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# Experimental investigation on the thermal behavior of cylindrical battery with composite paraffin and fin structure

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ABSTRACT

The thermal behavior of the cylindrical battery was examined with composite paraffin and fin structure through experimental measurements and benchmarking with other thermal management techniques. The mock-up cylindrical battery, made of aluminum, had vertical straight fins as enlarged heat transfer area to submerge in the paraffin wax as phase change material (PCM) with a maximum melting temperature of 44 °C. For the pure PCM case, the melting process could be divided into AB segment with battery temperature ramp-up, BC segment with a clear-cut temperature plateau, and CE segment to reach complete melting, which is also basically represented in the evolutionary trend for the battery top to bottom temperature variation. The instantaneous Nusselt number would increase around the CE segment with a small portion of unmelted PCM as visualized by the numerical analysis, but the battery temperature would ramp up from the plateau in spite of the incomplete melt. Thermal enhancement with the PCM-fin cases was examined experimentally and the logarithmic dependence of the time-averaged Nusselt number is correlated with the heat transfer area ratio. In addition, the effective thermal control point C is found to relate to the melting front intersecting the bottom of the metal housing, and the corresponding thermal resistance is used to benchmark the thermal performance of PCM based thermal management systems. Independent of heating power, such a parameter can be correlated with the melting temperature to the ambient temperature difference for existing thermal management systems. It is found that the present composite PCM-fin system had the advantages of good thermal performance with prolonged work time.



## 1. Introduction

Due to global issues of environmental pollution and energy shortage, researchers from both academy and industry are paying more and more attention to the new energy vehicles, especially with li-ion batteries (LIBs) as power sources [1]. LIBs provide high voltages, high energy density and long cycle life, which are the most commercially feasible power sources for electric vehicles and hybrid electric vehicles [2]. Nonetheless, the battery degradation is highly accelerated by high temperature [3]. Ramadass et al. [4] did a capacity fade analysis and elucidated that battery cells lost more than 60% of initial capacity after 800 cycles at 50 °C and 70% after 500 cycles at 55 °C. Wu et al. [5] found that capacity of a fresh $LiCoO_2$ Li-ion battery at 3C discharge was decreased from 800 mAH to merely 20 mAH after storing at 60 °C for 60 days. Väyrynen and Salminen [6] suggested the LIB battery should operate between −20 °C and 60 °C and further development are required to improve the lifetime at higher temperature. In general, high temperature affects the battery performance including electrochemistry, round trip efficiency, power and energy capability, reliability, cycle life [7]. Due to the significant impact of the temperature on the battery, it is necessary to develop dedicated thermal management system to maintain the battery within acceptable temperature range under high rate charge and discharge.

The paraffin PCM based thermal management devices and systems have been of great research interest due to the characteristics of isothermal heat absorption with high latent heat, almost no subcooling phenomenon, no chemical reaction and low cost. Nonetheless, the heat exchange efficiency of paraffin is significantly constrained by its low thermal conductivity [8,9]. Therefore it is necessary to add high thermal conductivity materials such as porous foams, conductive particles and structure in the PCM to improve the effective thermal conductivity of the PCM. The thermal enhancement of PCM can be traced back to Abhat's work [10], in which a PCM-based thermal capacitor with a honeycomb structure for space applications was investigated. The addition of

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**Nomenclature**

| | |
|---|---|
| A | heat exchange area of the housing ($m^2$) |
| $A_b$ | heating area ($m^2$) |
| c | specific heat (J/kg·K) |
| $c_1$, $c_2$ | fitting coefficients |
| $h$ | heat transfer coefficient ($W/m^2$ K) |
| H | battery height (m) |
| $k_f$ | thermal conductivity of liquid PCM (W/mK) |
| m | mass (kg) |
| Nu | instantaneous Nusselt number |
| Points A, B, C and E | time points corresponding to the onset of melting, onset of the temperature plateau, effective thermal control time point, complete melting |
| q | heating power (W) |
| $R_{Cm}$ | thermal resistance at effective thermal control time point C (K/W) |
| $R''_{Cm}$ | specific thermal resistance at effective thermal control time point C (K·$cm^2$/W) |
| t | heating time (s) |
| T | temperature (°C) |
| $T_b$ | battery temperature (°C) |
| $T_C$ | battery temperature at the effective thermal control time point C |
| $T_m$ | maximum melting temperature of PCM (°C) |
| $T_w$ | housing wall temperature (°C) |
| $V_{pcm}$ | volume of the PCM domain ($cm^3$) |
| W | gap between the battery and housing (m) |
| $\Delta H$ | latent heat of PCM (J/kg) |

