Two Air-cooling Configurations for Battery Management System

Shuang Lv¹, Qie Sun¹*, Ronald Wennersten¹
¹ Institute of Thermal Science and Technology, Shandong University, China
* Corresponding author. Email address: qie@sdu.edu.cn

Abstract
The calendar life and performance of power battery are closely related to its operating temperature; hence, the battery thermal management system (BTMS) is the key technology for electric vehicle. An air cooling based thermal management system for 18650 battery pack is studied in this paper. First, A coupled electrochemical thermal model is constructed to evaluate the heat generation under different discharge rate. Then transient temperature distribution of one cell during discharge is studied. Following that, the effect of air mass flow rate on the temperature of the cells and the maximum temperature appear area are investigated. Results show that the temperature uniformity could be satisfied for the designed U-type structure when the air mass flow rate is larger than 0.02 kg/s. But it is hardly to achieve the requirement of temperature uniformity for Z-type, and the maximum temperature appears at the first column at the airflow direction.

Keywords: Battery thermal management system, Airing cooling, Z-type and U-type, Temperature distribution

Nomenclature
Abbreviation
BTMS Battery Thermal Management System
EV Electric Vehicle
HEV Hybrid Electric Vehicle
PCM Phase Change Material
TEMs Thermoelectric Modules
Symbols
C Discharge rate
Rint Internal resistance, mΩ
I Electric current, mA
ρ Average density of the battery, kg/m³
Cp Specific heat capacity, J/(kg⋅K)
λ Heat conductivity coefficient, W/(m⋅K)
t Time, s
T Temperature, K
kT,r Radial heat conductivity coefficient, W/(m⋅K)
kT,len Length heat conductivity coefficient, W/(m⋅K)
Li Thickness of different layers, mm
kT,i Heat conductivity coefficient of different layers, W/(m⋅K)
Qgen Heat generation per unit volume, W/m³
Subscript
i i-th layer of the cell
r Radius direction of the cylindrical battery
len Length direction of the cylindrical battery

1. Introduction
Under the pressure of climate change and environmental pollution, transformation of automobile power source from fossil energy to green energy is the priority for automobile manufacturers[1-3]. According to calculations based on figures issued by the China Association of Automobile Manufacturers, the sales of new energy vehicles in China from January 2016 to September 2018 are shown in Figure 1. The sales of EV and HEV change monthly, but the total sales shows a growth trend by year. From January to September in 2018, the sales reached 721000-unit increase, which increased 81.1% compared with the same period last year.

High specific power, high specific energy density and high safety performance batteries are required to meet the operational needs of electric vehicles. From previous research, the safety, energy density and calendar life are dramatically with the operating temperature of the battery[4]. The battery generates much heat during rapid charge and discharge cycles, especially in starting, accelerating or hill climbing process. If the heat...
generated not be released seasonable and timely, the temperature of the batteries will increase rapidly, which may cause deterioration of the battery performance and reduction of the battery’s cycle life, even cause an explosion and threaten human life. The optimum operating temperature of Li-ion battery is investigated to be 25~40°C and desirable temperature difference within the cells in battery pack is found to be less than 5°C[5]. Therefore, an efficient BTMS is critically significant to reduce the maximum temperature and improve the uniformity of temperature distribution of the battery packs, which can ensure safety and sustainable power supply for EV and HEV.

BTMS consisting of prismatic batteries of 16mm × 65mm × 151mm were investigated using flow resistance network model in Ref[6, 7]. Purely for the purpose of cooling, the prismatic cell seems to be most suitable for vehicles because a relatively large surface area in dissipating heat from cell interior to the exterior is available. However, considering the factors such as production maturity, availability, safety, lifecycle, and cost, cylindrical cells seem to be better, especially the 18650 cells, which is in frequent uses, e.g. Tesla, BMW mini[8]. Besides, the temperature and flow field distribution of the battery pack cannot be clearly displayed through the flow resistance network model. Therefore, battery pack composed of 18650 cells are investigated through COMSOL Multiphysics software in this paper.

This paper aims to investigate the effect of air mass flow rate on the temperature and temperature difference of the cells first, then analysis the temperature distribution of the battery pack.

2. Thermal characteristic of a single cell

When investigating the thermal management of the battery pack, it is significant to understand the mechanism of heat generation in the process of the battery’s charge and discharge first. Reaction heat, Ohmic heat, reversible heat and external terminal contact resistance heat are the heat sources associated with the operation of Li-ion batteries[4]. The reaction heat generation results from the transfer of electrons to or from the electrode, it may be exothermic or in the solid active materials and electrolyte, and it is dominant at high charge or discharge rate[9]. The total reversible heat generation is related to cathode and anode entropy changes while the last component of heat is due to the contact resistance between the cell terminals and the external interconnect.

