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Thermal Control in Battery Systems: Experimental Analysis using Phase Change Materials

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Abstract

Effective thermal management of lithium-ion batteries is essential for the safe operation of electric vehicles in optimal temperature conditions. The proposed study suggests a battery thermal management systems (BTMS), using Paraffin Wax as a solid-liquid phase-change material (PCM), with a latent heat of melting of 195.7 kJ/kg with a nominal melting temperature of 58-60°C. In the experimental setup, four cylindrical heaters are installed each having a capacity of 20 W, Paraffin Wax PCM is filled around the heaters and submerged inside the PCM which absorbs heat from PCM. To reproduce the discharge rate of an 18650 Li-ion battery, a battery with cylindrical cartridge heaters (20 W, 18 mm 65 mm) was employed in the experimental setup. The experimental setup is run for 15W, and 20W as a heat input. The thermal response of Paraffin wax was captured every 10sec time interval using a data logger, Time versus Temperature graphs were plotted for each heat input.

Keywords: Battery Thermal Management, Phase Change Material, Cylindrical Heater, Thermal Analysis, Temperature, Melting Point, Latent Heat

1. Introduction

Recent research into renewable energy sources has increases in response to the impacts of global climate change. As internal combustion engines (ICEs) continue to dominate the

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current transportation landscape and significantly contribute to environmental pollution, electric vehicles (EVs) and hybrid EVs are increasingly being viewed as appealing alternatives [1-3]. EVs primarily utilize Li-ion batteries due to their advantages, such as slow self-discharge rates, high energy density, and extended cycle life[4,5]. However, during charging and discharging cycles, Li-ion batteries generate substantial heat as a result of electrochemical reactions [6,7]. This heat generation leads to an increase in battery surface temperature and causes non-uniform temperature distribution within the battery module. Without an effective heat dissipation mechanism, the accumulated heat can degrade battery capacity and, in severe cases, may lead to thermal runaway or explosions [8-10].

2. Materials

Paraffin wax is a soft, colourless substance composed of hydrocarbon molecules containing 20 to 40 carbon atoms. Derived from petroleum, coal, or oil shale, it has a boiling point exceeding 370°C (698°F) and remains solid at room temperature, melting at approximately 37°C (99°F). Paraffin wax is commonly used in applications such as lubrication, electrical insulation, and candle making. When dyed, it can also be made into crayons. It is important to note that paraffin wax is distinct from kerosene and other petroleum products that are sometimes referred to as paraffin. Typically, unscented and undyed paraffin candles are bluish-white in color and emit no odor. The first production of paraffin wax occurred in Germany in 1830, thanks to Carl Reichenbach. This innovation represented a significant advancement in candle-making techniques, as paraffin was more cost-effective to produce and offered a cleaner, more consistent burn compared to traditional tallow candles.

3. Methods

3.1 Differential Scanning Calorimetry

A widely used technique for measuring heat flow associated with thermal transitions in materials is differential scanning calorimetry (DSC). This method is particularly effective for studying phase change materials (PCMs), which are capable of storing and releasing thermal energy during phase transitions such as melting and solidification. By monitoring the heat flow linked to these transitions, DSC can be employed to analyze the thermal behavior and energy storage potential of PCMs. This technique provides valuable insights into the heat capacity, enthalpy of melting, and the temperatures of melting and solidification of PCMs. Additionally, DSC can be utilized to examine the impact of additives or contaminants on the thermal behavior of these materials. The Figure 1 depicts the Heating Curve of DSC

