A thermal-optimal design of lithium-ion battery for the container storage system

Hong Shi1 | Wenbing Xu1 | Xinlong Zhu1 | Junyi Wang1 | Kaijie Yang2 | Yitao Zou2 | Zhaolin Chen2

1College of Energy & Power Engineering, Jiangsu University of Science and Technology, Jingkou, China
2Key Laboratory of Aircraft Environment Control and Life Support, MIIT, Nanjing University of Aeronautics & Astronautics, Nanjing, China

Correspondence
Hong Shi, College of Energy & Power Engineering, Jiangsu University of Science and Technology, 2 Mengxi, Jingkou, Zhenjiang 212003, China. Email: shihong@nuaa.edu.cn

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Abstract
In this paper, the permitted temperature value of the battery cell and DC-DC converter is proposed. The flow and temperature field of the lithium-ion batteries is obtained by the computational fluid dynamic method. Thus, the package structure of the battery pack is optimized based on four influencing factors. The results indicate that (1) setting a new inlet on the wall, I can improve ventilation and the inlet is better located below the waist of the battery pack. (2) Air inlet location close to the fan is easy to generate short air circuit, which leads to DC-DC converter in poor condition of heat dissipation. (3) Adjusting the size of the air inlet mainly affects the temperature distribution of the cells but has little effect on the temperature of the DC-DC converter. (4) Regulating the gap size can enhance the cell temperature uniformity. (5) The optimized battery pack structure is obtained, where the maximum cell surface temperature is 297.51 K, and the maximum surface temperature of the DC-DC converter is 339.93 K. The above results provide an approach to exploring the optimal design method of lithium-ion batteries for the container storage system with better thermal performance.

KEYWORDS
air cooling, computational fluid dynamic method, container storage system, heat dissipation, lithium-ion battery

1 | INTRODUCTION

Energy storage system (ESS) provides a new way to solve the imbalance between supply and demand of power system caused by the difference between peak and valley of power consumption.1–3 Compared with various energy storage technologies, the container storage system has the superiority of long cycle life, high reliability, and strong environmental adaptability, which attracts more and more attention.4,5 The ESS has some vertical racks, equipped with a battery management system, a heating ventilation air conditioning system, and a fire detection and suppression system.6,7 Unfortunately, there were many energy storage battery fires in previous years.8–10 A Korean government report indicated that a significant factor in the cause of the fires was the thermal runaway of batteries.11 Therefore, a well-designed battery thermal management system (BTMS) is highly needed.12–14 It has been found that air cooling is currently the most widely used cooling method due to its low manufacturing cost, low energy consumption, and low layout requirements.15–18
Many scholars have done some research on the forced-air convection. Li et al. investigated the influence of air inlet angle, air outlet angle, and battery spacing on the maximum and the minimum temperature of the cells. Multiple iterations are often utilized to obtain the optimal local scheme of the air-cooling heat dissipation structure. Fan et al. reported that improving the spacing of cells to some extent would enhance the uniformity of battery heat distribution but increase the maximum temperature of the cell in the meantime. Wang et al. studied the effects of the width and the ventilation location on the heat dissipation of the batteries. Mahamud and Park demonstrated that the reciprocating airflow for cooling would improve temperature uniformity and reduce cell temperature.

To sum up, the earlier works concentrate more on the air supply parameters and the layout of the cells. However, the container storage system generally uses normalized commercial cells, in which the cell arrangement is fixed. Therefore, the above results are not suitable for solving lithium-ion batteries with serious heat dissipation problems for the container storage system. In addition, due to the low specific heat capacity and thermal conductivity of air, the application of forced-air cooling in the problem of battery heat dissipation with high heat flux needs further research.

In this paper, a parametric study is conducted to analyze both the peak temperature and the temperature uniformity of the battery cells. Furthermore, four factors, including setting a new inlet, air inlet location, air inlet, and gap size between the cell and the back wall on the thermal performance of the battery pack, are investigated. Finally, the optimal structure of the heat dissipation is given. The achieved results can provide technical reference for the BTMS of the container storage system.

2 | THEORY AND MATHEMATICAL MODELING

2.1 | Mathematical modeling

The mathematical model is the basis of CFD calculation. The following fluid flow and energy equations are shown as follows:

Conservation of mass (continuity):
\[ \nabla \cdot V = 0 \]  \hspace{1cm} (1)

Conservation of momentum:
\[ \frac{\partial (\rho V)}{\partial t} + V \cdot \nabla (\rho V) = - \nabla p + \mu \nabla^2 V \]  \hspace{1cm} (2)

where \( V \) is velocity vector, \( p \) is pressure, and \( \rho \) and \( \mu \) are density and viscosity of coolant, respectively.