2.1 Model development of a single cell

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery diameter</td>
<td>18mm</td>
</tr>
<tr>
<td>Battery height</td>
<td>65mm</td>
</tr>
<tr>
<td>Thickness of battery canister</td>
<td>0.25mm</td>
</tr>
<tr>
<td>Mandrel radius</td>
<td>2mm</td>
</tr>
<tr>
<td>Battery heat capacity</td>
<td>1399.1J/(kg·K)</td>
</tr>
<tr>
<td>Battery density</td>
<td>2055.2kg/m³</td>
</tr>
<tr>
<td>Thermal conductivity in X and Y direction</td>
<td>0.89724W/(m²·K)</td>
</tr>
<tr>
<td>Thermal conductivity in Z direction</td>
<td>29.557W/(m²·K)</td>
</tr>
<tr>
<td>Cathode material</td>
<td>LiMn2O4 Spinel</td>
</tr>
<tr>
<td>Anode material</td>
<td>Graphite</td>
</tr>
</tbody>
</table>

In this research, a coupled electrochemical thermal model is constructed to analysis the heat generation and temperature distribution in cell level. To reduce the computation time, the two-dimensional axisymmetric model is used instead of three-dimensional model. Heat generated by the one-dimensional model is used as the heat source for the two-dimensional axisymmetric model, the temperature of the two-dimensional axisymmetric model is used in the one-dimensional model. The relevant parameters are listed in Table1. And the energy balance equation is shown in Eq.1.

\[
\rho C_p \frac{dT}{dt} = \lambda \frac{\partial^2 T}{\partial x^2} + Q_{gen} \quad \text{(Eq.1)}
\]
Since the single-cell is made of several layers of materials, the thermal conductivity of the battery in the model is anisotropic. The thermal conductivity need to be calculated in the length direction and radius direction of the cell, separately, and the formula are shown as follows:

$$k_{T,r} = \frac{\sum L_i}{\sum L_i / k_{T,i}}$$  \hspace{1cm} (Eq.2)

$$k_{T,len} = \frac{\sum L_i k_{T,i}}{\sum L_i}$$  \hspace{1cm} (Eq.3)

Similarly, the density and specific heat capacity of active battery materials are calculated according to the formula below:

$$\rho_{batt} = \frac{\sum L_i \rho_i}{\sum L_i}$$  \hspace{1cm} (Eq.4)

$$C_{p,batt} = \frac{\sum L_i C_{p,i}}{\sum L_i}$$  \hspace{1cm} (Eq.5)

The calculated final parameters are listed in Table 1.

### 2.2 Heat generation of a single cell

![Heat generation of the cell during various C-rate of discharge](image)

**Figure 2** Heat generation of the cell during various C-rate of discharge

Fig 2 shows the intensity of heat generation in a 10 Ah Li-ion cell under nature convection during various rates of discharging calculated by the model. The maximum heat generation are 43386 W/m³, 86561 W/m³, 136140W/m³, 186920W/m³ and 251300W/m³ for 1C, 2C, 3C, 4C and 5C rate of discharge, respectively. The illustration indicates that the heat generation increase rapidly with the increase of the C-rate discharge, may be caused by the irreversible heat, mainly due to Ohmic heat, which is proportional to the cell’s internal resistance and the square of the current ($R_{int} I^2$). This indicates that the demand for heat dissipation is higher under high discharge rate.

### 2.3 Temperature distribution of a single cell

The temperature distribution within an 18650 cell at 5C discharge rate under nature convection (the convective heat-transfer coefficient is set as 5 W/(m² · K)) at 25 °C environment temperature for 5 minutes is shown in Fig 3. Temperature distribution varies in radius direction and length direction, this may due to the different thermal conductivity in the two directions as shown in Table 1. The picture shows that the internal temperature is higher than the surface of the cell, but it is difficult to dissipate the heat from the center of the battery directly[10]. Therefore, improving the structure of battery pack and enhancing the heat transfer efficiency between the cells surface and the heat transfer medium are main approaches to keep the battery in safe operation condition.

