A Review on Design and Optimization of Cooling Plate for Battery Module of an Electric Vehicle

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Abstract: *With advancements and innovations in electric vehicles, thermal management of the batteries has been the key focus of the study. As evident by previous research carried out, the liquid cooling method has replaced conventional Air cooling method. In the following study a lithium iron phosphate battery along with two cooling plates was used to design a battery module. . A single battery numerical model was first created and verified as the basis of the module heat transfer model.*

Orthogonal design technique was incorporated while designing the thermal model to optimize the main characteristics of battery module, i.e. Battery gap, number of cooling channels in the cooling plate. After these secondary optimizations the model was utilized further to optimize the primary objective that is geometry of the cooling plate. Finally the optimized geometry was rebuilt in the thermal model of the module for analysis. The comparison showed that in the optimized geometry of the model the temperature gradient was reduced by 9.5% and the pressure drop was reduced by 16.88% in the cooling plate. All this was achieved by increasing the cross section and number of cooling channels of the cooling plate inlet when the flow rate of the coolant was constant.

Key words *: electric vehicles, thermal management of the batteries, lithium iron phosphate battery, cooling channels, battery module.*

1. INTRODUCTION

As the primary type of energy storage units in satellites, robots, electrical vehicles, and many other electrical appliances li-ion batteries have been continuously worked upon for many years and their performance has greatly improved. Many electric vehicles are being manufactured and li-ion batteries are used to power majority of these vehicles. Major problem faced by li-ion batteries is heat generation, thus negatively affecting service life, capacity performance and internal resistance of batteries. In order to increase the service life of the battery it is imperative to design a battery module with good heat dissipation abilities. Phase change material (PCM) cooling system controls the temperature of the battery module by the heat absorption and heat release when its material phase changes.

Air cooling is sufficient in common conditions however the temperature of the battery pack will be significantly higher. Due to technological advancements faster EV have been produced, thus when the vehicle is operated at high speeds or when the speed of the vehicle is changed frequently the discharging rate of the battery is very high leading to increase in battery temperature. Air cooling can be used by changing the angle of the cooling vents and increasing the number of cooling channels however these alternatives are not feasible to each and every type of EV and it can differ from vehicle to vehicle due to differences in size, manufacturer, cost etc. . Phase change material (PCM) cooling system controls the temperature of the battery module by the heat absorption and heat release when its material phase changes. PCM meets the needs of Li-ion battery cooling system however it costly and thus rarely used in EV.

Since the introduction of a liquid cooling system with high cooling efficiency and reliability [14–16], it has gradually occupied the electric vehicle market. The liquid cooling system in the BMW I3 and the Tesla model S, have good sealing and reliability, and can take away the heat of each battery evenly and exhibit good performance in electric vehicles.

The cooling efficiency was enhanced by low inlet coolant temperature, low inlet mass flow rate and increase in no. of cooling channels. Panchal et al [18] investigated the distribution of temperature and velocity within the cooling channels of the cooling plate placed on prismatic Li-ion battery cell using liquid cooling methods. Wang et al. [19] carried out experimental and simulations to study the effect of cooling channels, flow rates, and flow directions at different discharge C-rates. It was found that the maximum temperature reached within the battery decreased as the amount of thermal silica plates and liquid channels increased. Wang et al. [20] designed a new liquid cooling strategy based on thermal silica plates combined with the cooling effect of water. The experimental results demonstrated that the addition of thermal silica plates can greatly improve the cooling capacity.

In this paper, A Li-ion phosphate battery was used to design a module used in a conventional EV and thus analysis on the cooling plate was carried out by numerical heat transfer. Then the data from the analysis and the updated model was used to further supplement the geometry and performance of the cooling plate.

2. Theory

Battery technology is developing rapidly. However, lithium-ion (Li-ion) batteries are by far the most commonly used in electric cars and other alternative mobility options today. They may seem safe but the potential is there for catastrophe if they aren't kept cool.

Liquid cooling is one of the best options to keep the battery pack under optimum working temperature. The most commonly used coolant is Glycol mixed with water.

There are two types of liquid Cooling:

Indirect liquid cooling system

The most common way to cool EVs currently is with indirect liquid cooling systems. In this design, a series of pipes are routed through and/or around the battery pack much like a cooling system on an ICE vehicle. The fluid, typically glycol, is excellent at storing heat that is transferred from the warmer battery pack and circulating it to a heat exchanger like a radiator. This is the style used in EVs manufactured by Tesla, BMW, Jaguar, and Chevrolet, plus others. Although the indirect cooling system is most common, it isn't without its own issues. Fluid leaks inside the battery pack, for example, could be dangerous and there are environmental concerns regarding glycol disposal. For now, it remains the most desirable solution.

