

Passive Thermal Management Using Phase Change Material (PCM) for EV and HEV Li-ion Batteries

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Abstract— Researchers at the Illinois Institute of Technology (IIT, Chicago, IL) have successfully demonstrated a passive thermal management system using phase change materials (PCM) in Li-ion batteries for electric vehicle and scooter applications. Thermal characterization of Li-ion battery modules using PCM is presented and discussed. In addition, a battery pack design for Plug-In hybrid vehicles (PHEV) is proposed and discussed.

I. INTRODUCTION

Thermal management of Li-ion batteries is critical for high-power applications; it is vital to safety and to enhance battery performance and extend cycle life. The operating temperature controls the electrochemical performance of the Li-ion battery. One of the side effects of exposure to high temperature is premature aging and accelerated capacity-fade. Governing the thermal environment is critical in Li-ion technology. Therefore, efficient thermal management that continuously regulates battery operating temperature is essential to safety and optimal performance in high temperature and high discharge Li-ion applications. Resolving the thermal management issues with Li-ion batteries will benefit their use in hybrid electric vehicles (HEV).

Plug-in hybrid electric vehicles (PHEV) are an emerging market for battery HEVs. The PHEV is an attractive alternative to conventional vehicles especially because of its lower fuel consumption and less pollution even compared to HEVs¹. However,

there are still some technical barriers to make PHEVs more efficient and reliable for consumers.

The major issues for HEVs and PHEVs are battery life, compactness, weight, driving range, and cost². Various battery chemistries are being tested and promoted, of which NiMH and Li-ion are, so far, the most promising.

The NiMH is the leading battery type for PHEVs since it is presently being used in the HEV market³. On the other hand, Li-ion batteries have higher energy densities but they require thermal management solutions for this high-power applications.

Li-ion batteries with thermal management using phase change materials (PCM)⁴ eliminates the need for additional cooling systems and improves available power. Battery packs can be maintained at an optimum temperature with proper thermal management, and can be further optimized by integrating PCM in the battery⁴. The PCM is capable of removing large quantities of heat due to its high latent heat of fusion. In principle, during discharge of the battery, the heat generated can be absorbed by the PCM which is integrated between the cells in the battery module. The PCM acts as a heat sink absorbing the heat generated by the battery.

When the temperature of the module exceeds the melting point of the PCM, it starts to melt and the high latent heat of the PCM prevents the

battery temperature from rising sharply. This method of thermal management eliminates the need for any kind of manifold, fans, or pumps, which are usually necessary in existing conventional thermal management systems. The rate of heat removal is improved by impregnating the PCM in a graphite matrix which provides higher thermal conductivity.

II. MATERIALS AND METHODS

a) Preparation of Battery Module

The graphite matrix filled with commercial PCM was prepared with Li-ion cells connected in series and parallel configuration to meet the voltage and current requirement of the module. Commercially available Li-ion cells (Type 18650) similar to the ones used in laptops and camcorders were used in the battery module. The module was integrated with safety circuits to regulate cell voltage and prevent over-charge. All of the strings in the module were connected with a safety circuit that was rated for a required current and potential. The specifications of the battery module are summarized in Table 1.

b) Thermal Characterization of Battery Module

Battery modules with and without PCM were assembled and tested at room temperature and 45°C. Two thermocouples (K-type) were placed inside the battery module; one at the center and the other at one of the corners, to measure the temperature response at the extreme locations in the pack. The battery pack was charged first in galvanostatic mode at 0.7 C-rate to the top voltage cut-off limit and then in potentiostatic mode until the current dropped to 100 mA. An hour rest period was then followed by discharge at various rates until the voltage dropped to the lower cut-off voltage after which a 2-hour discharge-rest period completed one full cycle.