![Temperature distribution at 5C discharge rate under nature convection for 5 minutes](image)

**Figure 3** Temperature distribution at 5C discharge rate under nature convection for 5 minutes

### 3. Model development for battery pack

After investigating the heat generation intensity and temperature distribution in cell level, the heat dissipation scheme need to be considered for pack level research.

Different BTMS affects the performance, life time and investment of the battery pack, and the BTMS can be categorized into air, liquid, PCM, heat pipe, solid state TEMs or a combination of above according to the heat transfer medium[1]. Liquid cooling is at risk of leakage, PCM cooling has a high cost. Air cooling is preferred in electronic cooling generally as it is a bad conductor of electricity, it offers a strong resistance to any possible short circuit. Considering the simplicity, safety and low operation and maintenance cost of the air-based BTMS, it is used in some EV and HEV manufacturers. Due to the poor heat capacity and low thermal conductivity, some researchers have tried several ways to improve the air-cooling efficiency and reduce the inhomogeneity of temperature distribution, mainly through optimizing the structure of the flow channel[6, 7, 11, 12]. According to the above description, the airing cooling method with better economy and safety is adopted in the paper.

### 3.1 Structure design of battery pack

Compactness, safety and economy are the three main criteria for an optimum BTMS. Due to the limited space of the car, compact battery is required, so the structure of the battery pack needs to be properly designed. There are two main cooling structures for air cooling as shown...
in Fig 4 according to the literature[7, 11]. Fig 4 (a) and (b) shows the Z-type and U-type air cooling structures of the BTMS, respectively.

In this research, the U-type and Z-type structures are used and compared to investigate the temperature distribution of air-cooling-based battery pack composed of 32 18650 cells through the CFD method. And the relevant parameters of the battery pack are selected similar with the Ref[7], which found that \( W_4 \) equal to \( W_{\text{out}} \) is the optimal structure for Z-type, but U-type is different. The parameters of the structures are summarized in Table 2. For the The side view and related parameters of the two structures adopted in this paper are shown in Fig 5.

![Figure 4 Structures of air cooling based BTMS. (a)U-type. (b)Z-type](image)

**Figure 4 Structures of air cooling based BTMS. (a)U-type. (b)Z-type**

### 3.2 Model development for battery pack

The COMSOL Multiphysics software is used to investigate the temperature distribution and flow field, which is difficult to be observed in experiment. The conjunct heat transfer module for heat transfer and laminar flow is used, and the governing equation are shown as follows.

\[
\rho C_p \frac{dT}{dt} = \lambda \frac{\partial^2 T}{\partial x^2} + Q_{\text{gen}} \quad \text{(Eq.6)}
\]

\[
\frac{\partial \rho}{\partial t} + \frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} + \frac{\partial \rho w}{\partial z} = 0 \quad \text{(Eq.7)}
\]

For heat transfer equation, the thermal conductivity coefficient density, and specific heat capacity of the cells are the same as the single cell listed in Table1, the heat source is selected as 80000W/m^3, which is the heat generation for 900s 3C discharge as shown in Fig 2. For the initial and boundary conditions, the mass flow rate is chosen constant, the inlet air temperature is selected as 25°C. At the interface of the cell, a no-slip boundary condition is applied, as well as continuity of heat flux between the cell and the flowing air.

32 pieces of 10Ah 18650 cells are assembled according to eight series and four parallel (8S4P) connection, and side views are shown in Fig.5. The steady-state simulation is selected to investigate the influence of air flow rate on temperature distribution, which is chosen as 0.001, 0.003, 0.005, 0.01-0.05 kg/s increased by 0.005 kg/s, respectively, through the parametric scanning method. Besides, three domains probes were defined to determine the maximum, average and minimum temperature of the 32 cells.

**Table 2 relevant parameters of the battery pack**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell spacing</td>
<td>2mm</td>
</tr>
<tr>
<td>Length of entrance, Lin</td>
<td>40mm</td>
</tr>
<tr>
<td>Length of exit, Lout</td>
<td>40mm</td>
</tr>
<tr>
<td>Width of airflow inlet, ( W_{\text{in}} )</td>
<td>20mm</td>
</tr>
<tr>
<td>Width of airflow outlet, ( W_{\text{out}} )</td>
<td>20mm</td>
</tr>
<tr>
<td>The plenum width, ( W_1 ) (U-type)</td>
<td>8mm</td>
</tr>
<tr>
<td>The plenum width, ( W_2 ) (U-type)</td>
<td>10mm</td>
</tr>
<tr>
<td>The plenum width, ( W_3 ) (Z-type)</td>
<td>5mm</td>
</tr>
<tr>
<td>The plenum width, ( W_4 ) (Z-type)</td>
<td>20mm</td>
</tr>
<tr>
<td>Number of cells in X direction</td>
<td>8</td>
</tr>
<tr>
<td>Number of cells in Y direction</td>
<td>4</td>
</tr>
</tbody>
</table>

