experiment under these three discharge currents for passive (fan blower off) and hybrid battery module thermal management, respectively. The so-called hybrid thermal management or cooling system refers to the combination of forced convection by the blower and the passive heat transfer by means of the latent phase-change condition. Since the values presented in the figures are the difference between the module with fatty acid and with paraffin, an experimental error tolerance range of ± 2°C is drawn in grey. The bars within this square indicate that the temperature difference is relatively insignificant hence its meaning could be assumed negligible.
Figure 2. Different latent heat curves between paraffin (broken line) and fatty acid (solid line) used in this study based on the thermoanalytical characterization using DSC (ASTM F2625-10).

For the first configuration, where the first ten batteries are stored between two PCM “barriers”, the gradual phase temperature profiles of the paraffin absorbs the dissipated more effectively, resulting in a lower temperature, as shown in figure 3(a). In contrast, the advantage of the fatty acid with notably larger latent capacity despite its narrow phase-change temperature is shown for the remaining ten batteries. Considering fewer PCM tubes nearby, having more than 10°C lower temperature in the fatty acid module is significant. It can also be concluded that the latent heat capacity of PCM could be dramatically more important than having a wider melting temperature range. On the other hand, the paraffin shows an advantage when the PCM tubes are scattered, as in figure 3(b) [20]. It can be observed that qualitatively the heat dissipation from each battery cell is effectively absorbed by a material that has a lower melting temperature. Such early and gradual heat absorption does not occur in fatty acid tubes, causing the battery surface temperature to rise before the PCM melting point. Figure 3(c) justifies this as the effect of paraffin is more prominent in batteries 1-8, which has relatively more PCM tubes nearby, as compared to the right-hand side (batteries 11-20) that is somewhat denser cells with fewer heat absorbers nearby.

When the fan blower is in operation, hence forming a hybrid thermal management system, it is found that there are no significant temperature differences among the two PCM under investigation regardless of the PCM placements, as shown in figure 4. The presence of forced convection seems superior in removing away the dissipated heat from the battery module. However, an exception could be found at the straight wall configuration under 200 A discharge currents. With such an extreme load required from the module, each battery cell would release much heat to its surroundings in a short period. As a result, the surface temperature is expected to increase dramatically. In this case, the presence of heat-absorbing material with a higher latent heat capacity such as fatty acid in this study would be more beneficial. As seen in figure 4(a), the temperature difference becomes more notable on the battery cells located downstream. Considering that the cells 11-20 would also receive the dissipated heat from the upstream besides their own required discharge load, the presence of fatty acid PCM, especially the tubes at the center of the module, helps to reduce the amount of dissipated heat transferred to the battery cells downstream hence the temperature is lower than in the module with paraffin. This phenomenon is somewhat different than the other two configurations. Therefore it can be concluded that the total latent heat capacity would be more important than having a wide melting range, especially in an extreme case where a large amount of heat is dissipated in a relatively short time.
Figure 3. Temperature difference between the saturated fatty acid and paraffin from battery cells 1–20 under various discharge currents, fan blower off, and three different PCM-battery arrangements: (a) straight wall, (b) scattered, and (c) bulk at the sidewall. A bar to the left side shows that the fatty acid module has a lower temperature than paraffin, and vice versa. The grey squares in the middle of the chart indicate ±2°C insignificant/tolerance range.

Figure 4. Temperature difference between the saturated fatty acid and paraffin with hybrid thermal management as the fan blower is on. Please refer to figure 3 for other details.
4. Conclusion

The comparisons between paraffin and saturated fatty acid as Phase Change Materials (PCM) in terms of their thermal performance in an Electric Vehicle (EV) battery module have been experimentally performed and discussed in this manuscript. The paraffin wax is found to have a wide range of phase change (melting) temperatures, while the fatty acid used in this study has a pointy temperature at about 56°C and a slightly higher latent heat capacity. In passive thermal management based on PCM alone, the latent heat capacity could become more crucial than having a wider range of melting temperatures when the amount of PCM is strictly limited. However, when the PCM is evenly distributed through the module, the paraffin tubes have a better thermal profile than the fatty acid ones. In contrast, there are no significant temperature differences when there is forced convection heat transfer as the blower is on. The only exception under this hybrid thermal management system in this study is the straight configuration at a high discharge current, where the fatty acid shows a superior condition.

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Nomenclatures

\begin{tabular}{ll}
I & Charge/discharge current (A) \\
T & Temperature (°C) \\
V & Voltage (V) \\
\end{tabular}

Abbreviations

\begin{tabular}{ll}
ASTM & American Society for Testing and Materials \\
CC & Constant Current \\
CV & Constant Voltage \\
DSC & Differential Scanning Calorimetry \\
EV & Electric Vehicles \\
Li-ion & Lithium-ion \\
PCM & Phase Change Materials \\
\end{tabular}

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