*Subscripts*

| | |
|---|---|
| a | ambient |
| AC | time segment from Point A to Point C |
| b | battery |
| bot | bottom of battery |
| CE | time segment from Point C to Point E |
| m | related to the maximum melting temperature |
| pcm | phase change material |
| top | top of battery |
| w | gap between battery and housing wall |

*Greek symbols*

| | |
|---|---|
| $\Delta$ | Difference |

porous foams in PCM for thermal enhancement can be found in [11] and the cited references therein. It has been identified that the addition of metal foam provides much faster heat conduction rates than the case of pure PCM. For battery thermal management, Selman and Al-Hallaj [9] reported the test results of li-ion batteries designed for electric scooter application with different modes of heat dissipation. Their experiments showed that the best performance was obtained for the combination of aluminum foam and PCM, leading to a significant temperature drop of about 50% compared to the natural convection cooling, whereas it might be insufficient when operated at high environmental temperature such as those usually occurring in hot summer time. Ling et al. investigated the thermo-physical properties of a series of paraffin/expanded graphite (EG) composites applied to a simulative battery thermal management system [12]. Duan and Naterer conducted experiments for a heater of 6.35 mm in diameter installed in a container of 52 mm in diameter to demonstrate the effectiveness of temperature control with a plain PCM and a PCM jacket with thermally enhanced fillers [13]. In comparison, finned structure has the advantage of high effectiveness and ease of fabrication as thermal enhancement structures. It is not rare to use fins to enhance PCM heat storage for applications such as space and solar thermal storage, electronics cooling [14–18], to name a few, and the phase change regimes with isothermal heating and adiabatic boundary conditions are examined and understood [17–20]. Nonetheless, the combination of composite PCM and fin structure for the battery under given heat flux conditions and the corresponding thermal characteristics are not well reported in the literature. The thermal performance of PCM combined with various fin configurations for thermal control of power batteries requires in-depth investigation.

In this paper, the thermal behavior of a cylindrical battery with composite paraffin PCM and fin structure was experimentally investigated. The mock-up battery was fabricated with vertical straight fins attached onto the battery and submerged in PCM to form the thermal enhancement structure. The fabricated battery, with 18 mm in diameter and 65 mm in height, was installed with a concentric heater to simulate the heating from a commercial 18650 cylindrical battery. A test section was made to contain the battery with inserted fins and the paraffin wax as PCM for experimental measurement. The heat transfer characteristics and the melting process were examined to identify the temperature ramp-up plateau during the heating stage. The affecting factors such as battery heating power, ambient temperature and fin number were examined. Uniquely, the effective thermal control time point C is found to correspond to the melting front intersecting the bottom corner of the metal housing with the help of numerical analysis. In addition, the battery top to bottom temperature difference was found to describe the representative time points, such as the onset melting point A and complete melting point E. To benchmark different thermal management techniques available in literature, the thermal resistance at Point C is introduced for performance evaluation. The non-heating process was also recorded to study the temperature ramp-down plateau behavior. The present study would be useful in the development of battery thermal management devices and systems.

## 2. Experimental methodology

### 2.1. Test section for battery with composite PCM and fins

The test section consisted of a heat generating battery accommodated in a metal housing and filled with PCM in between. The mock-up battery made of aluminum was fabricated with 18 mm in diameter and 65 mm in height, and a concentric hole of 6.5 mm was drilled in the center to hold a heater supplied from Watlow (1/4″ in diameter and 40 mm in length) to simulate the heat generation of a commercial 18650 li-ion battery. The battery, either with or without fins, was vertically put in an aluminum housing, which had an inner diameter of 31 mm and wall thickness of 5 mm. The underside of the battery was insulated from the metal housing with a layer of acrylic plate of 1 mm. The PCM, 25 g in this work, was first melted and then poured into the housing to form the test section. The paraffin used in this paper was supplied from Luer, Hangzhou, and its thermophysical parameters are listed in Table 1.

For fin attachment, 8 rectangular slots of 1 mm wide and 5 mm deep were fabricated equidistantly along the circumference of the