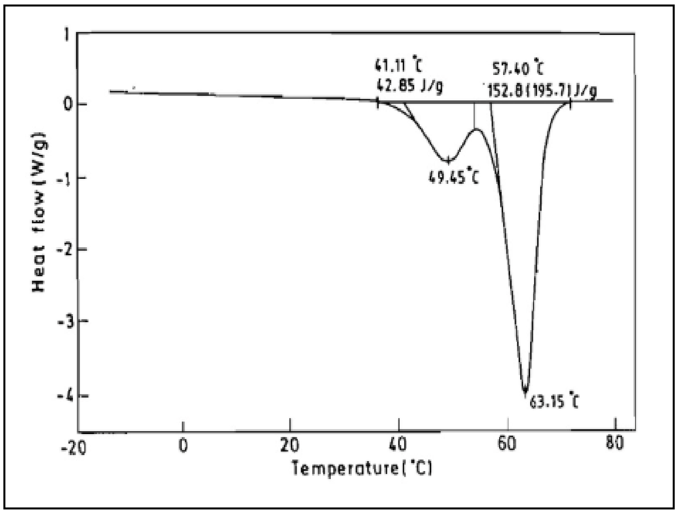

Figure 1. DSC Heating Curve

4. Experimental Setup

The Figure 2 illustrates an experimental setup designed for thermal management analysis, likely in the context of simulating Li-ion batteries. This setup includes various instruments and essential components for testing and monitoring thermal performance. On the left, a control unit displays key parameters such as temperature and potentially heating power, accompanied by a nearby fan that likely simulates air cooling. Centrally positioned is a laptop, presumably running data acquisition software or overseeing the experiment. Two containers can be seen holding the components under examination, possibly simulating battery cells, with thermal sensors connected to monitor temperature fluctuations. Another piece of equipment on the right appears to be monitoring electrical parameters such as voltage or current. Overall, this setup reflects a controlled environment aimed at studying the performance of a Battery Thermal Management System (BTMS) utilizing a hybrid PCM-air cooling method. The arrangement underscores the importance of real-time data monitoring and analysis to assess the effects of heat generation and dissipation in battery modules.

Table 1. Hardware Component Description

Hardware Component	Description
Control Unit (Temperature Controller)	Device with displays showing temperature and possibly power settings, used to control heating elements.
Fan	Small electric fan, likely used for air cooling within the experimental setup
Laptop	Computer used for data acquisition, control, and monitoring of the experiment.
Heater Setup with Containers	Two transparent containers, likely holding battery simulants or other experimental components, connected to heaters.
Multimeter or Data Logger	Device on the right side, likely used for measuring and logging electrical parameters such as voltage or current.

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Figure 2. Experimental Setup

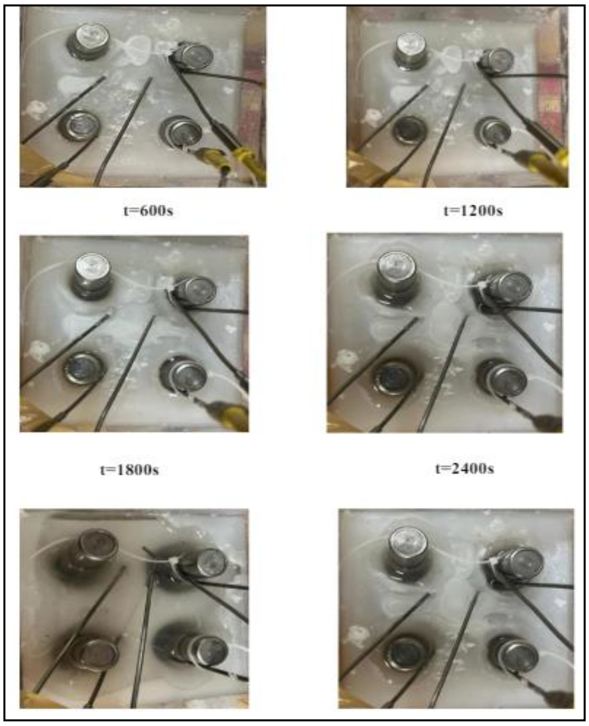

Figure 3. Stages of Crystallization of Paraffin

The Figure. 3 is used to observe the thermal behavior of a system over time. The system appears to involve cylindrical components, likely simulating battery cells, immersed in a medium—potentially a Phase Change Material (PCM) or another substance for thermal management. The time stamps indicate the progression of the experiment, capturing snapshots at intervals of 600 seconds, and up to 2400 seconds (or 40 minutes).

