Thermal Management of Battery Pack for Hybrid Vehicles Using PCM

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Abstract. Advancement in thermal management system which can be adopted to absorb heat generated in Li-ion battery pack for hybrid vehicle during charge and discharge cycles, by keeping the battery pack in optimum range of 15°C-25°C. Factors such as parasitic power, additional weight of cooling unit, temperature rise and cell temperature difference play a vital role. PCM (Phase Change Material) are compounds having high thermal conductivity and latent heat storage. They go through phase change when they absorb or release heat. The basic design is to manufacture a cooling jacket using phase change material which absorbs heat during the day and rejects it at night. The result show decreases in temperature by 1.5°C, additional increase in weight of battery pack by 17.5%, no parasitic power consumption, increase in safety and compactness to applications.

Keywords: Hybrid vehicle · Lithium-ion battery · PCM(Phase Change Material) · Thermal conductivity · Latent heat · Cooling jacket.

1. Introduction
Energy conservation by adaptation of energy saving products has become a major field of research and development. Hybrid vehicles consist of large battery packs which provide energy but also release a lot of heat during charging and discharging cycles. Ye and Pesaran [1,2] study showed that the most optimum temperature range for working under safety limits for lithium-ion battery to increase its battery life is 15°C to 25°C. During manufacturing of Li-ion cells, extremely flammable and volatile electrolytes are used [3], which might pose threat due to rise in temperature of the pack. Although high density battery pack is unavoidable but safety and durability play a more important and crucial role. Extreme conditions [4] and thermal runaway [5] also pose a major threat for the pack. Thus a well-designed and effective thermal management system is required for effective cooling for battery packs. There are different methods that can be adopted which have their own advantage and disadvantages. Air cooling is the easiest approach, which works effectively in small packs but fails in case of battery pack size adopted in hybrid vehicle due to formation of heat zones leading to overheating [6] as shown by CFD of cylindrical cells [7]. Heat exchangers especially metal foam based were used by Giuliani et al. [8] to study the effects of forced air cooling. The development of thermal model based on liquid cooling was very effective in optimizing the temperature, by using fluids like oil and water [9,10,11], but its complexity, cost, and potential leakage make manufacturers hesitate to use it. The use of PCM is another method of advanced cooling. PCM or Phase Change Material are compounds
that have high latent heat and undergo phase change in order to absorb or remove heat, over thousands of life cycles.

1.1. Objective
The objective of this paper is to develop an effective method for absorbing heat generated by the lithium ion cells of the pack during charging/discharging and keep them close to optimum range, thus resulting in increase in life cycles of the cells keeping in mind factors like manufacturer feasibility, parasitic power consumption, and easy replacement.

List of symbols

| Nomenclature   | Description                                           |
|----------------|-------------------------------------------------------|
| H              | Heat generated (J/s)                                  |
| I              | Current (Amp)                                         |
| R              | Resistance (ohm)                                      |
| A              | Area of heating pad (m²)                              |
| Ti             | Initial temperature (°C)                              |
| Tf             | Final temperature (°C)                                |
| m              | Mass of PCM (kg)                                      |
| L              | Latent heat (kJ/kg)                                   |
| h              | Heat transfer coefficient (W/m²)                      |
| ε              | Emissivity (W/m²)                                     |
| σ              | Stefan boltzmann’s constant (5.67 × 10⁻⁸ W · m⁻² · K⁻⁴) |

2. Battery Pack
The battery pack (dimensions: 20cm × 12cm; weight: 2.525kg) consists of 27 Li-ion cells, with each cell having a nominal voltage of 3.6V, at 2.2A of current supply. The total energy dissipated by each cell is ~7W. Since the battery pack has uneven heat generation, due to different amount of heat released by the cells at a given time and points, a uniform heating pad is manufactured with 2 terminals, which acts like a single cell which can dissipate an equal amount of energy at all given time and points. The pad is made by taking a phosphate resistance wire (resistance ~ 1.4Ω) that is embedded inside a Silicon-Aluminum sandwich casing (dimensions: 20cm × 12cm) which creates uniform temperature over the entire surface. Fig.1 and Fig.2 shows outside and inside pictures of the heating pad. When current is made to flow through the pad, heat is generated. Fig.3 and Fig.4 show the theoretical and actual relationship between time and rise in temperature for heating the pad at different current supplies.