Direct liquid cooling method

The optimum cooling performance occurs when the coolant is in direct contact with the battery's cells. A direct liquid cooling system would be able to absorb heat most efficiently, regulating the battery's temperature precisely. However, the coolant would be required to be non-conducting so there would not be an electrical hazard. Currently, no EVs use direct cooling systems but that could change soon. Developers such as XING Mobility and M&I Materials are leading the charge to get these non-conducting coolants into use in the auto industry.

3. Methods

The governing equations which were used to solve the time dependent three-dimensional flow problems include the continuity equation, momentum equation, and the energy equation. The equation of state was given in Equations (1)–(5) [21–24]:

Continuity equation

$\partial\rho /\partial t + \nabla\cdot(\rho u) = 0$ (1)

X-momentum

$\partial(\rho u)/\partial t + \nabla\cdot(\rho uu) = -\partial P/\partial x + \nabla\cdot(\mu \nabla u) + SMx$ (2)

Y-momentum

$\partial(\rho v)/\partial t + \nabla\cdot(\rho vu) = -\partial P/\partial y + \nabla\cdot(\mu \nabla v) + SMy$ (3)

Z-momentum

$\partial(\rho w)/\partial t + \nabla\cdot(\rho wu) = -\partial P/\partial z + \nabla\cdot(\mu \nabla w) + SMw$ (4)

Energy equation

$mCp\,.(dTc/dt) = \nabla\cdot(\lambda c \nabla Tc) + Qg$ (5)

The main working parameters of the lithium iron phosphate battery [25] are shown in Table 1.

Table 1. Working parameters of lithium batteries.

Parameters	Values
Nominal voltage (V)	3.2
Nominal capacity (Ah)	10
Internal resistance (mΩ)	≈10
Charging current (A)	≤ 10
Continuous discharge current (A)	≤ 20
Maximum discharge current (A)	50
Upper cut-off voltage (V)	3.65 ± 0.05
Lower cut-off voltage (V)	2.5
Cycle life (/)	≥ 2000
Weight (g)	275 ± 5
Dimension (mm)	131 × 65 × 16

The interior part of the battery was simplified as an equivalent solid model and the following assumptions were made for the model:

(1) The material properties in lithium batteries were uniformly distributed. Because of the multi-layer structure and manufacturing process of lithium batteries, only the thermal conductivity was anisotropic;

(2) Thermal radiation and convection can be neglected inside the lithium battery;

(3) The specific heat capacity and thermal conductivity of materials in the lithium batteries were constant and independent of the temperature;

(4) When the battery was charged and discharged, the current and heat generation were considered uniformly distributed. It was difficult to accurately obtain the heat generation rate of batteries due to the complexity of vehicle operating conditions and environment. The internal resistance of the battery was assumed constant under ambient temperature, and the battery resistance was set to 10 mΩ. According to the classic model proposed by Bernardi et al. [26], the heating generation rate of batteries was established below in Equation (6). The polarization heat, chemical reaction heat and the electrode cap heat was not considered in the model.

$$q = (I/V) [(U0 - U) - T (\partial U0/\partial T)] \quad (6)$$

where, V represents the volume of the battery, in cubic meters, U0, the open circuit voltage in volts, U, the working voltage of the battery in volts, T, the temperature in Kelvin, ∂U0 ∂T is measured experimentally, the value is very small at room temperature with a low discharge rate and can be neglected.

Therefore, Equation (6) can be simplified and expressed as follows:

$$q =(I/V)(U298.15 - U) =(I^2)/(RP + Re)V=(I^2)/RV \quad (7)$$

U298.15 represents the open circuit voltage of the battery in the temperature of 298.15 K, in volts; R is total internal resistance which is obtained by the internal resistance, Re, and the polarization internal resistance, Rp, in ohms. In addition to the complex heat generation inside the battery, the heat generation outside the battery will also occur, such as the positive and negative electrodes, the confluent and the welding position of the conductor. These heats can be neglected when studying the heat generation of the battery. Equation (7) was used in this paper to estimate the heat generation of the battery. The heat generation rate of the lithium battery at 2C discharge rate was 29, 359.953W/m3. C-rate is the measurement of the charge and discharge current with respect to its nominal capacity. Considering the experimental environment and the boundary conditions of simulation, the Boussinesq hypothesis was used for the calculation: (1) The dissipation of fluid viscosity was neglected during the process of fluid flow; (2) except the fluid density, other thermal properties were constant with varying temperature;(3) for density, only the terms related to volume force in momentum equation were included and the temperature of 25 ◦C was used as the reference temperature for calculation.

Table 2. Thermophysical parameters [25].