Each image shows the state of the system at different times:

t = 600s: The setup appears to be in the early stages of heat application, with the medium starting to show signs of melting or change around the components.

t = 1200s: The medium continues to change, with a more noticeable melt or phase change occurring around the components.

t = 1800s: By this time, the medium has likely absorbed more heat, with further phase change evident. The components are likely stabilizing at this stage.

t = 2400s: The system shows a more uniform change across the medium, indicating that the temperature has likely been distributed throughout the setup.

5. Results and Discussions

Thermal analysis is an essential process in the design and development of battery thermal management systems (BTMS) filled with phase change materials (PCMs). PCMs are substances that absorb and release large amounts of heat energy when they melt and solidify, respectively. BTMS models filled with PCMs are used to regulate the temperature of batteries in various applications, including electric vehicles and portable electronic devices. It helps to identify the potential risk of thermal runaway, which can occur when the heat generated by the battery exceeds the cooling capacity of the PCM. In summary, thermal analysis is a essential step in the design and optimization of BTMS models filled with PCMs. It ensures the efficient and safe operation of the BTMS, which is critical in extending the life of batteries and ensuring their optimal performance in various applications.

The pure battery system and the pure PCM system were key BTMSs evaluated for their thermal management performance. Figures 4 and 5 clearly demonstrate how the battery's surface temperature fluctuates over time with varying heat inputs. The pure PCM system is capable of operating for an impressive 1200 seconds at 20W. When combined with fins, the operating time increases to 1600 seconds—approximately 1.67 times longer than that of the PCM alone. This strongly indicates that the fin structures proposed in this study significantly enhance the thermal management performance of the PCM-based BTMS.

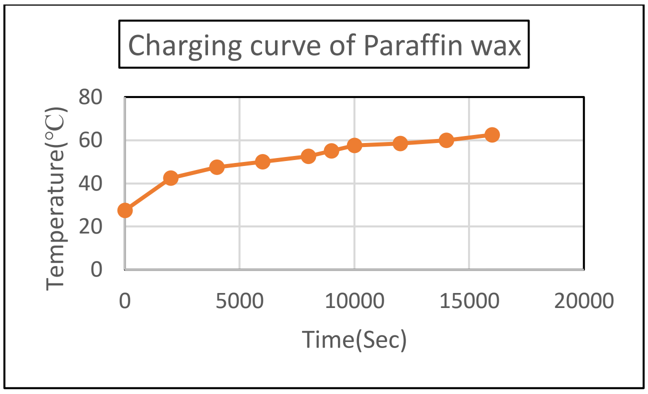

Figure 4. 20W Heating Result

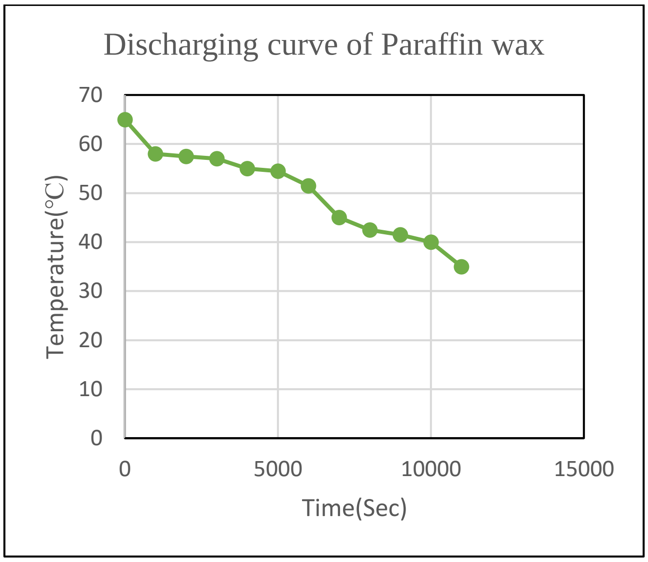

Figure 5. 20W Cooling Result

5.1Temperature Distribution for Pure PCM BTMS System

PCM surrounding the heater attains temperature more quickly compared to PCM which is near to the housing. Temperature distribution varies along the radial direction where the temperature around the heater is more than that at the housing. Figure. 6 and 7 illustrates the temperature distribution for pure PCM BTMS system.