Table 1 Specification of Li-ion Battery Module

Cell Type.....	Type 18650
Module Capacity.....	4.8 A-hr
Pack Operating Voltage	21.0 –29.4 V
Max. Discharge.....	10 Amp
Max. Charge.....	3.36 Amp (2 hr)
Operating Temperature...	25 - 45 °C
Total weight of pack	~ 2.1 lbs

c) Cycle Life Testing

Capacity fading of Li-ion batteries was studied at room temperature for battery modules with and without PCM. The packs were both cycled at C/1 discharge rate (one-hour discharge) and C/3 charge rate (three-hour charge). The module temperature, voltage, current, and charge and discharge capacities were measured and analyzed to evaluate cycle life of the tested modules.

III. RESULTS

a) Thermal Characterization of Battery Module

Figure 1 shows the temperature profiles at the center and corner of a battery module without PCM at different discharge rates and at room temperature. When the discharge rate was 4.8 Amp, the battery module ran for 56 minutes and utilized near 93% of its nominal capacity. On the other hand, at high discharge rates, such as 8 Amp and 10 Amp, the module ran for only 20 minutes (55% utilization) and 12.7 minutes (44% utilization), respectively, and the experiments had to be stopped manually to protect the module due to the high battery temperature. Based on the above results it was concluded that the battery module was unable to complete discharge at high discharge rates without thermal management even when discharged at room temperature.

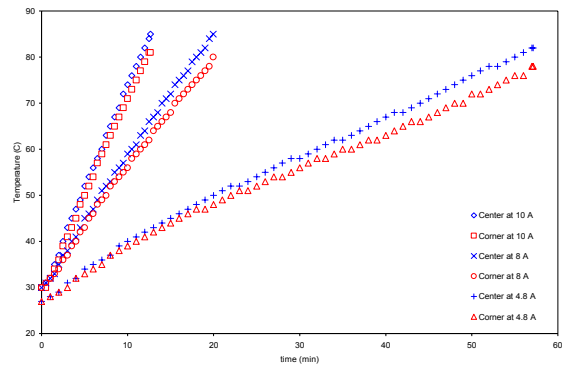


Figure 1. Temperature profiles of battery module without PCM at different discharge rates at room temperature.

The temperature profiles of the battery modules with and without PCM at 10 Amp discharge rate are shown in Figure 2. The modules were tested at 30°C, and it was observed that the PCM was capable of removing heat from the module. The high thermal conductivity of graphite used to contain the PCM allowed high rate of heat removal and

minimized nonuniform temperature distribution in the battery pack. As illustrated in Figure 2, the PCM started melting when the temperature of the pack exceeded the melting point of the PCM (~55 °C), and regulated the battery module temperature around the melting point of the PCM. The module temperature resumed its steep increase after all PCM has completely melted. Unlike the case without PCM, the module with PCM discharged completely until full capacity utilization was achieved.

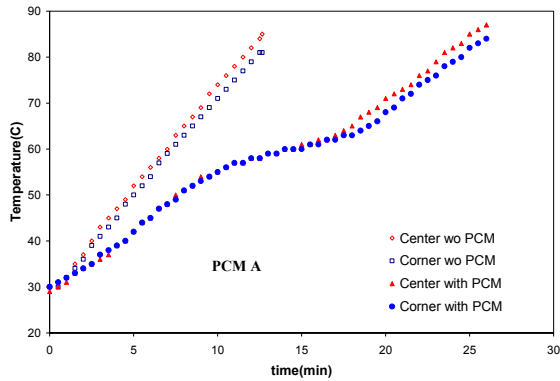


Figure 2. Temperature profiles of modules with and w/o PCM during discharge at 10 Amp at 30°C.

Figure 3 shows the temperature profile of the battery module with PCM for two charge-discharge cycles at 45°C and 10 Amp discharge rate. Under these extreme operating conditions for Li-ion batteries, the maximum temperature at the end of discharge was only 88 °C at the center of the pack. The small temperature difference (2-3 °C) along the pack confirmed the uniform distribution of PCM in the module and the efficient heat conduction throughout the graphite/PCM matrix.