Name	Density (kg·m^−3)	Specific Heat Capacity (J·kg^−1·k^−1)	Thermal Conductivity (W·m^−1·k^−1)	Viscosity (kg·m^−1·s^−1)
Cell	1958.7	733	0.9/2.7/2.7	-
Air	1.185	1005	0.0263	0.0000184

The dimension of the battery is 131mm × 65mm × 16mm, the positive and negative electrode columns were not included in the model. The simplified model of the battery was established by CATIA as shown in Figure 1b, the fluid field was created according to the cooling method in Ge's experiment [16], as shown in Figure 1c. In the analysis, the natural cooling process of the lithium battery was simulated at 2C discharge rate for a period of 1800 s. The temperature evolution was monitored and outputted at the end of each time step. The results of the cell surface temperature after 1800 s at 25 ◦C are shown in Figure 2. The maximum temperature was 325.8 K and located in the central area of the battery surface. Surface temperature decreased gradually to the periphery. The lowest temperature of the battery was 322.2 K at the four corners. The temperature difference of the whole battery surface was 3.6 K.

The velocity streamline diagram of air in a natural convection condition surrounding the lithium battery is shown in Figure 3. It can be seen that air flew from boundaries of air domain to the surface of the batteries, and buoyancy increased with the increase of the temperature on the surface of the battery. The air velocity in the central region leaving the battery surface with the highest temperature was 0.1362 m/s. To verify the thermal model of the single battery, comparison with the experimental results in paper [25] was plotted in Figure 4. The surface temperature was measured by a K-type thermocouple during the experiment. During the discharging process, the temperature at the monitoring point gradually increased with time. The highest temperature in the experiment and numerical analysis were 53.84 ◦C and 51.39 ◦C, respectively, implying a difference within 5%. The reasons for this error may result from the assumptions made in the simulation and the heat generation equation did nottake into account the polarization heat, chemical reaction heat, and the electrode cap heat. The cell discharged at 25 ◦C without cooling, the maximum temperature can reach 53.84 ◦C, which was higher than the optimum operating temperature range of the battery. Because of the various usage conditions of the EV battery, high power discharge will occur inevitably. When power batteries are assembled in large quantities, the heat dissipation efficiency becomes low. To solve this problem, it is necessary to design a standard battery module and incorporate a cooling system *to ensure the working environment temperature of batteries.*

5. Conclusions

The thermal analysis results foreseen by the only battery thermal model showed smart agreement with experiments by a distinction but five-hitter, implying that the warmth generation model and therefore the assumptions were cheap. A method for the planning and optimisation of the cooling plate for the battery module was projected. a fancy heat transfer model for the total module was created, together with batteries, 2 cooling plates, silicone polymer gel pads, and agent. Orthogonal experimental style was enforced by the numerical analysis to optimize the most parameters of the module. The cooling plate pure mathematics was more optimized by the surrogate model technique. With the optimized pure mathematics, the cooling plate was restored within the module thermal model for the analysis. The comparison showed that the most and minimum temperature distinction within the cooling plate was reduced by five.24% and therefore the pressure drop was reduced by sixteen.88%. it had been complete from the orthogonal style analysis that the battery temperature distinction and therefore the pressure drop faded with the rise of the crosswise and variety of the agent channel once the agent flow was constant at the water. From the sensitivity analysis of the plate, the most temperature and pressure call in response to the plate geometric parameters within the surrogate models, it had been found that the centre channel distance, L1, and therefore the size of the water plenum exhibited the best influence on the pressure drop.

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Nomenclature

A Factor in orthogonal experimental design, cross section

B Factor in orthogonal experimental design, battery spacing

C Factor in orthogonal experimental design, number of channels

Cp Specific heat capacity, J kg−1 K−1

Δt coolant Temperature difference for coolant, ◦C

H Geometric parameters at the inlet of the cooling plate

L Channel distance in the cooling plate

m Mass, kg

min Flow rate of the coolant at the entrance, kg s−1

N Number of batteries

P Pressure, Pa

Qg Generated heat

q Heat generation rate of batteries, W m−3

q f lux Heat flux on the cooling plate surface

R Total internal resistance, Ω

Re Internal resistance, Ω

Rp Polarization internal resistance, Ω

SMx, SMy, SMz Body forces

T Temperature, ◦C

t Time, s

U Working voltage of the battery, V

U0 Open circuit voltage of the battery, V

U298.15 Open circuit voltage of the battery in the temperature of 298.15 K, V

u Flow velocity vector

u Velocity in x direction, m s−1

V Volume of the battery, m3

V Velocity in y direction, m s−1

W Velocity in z direction, m s−1

Z Coordinate Z direction, mm

Abbreviations

EV Electric vehicles

PCM Phase change material

UDF User defined functions

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