Design and simulation of liquid cooled system for power battery of PHEV

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Abstract. Various battery chemistries have different responses to failure, but the most common failure mode of a cell under abusive conditions is the generation of heat and gas. To prevent battery thermal abuse, a battery thermal management system is essential. An excellent design of battery thermal management system can ensure that the battery is working at a suitable temperature and keep the battery temperature difference at 2-3 °C. This paper presents a thermal-electric coupling model for a 37Ah lithium battery using AMESim. A liquid cooled system of hybrid electric vehicle power battery is designed to control the battery temperature. A liquid cooled model of thermal management system is built using AMESim, the simulation results showed that the temperature difference within 3°C of cell in the pack.

1 Introduction
To meet the needs of the market, electric vehicles must have performance especially considering safety, range and battery reliability comparable to that of a modern combustion engine vehicle [1]. Research shows that the battery components are completely stable below 80°C, but once the temperature reaches 120-130°C, the passivation SEI (Solid Electrolyte Interface) layer starts dissolving progressively in the electrolyte, which causes electrolyte to react with the least protected surface of graphite generating heat. The battery temperature impacts on life, safety and performance of lithium-ion batteries and suggested a range of 15-35°C as desired working temperature. One of the key is in the thermal control of the battery: operation at low temperature reduces the power output due to suppressed electro-chemical reactions, while elevated temperature accelerates corrosion leading to reduced battery life [2]. It is also important that the temperature within a battery cell is uniform: variations will cause the electrochemical reactions to proceed at different rates in different regions of the cell, thereby leading to incomplete energy utilization, and inefficient management of the battery life [2]. Any power consumed for the regulation of temperature reduces the power available to the primary vehicle functions, and so the efficient operation of a thermal management system is also desirable[3].

An air-cooling system worked very well in HEVs during standard drive cycles that could control the maximum temperature below the limit of 55 °C and the temperature difference was no more than 5°C. Excessive ambient temperature and higher energy density batteries, an active liquid cooled system gives the most effective and efficient thermal management[4].
2 Structure design

Table 1 shows the parameters for a PHEV battery pack. The cell type is NCM (Nickel Manganese Cobalt Oxide), which has 3.6 V nominal working voltage and shall be cut-off power at 4.15-4.2 V per cell during charging.

Table 1: Battery pack specification

| Geometric values   | Value          |
|-------------------|----------------|
| Total voltage     | 310.8V         |
| Cells (parallel/series) | 1P84S     |
| Cell voltage      | 3.7V           |
| anode             | NCM            |
| Cell capacity     | 37Ah           |
| Total energy      | 11.4kWh        |

The total pack nominal voltage is 310.8 V. The total energy is 11.4 kWh. Figure 1 shows three dimensional representation of the lithium-ion battery pack layouts considered in this study. There are 84 battery cells total which are packed in seven modules.

![Figure 1. Three dimensional representation of the battery pack layouts](image1)

Figure 2 shows the three dimensional representation of the cooling plates and pipes. There are four cooling plates, which are in series by water pipes. Liquid coolant, comprising of a 50/50 water-glycol mixture.

3 Thermo-electric model

Bernardi derived an expression for battery heat using a thermodynamic energy balance on a complete cell [5]. Its simplified form [6] :

\[
\varphi = -IT \frac{du_o}{dt} + I(U_o - V)
\]  

where:

\[
\varphi = \text{battery heat}
\]

\[
I = \text{current in the cell [A]}
\]

\[
\frac{du_o}{dt} = \text{cell voltage change rate}
\]

\[
U_o = \text{open circuit voltage}
\]

\[
V = \text{battery voltage}
\]

The first term is the reversible reaction heat and the second term is irreversible reaction heat. The reversible heat flow rate can be calculated by the following relationship:

\[
\delta h_s = \left( \frac{du_o}{dt} \right)_{SOC} \cdot I \cdot T
\]  

Where:

\[
\delta h_s = \text{reversible heat flow rate [W]}
\]

\[
SOC = \text{state of charge}
\]

\[
T = \text{temperature [K]}
\]

I is the current in the cell [A]
$T$ is the temperature [K]
$U_0$ is the Open Circuit Voltage [V]

![Battery thermoelectric model diagram](image)

Figure 3. Battery thermoelectric model diagram

Fig.3 shows the principle of battery temperature calculated in the AMESim, which means electrochemical model and thermal model coupling calculation. Eq.1-3 can be used to obtain the battery temperature.

$$C_p m \frac{dT}{dt} = -IT \frac{dU_o}{dT} + I(U_o - V) - hA(T - T_{air}) - \varepsilon A \sigma (T^4 - T_{air}^4) - KA_{wall} (T - T_{wall})$$ (3)