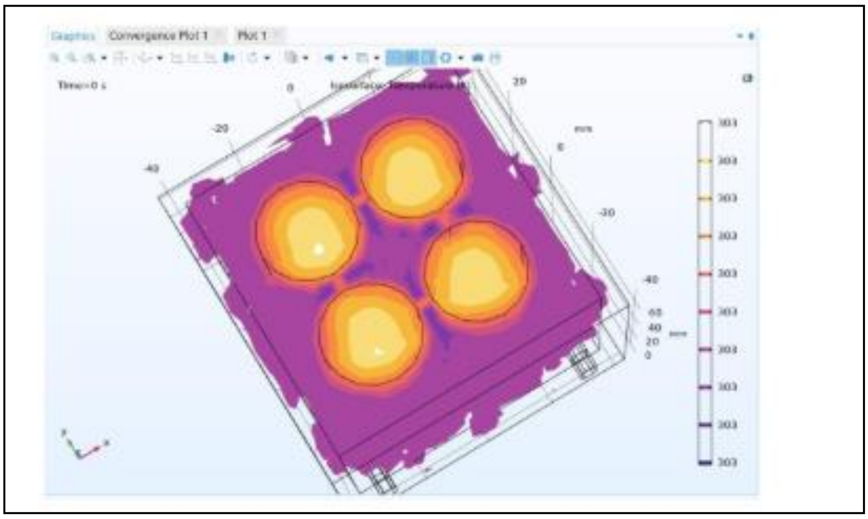

Figure 6. Temperature Distribution of BTMS

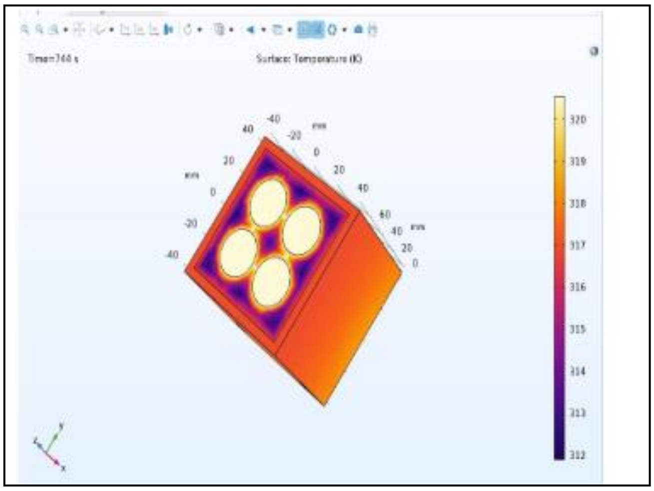

Figure 7. Isothermal Contours

6. Conclusions

In this study, a compact module designed for the thermal management of simulated Li-ion batteries was analyzed using a hybrid system that combines Phase Change Material (PCM) with air cooling. The analysis considered heat fluxes, with each heater generating a heat rate of 20W, to evaluate the thermal performance. The key conclusions drawn from this study are as follows:The Battery Thermal Management System (BTMS) model effectively maintained the maximum temperature of the module within the normal operating range, ensuring a more uniform temperature distribution. The BTMS model was further examined through numerical simulations, which yielded results consistent with the experimental findings. However, in the BTMS model, the temperature continued to rise, leading to suboptimal thermal performance. The combination of PCM and air cooling successfully dissipated the generated heat, resulting in a lower and more uniform temperature distribution.

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