Figure 1: Outside of heating pad
Figure 2: Inside of heating pad
3. Thermal Management System

The thermal management involves manufacturing of a cooling jacket which is filled with PCM (latent heat: 190 kJ/kg) which absorbs heat during the day and rejects it at night. The pack is sealed and made leak proof, Table 1 shows specification of PCM. Fig.5 represents cooling jacket (Dimensions: 20cm × 20cm; Weight 0.700kg) manufactured by taking plastic sheets of thickness (0.2mm) that are filled with PCM, and sealed using a laminating machine. The pouch also consist of a valve to remove excess air and create a vacuum. This is done as a protective measure as hot air puts more pressure on the jacket walls during heating phase that may lead to bursting of jacket in extreme conditions.

| Property       | Value | Unit  |
|----------------|-------|-------|
| Melting Temp   | 29.0  | °C    |
| Freezing Temp  | 29.0  | °C    |
| Latent Heat    | 190   | kJ/kg |
| Liquid Density | 1530  | kg/m  |
| Solid Density  | 1830  | kg/m  |
| Specific Heat  | 2.3   | kJ/kg·K |

4. Calculations

During charging/discharging cycle, heat generation takes place inside the cell. Similarly, when the current is made to flow through the heating pad, heat generation takes place. The total heat generated (H) by the heating pad is calculated by

\[ H = I^2 R \]

After some time, the pad temperature reaches a constant value as shown in Fig.4, but continuously emits a constant amount of heat for the remaining time. The heat emitted by heating pad in the form of convection and radiation per second is given by

\[ I^2 R = 2hA\Delta T + 2\epsilon \sigma A (T_f^4 - T_i^4) \]

Mass of PCM (m), required to absorb the heat emitted by the heating pad in order to keep the pack in constant temperature is calculated by

\[ Q = mL \]
Using above stated equation a linear relationship is observed between mass of PCM required and heat generated. The maximum total heat produced by the heating pad in 5 hours at 2.2A current supply is 18 KJ/kg-K, and mass of PCM required to absorb the heat is 0.6419kg.

5. Experimental Setup
The pack is connected to a data acquisition (DAQ) system which consists of sensor (thermocouple), DAQ measurement hardware, and a computer with programmable DAQ system. Fig.6 represents the experimental setup.

![Figure 6: Experiment setup](image)

The heating pad terminals are connected to a constant current source of 2.2A for 5 hours, and rise in temperature is recorded. Now the heating pad is covered with PCM filled cooling jacket which covers the entire surface in such a way that it sticks to the surface tightly and constant current of 2.2A is made to flow through the pack for 5 hours, Fig.7 represents time and rise in temperature for heat pad covered with and without PCM jacket.

6. Results
The results show that temperature of heating pad covered with PCM jacket remained ~1.5°C less than the actual temperature for a constant current supply of 2.2A for 5 hours. Increase in temperature is inversely proportional to the life cycles of a lithium ion cell. Factors such as increase in internal resistance leads to high temperature profile for the cells. The PCM jacket when attached to the pack increases the pack weight by 17.5% but lowers the temperature profile for the pack by ~1.5°C, thus bringing it closer to the optimum range as a result increasing life cycles of the pack. Also, PCM acts as a safety measure in case of short circuit/fire in the pack. Other factors such as manufacturer feasibility, no parasitic power consumption, easy replacement lay an upper hand as compared to the conventional methods. PCM jacket absorbed all the heat generated in the form of convection and radiation and underwent phase change, though minor amount of PCM crystal were still visible inside the jacket.

7. Conclusion
The use of PCM jacket lower the temperature. Fig.7 represents the difference between with and without the use of PCM jacket. A clear difference of 1.5°C can be observed. There is no parasitic power consumption, additional weight of pack was increased by 17.5%. The replacement cost is low, with high life cycles. PCM are inflammable thus enhancing safety in case of fire, in battery pack. The use of PCM jacket also provides compactness to application.
Figure 7: Rise in temperature with time at constant current supply of heating pad with and without PCM jacket

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