Where:
- $C_p$ is the specific heat
- $m$ is the battery mass
- $h$ is the convective heat transfer coefficient
- $A$ is the convective surface or radiation surface
- $\varepsilon$ is the emissivity
- $\sigma$ is the boltzmann constant
- $T_{air}$ is ambient air temperature
- $A_{wall}$ is the condution surface
- $K$ is the condution heat transfer coefficient
- $T_{wall}$ is the battery contact solid temperature

4 Simulation

| Geometric values         | Value   |
|--------------------------|---------|
| Cathode material         | NMC     |
| capacity                 | 37Ah    |
| mass of material         | 0.8kg   |
| specific heat of the material | 950J/kg/K |
| density of the material  | 2100kg/m3 |
| heat conductivity        | 20W/mK  |

Table 2. shows the thermal parameters of a cell, it is a prismatic battery.

![Thermal management system schematic](image)

Figure 4. The thermal management system schematic
Fig. 4 shows the battery cooling system contains a water pump, liquid cooled plate, chiller, expansion valve, condenser, compressor, evaporator and chiller. The heat generated from the battery is passed through the cold plate to the coolant. The coolant was driven into the chiller by the water pump, where happen heat exchange with the refrigerant.

![Diagram of battery cooling system](image)

**Figure 5 Liquid cold plate modeling principles**

In order to model in AMESim, the cold plate was discretized. Figure 5 shows the liquid cold plate is divided into battery discrete mass, cold plate discrete mass and flow channel discrete region.

![Diagram of liquid cold plate modeling in AMESim](image)

**Figure 6 show that the entire AMESim model for a liquid cooled system of a PHEV.**

![Diagram of AMESim model for PHEV](image)

**Figure 7 Liquid cold plate modeling principles in AMESim**

Cold plate modeling needs to consider the simulation accuracy requirements and the complexity of the cold plate structure. Based on lumped thermal capacity, a battery cell can be regarded as a thermal mass, cold plate can be discreted into many mass units and flow channel inside the plate can be discreted into many regions, as shown in Figure 5. Figure 7 show that the cold plate AMESim model, the heat convection coefficient is setted to 5.

Water pump model need to enter the pump head, flow and speed test data, as shown in Figure 8. If only limited data or the pump operating status is out of existing data range, the data will be interpolated based on the principle of similarity.
Fig. 9 shows the air conditioning system amesim model, including the compressor, condenser, chiller, expansion valve model, more detail can be found in [5].

Figure 9 Air conditioning system amesim model

5 Thermal management Strategies
When battery maximum temperature in the pack rise to 35 ℃, the water pump and air conditioning open at the same time; when the battery minimum temperature down to 30 ℃, the water pump and air conditioning close at the same time.

6 Results and discussion
Fig. 10 shows that current and heat generation rate of battery. The battery is charged-discharged at C-rates, the heat generation rate was calculated from the battery model in AMESim. Next the battery
temperature and maximum temperature difference at 8L/min, 4L/min and 2L/min flow rate will be simulated based on the same working condition in Fig.10.

![Figure 11](image)

**Figure 11.** The battery temperature and coolant flow rate

The flow rate and pressure drop of the Liquid cooled system determine the heat transfer effect of the battery pack and the selection of components such as pumps. The flow rate and pressure drop of the Liquid cooled system are shown in Figure 11.

![Figure 12](image)

**Figure 12.** The flow rate and pressure drop of the liquid cooling system

Fig.12 shows the coolant flow rate of 8L/min, the battery pressure drop includes four cold plate pressure loss and pipe pressure loss, it is 28.9kPa in total.

![Figure 13](image)

**Figure 13.** The maximum battery temperature difference in the pack

Compared with air cooling system, the advantage of liquid-cooling system is that the better uniformity of battery temperature. The simulation results show that the maximum battery temperature difference in pack is 2℃ at 8L/min flow rate. The maximum temperature difference occurs when the air conditioner is turned off.
Figure 14. The cell temperature and refrigerator power

Fig. 14 shows the air conditioning system is working when the battery temperature rose to 35; the air conditioning to stop working when the battery temperature dropped to 30 °C.

Figure 15. The maximum temperature difference among cells at 4L coolant flow

The simulation results show that the maximum battery temperature difference in pack is 3 °C at 4L/min flow rate.

Figure 16. The maximum temperature difference among cells at 2L coolant flow

The simulation results show that the maximum battery temperature difference in pack is 5 °C at 2L/min flow rate.

7 Conclusions

In this paper, a novel Liquid cooled system is designed for a battery pack of PHEV. A liquid-cooling system model in AMESim was developed to research the battery thermal concern, it is very important especially at the initial stage of the design.

1. The maximum temperature difference occurs when the air conditioner is turned off;
2. As the coolant flow decreases, the battery maximum temperature in pack decreases increases;
3. The simulation results show that the power battery cooling system to meet the design requirements, the liquid cooling system can control the battery temperature difference within 3 °C.

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