### 4. Results and analysis

Battery temperature and uniformity have a strong influence on the availability of the charging and discharging power. A temperature difference of 5°C would lead to about 10% degradation of power capability, and an increasement of 25% of thermal aging kinetics[13]. Hence, variation of temperature across the battery pack should be kept within 5°C. The influence of air mass flow rate on temperature of the batteries and
the temperature distribution of U-type and Z-type air-cooling based structures are investigated in the following section.

### 4.1 Effect of air mass flow rate

The maximum temperature and temperature uniformity of the battery has significant influence on its performance and life. The changes of battery surface temperature with air mass flow rate of the two configurations are shown in Fig 6. Overall, the greater the air mass flow rate, the lower the average, maximum and minimum temperature. This can be explained as: with the increase of air flow rate, the convection heat transfer coefficient increases, then the heat exchange between the battery and air increases, which making the battery temperature drop in time.

For the U-type configuration, as shown in Fig 6 (a), temperature decreases rapidly with the increase of air mass flow rate, the maximum temperature less than 30 ℃ and temperature difference less than 5 ℃ , when the air mass flow rate reaches 0.02 kg/s. However, for the Z-type configuration, as shown in Fig6 (b), temperature decreases relatively slowly with the increase of air mass flow rate, the maximum temperature still larger than 30 ℃ and the temperature difference still larger than 5 ℃ even when the air mass flow rate reaches 0.06 kg/s.

That is to say, the U-type structure can reach safety operation condition, for which the variation of temperature with 5 ℃ when air mass flow rate reaches 0.02kg/s. However, it is hardly to satisfy the requirement of temperature uniformity for Z-type structure. In this respect, the U-type structure has advantages for air-based BTMS compared with the Z-type structure.

### 4.2 Temperature distribution

As described earlier, temperature inconsistency of battery pack will increase the capacity inconsistency of single cell, which will cause the overall performance of battery pack decline rapidly. In this section, the temperature distribution of the battery is mainly analyzed.

Due to temperature distribution of the cells is related to air mass flow rate, the temperature distribution for Z-type and U-type at air mass flow rate 0.001, 0.01, 0.025, 0.05 kg/s are selected and shown in Fig 7. When the air mass flow rate is set as 0.001 kg/s, as shown in Fig.7 (a) and (e), the high temperature occurs at the downstream and upstream in the air flow direction for U-type and Z-type, respectively. When the air flow rate increase to 0.01 kg/s, as shown in Figure 7 (b) and (f), the high temperature area still appears at the upstream in the air
flow direction for Z-type, but it seems that there are no obvious boundary of high temperature area and low temperature area for U-type configuration. Then, as the air mass flow rate continues increasing, the overall temperature of the battery pack shows a downward trend for both the U-type and Z-type structure. However, the areas of high temperature and low temperature are the same as the distribution of 0.01 kg/s air mass flow rate.

![Figure 8 Velocity distribution in the middle section](image)

The two different results can be explained by the velocity profile shown in Fig 8, which shows the velocity distribution of U-type and Z-type configuration at 0.02 kg/s air mass flow rate. The velocity distribution uniformity is better of U-type, results in the uniform heat transfer coefficient, then lead to the temperature uniformity. On the contrary, velocity in upstream of the air flow direction of Z-type are obvious lower than the downstream, result in the lower heat transfer coefficient, then lead to the high temperature in the upstream area.

5. Conclusions

This paper investigates two structures for air cooling based Li-ion BTMS, the U-type and Z-type air cooling structures are used to study the effect of air mass flow rate on the cell’s temperature and temperature distribution in battery pack. And we found that for the same cells configuration and heat generation, temperature difference can be less than 5°C when the air mass flow rate is larger than 0.02 kg/s for U-type configuration, but the Z-type have not achieve the requirement of temperature uniformity at the simulated range of air mass flow rate. Besides, the maximum temperature distribution area is analyzed, simulation results show that the maximum temperature appears at the first column in the airflow direction for Z-type structure, and it mainly related to the velocity field distribution, the lower the velocity, the lower the heat transfer coefficient, then the heat generated by the cells cannot be dispersed in time, then resulting in high temperature.

Acknowledgement

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Reference