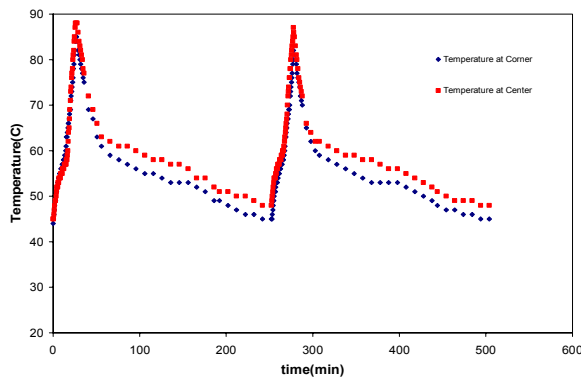


Figure 3. Temperature profiles of the module with PCM during cycling with 10 Amp discharge rate and 45 °C operating temperature.

The amount of PCM and its melting temperature have a significant effect on maintaining the temperature of the battery pack within safe limits. The results also show that near 90% of the nominal capacity was utilized with PCM thermal management even at extreme conditions with high discharge rate and high operating temperature.

b) Cycle Life Testing

Figure 4 shows cycle life test results for two battery modules with and without PCM. The modules were cycled continuously at C/1 discharge rate and C/3 charge rate to investigate the effect of PCM thermal management on battery cycle life. As shown in Figure 4, the measured discharge capacity decreased at a rate of 0.20 Whr/cycle when no PCM was used. On the other hand, the capacity fade rate for the module was only about 0.09 Whr/cycle with PCM.

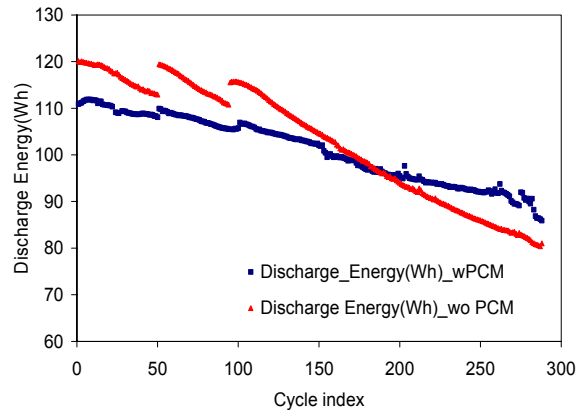


Figure 4. Capacity fade testing of battery modules with and w/o PCM

The results clearly demonstrate that PCM is effective in a passive thermal management system for Li-ion battery modules. Furthermore, the presence of PCM is beneficial for performance of batteries operating under extreme conditions. In addition, the temperature is successfully regulated and uniformly distributed throughout the module. The temperature control produced a significant improvement in battery cycle life, which is consistent with similar results reported elsewhere in the literature⁵. As shown in Figure 4, the utilized capacity of the battery module showed an unexpected sudden increase when cycling was interrupted due to maintenance or power outages. Further investigation is currently underway to obtain reasonable explanation for this behavior.

IV. PROPOSED Li-ION BATTERY DESIGN FOR PLUG-IN HEV

A new design using commercially available high-power Li-ion batteries (HPPC 18650) with a PCM thermal management system is proposed in this work as an alternative to NiMH batteries. Figure 5 shows a schematic of the proposed battery module, and the module specifications are summarized in Table 2.

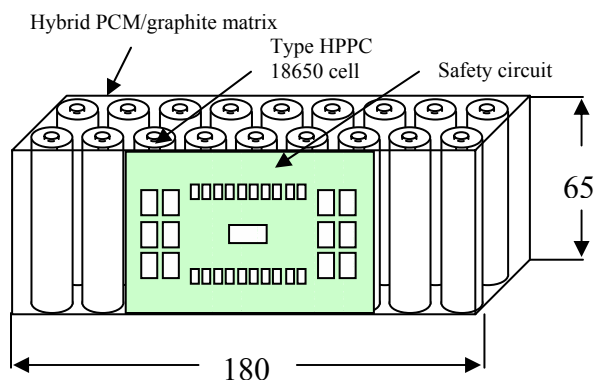


Figure 5. Schematics of the PCM/Li-Ion Battery Module (dimensions are in mm)

Table 2. Specification of PCM/Li-Ion Battery Module for PHEV Application

Cell Used:	Type HPPC 18650
Cell Capacity:	2.0Ah
Module Voltage:	32.4V
Module Capacity	4.0Ahr
Maximum Discharge	20A (5C)
Maximum Charge	10A (2.5C)
Max. Operating Temp.	50°C
Volume	0.585 Liter

As shown in Figure 6, seven PCM/Li-ion modules are connected in series and twelve in parallel to meet the design requirements for a PHEV battery system. The proposed PHEV Li-ion battery pack is rated at 226.8 V nominal voltage with 120 Amp and 240 Amp maximum charge discharge currents, respectively. More specifications of the PHEV battery pack are listed in Table 3. It is worth noting that the volume of the battery pack will be roughly 50 liters which is nearly 50% of the available trunk space for the 2005 Toyota Prius, while lead acid batteries would require twice the trunk size for the same energy capacity. In addition, only two hours

are required to fully charge the proposed Li-ion battery pack from its full discharged state while lead acid batteries require 8-12 hours to be fully charged.

One of the main goals of the proposed PHEV battery design is to minimize imbalance among cells across the module and among modules across the whole battery pack. Therefore, each module is designed with integrated charging and safety circuits.

A single AC-DC power supply is used to charge the battery pack. Each battery module is integrated with a safety circuit to ensure safety and charge balance among all battery modules. On the other hand, all modules are designed with individual charger circuit and power supply. All module circuits are connected in parallel to a single AC source. Using this approach, each module is individually charged. Since all of the modules would be charged independently of each other, each could be charged to its maximum voltage without being limited by the other modules. This approach minimizes imbalance among the individual modules.

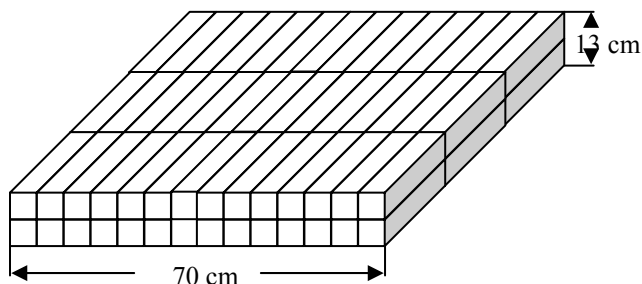


Figure 6. Schematic of PCM/Li-Ion battery pack for PHEV Application

Table 3. Specification of Li-Ion Battery Pack for PHEV Application

Modules configuration	
<i>series</i>	7 modules
<i>parallel</i>	12 modules
Nominal Voltage	226.8V
Nominal Capacity	48.0Ahr
<i>Nominal Energy</i>	10.89 kWh
Maximum Discharge	
<i>power</i>	54.4 kW
<i>current</i>	240 Amp
Maximum Charge	
<i>power</i>	27.2 kW
<i>current</i>	120 Amp
Volume	~ 50 liters

V. CONCLUSIONS

In this work, a Li-ion battery module and battery pack using PCM thermal management system is proposed and demonstrated for PHEV applications in this work. The preliminary results showed that the capacity of a Li-ion battery modules with PCM can be safely and fully utilized even under extreme temperature and operating conditions. In addition, the PCM thermal management significantly improves the cycle life of a Li-ion battery modules compared to comparable modules without PCM.

The proposed PHEV Li-ion battery system is capable of meeting the vehicle's power and stored energy capacity requirements and with a significant reduction in occupied volume and charge time over lead acid batteries.

ACKNOWLEDGMENT

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