Conservation of energy:
\[ \frac{\partial (\rho C_p T)}{\partial t} + V \cdot (\rho C_p T) = \nabla \cdot (k \nabla T) + \cdot q \]  \hspace{1cm} (3)

where \( k \) is thermal conductivity, \( C_p \) is specific heat, and \( \cdot q \) is volumetric heat generation rate in the battery.

2.2 | Model of the battery pack cooling system

The battery pack is composed of 16 polymer lithium iron phosphate powered cells, a DC-DC (Direct current to direct current) converter, and five coolant channels. The battery pack has its dimension of 864.8 mm in length, 785 mm in width, and 201 mm in height. The specification parameters of cells are listed in Table 1. The geometry of the battery pack is shown in Figure 1(A), and the definition of structural part number is shown in Figure 1(B).

2.3 | Boundary conditions and performance indexes

Boundary conditions are set as realistic as possible, which are presented in Table 2.

The battery pack cooling system has three evaluation indexes: (1) The operating temperature of the battery surface is 283–308 K. (2) The maximum temperature difference between the cells is 5 K. (3) The maximum surface temperature of the DC-DC converter is 343 K.

2.4 | Mesh sensitivity study

The structured mesh is built by ANSYS ICEM 18.0. To select the appropriate grid number, five different grid numbers of 1.4, 2.1, 2.8, 3.5, and 4.2 million are selected for meshing validation. When the number of grids exceeds

| Parameter                          | Value          |
|-----------------------------------|----------------|
| Nominal capacity/Ah               | 60             |
| Nominal voltage/V                 | 3.2            |
| Internal resistance/mΩ            | ≤1.0           |
| Maximum charge/discharge rate     | 1/2            |
| Size/mm                           | 173.6 × 152 × 137.5 |
2.8 million, the average temperature of the battery surface and DC-DC converter surface tends to be constant. Therefore, a grid of 2.8 million cells is selected for the whole simulation computational domain.

2.5 | Algorithm verification

The heat dissipation experiment results in the literature are used to verify the reliability of the simulation algorithm in this paper. Figure 2 shows the comparative analysis results of BTMS simulation with different eddy-viscosity turbulence models.

From Figure 2, the numerical simulation results by the k-ω SST model and the experimental results are consistent. Therefore, the k-ω SST model is preferred over the other models for CFD simulation of BTMS.

3 | RESULTS AND DISCUSSIONS

Figure 3 shows the flow and temperature fields inside the battery pack under initial conditions.

Figure 3(A) shows three high-temperature regions (A, B, and C) in the battery pack. The main reason for the above phenomenon is that the channel between the sidewall of the battery pack and the cell is wider than that of among the cells. Then, most cooling air flows through this channel to the fan, shown in Figure 3(C). Since the regions of A and B are close to the fan, less cooling air flows to the channels in the cells, resulting in poor heat dissipation performance in parts A and B. This could cause some cells to be thermal runaways, such as cell No. 5, No. 6, No. 13, and No. 14, and even spread excessive heat throughout the pack. The maximum surface temperature of the DC-DC converter is up to 435.4 K, which is higher than the design requirement. As stated in Figure 3(B), the high-temperature area is located on the inner ring of the DC-DC converter.

From the above results, the thermal performance of the battery pack of the initial condition does not meet the design requirements and needs to be improved. The procedure of optimization is shown schematically in Figure 4.

According to the flow and temperature fields in the initial condition, we initiate the optimization by firstly mounting a suitable new air inlet (Inlet III) in wall I. On this basis, we adjust the air inlet location, air inlet size,
and gap size progressively. Thus, the final optimization structure of the battery pack is achieved.

4 | INFLUENCING FACTORS OF THE HEAT DISSIPATION PERFORMANCE

4.1 | Setting a new air inlet in the wall I of the battery pack

The cell arrangement is fixed because of the layout limitation of the battery pack. Therefore, the heat dissipation performance can be improved by adjusting the packaging structure. Due to the poor fluidity of the initial condition, a new inlet is set on the wall I of the battery pack to improve the airflow ventilation, as shown in Figure 4. Figure 5 shows the temperature fields of the battery pack under four different inlet size conditions.

From Figure 5, the temperature distribution of the battery cells in Case 1(d) is relatively better. The location of the new air inlet at the bottom side is conducive to airflow through the gap space at the bottom of the cells, and the cells can be thoroughly cooled. Therefore, Case 1(d) provides a better solution for structural design.

4.2 | Air inlet location

In order to evaluate the influences of air inlet location on the heat dissipation performance of the battery pack, six inlet locations were designed; the six inlet locations on the sidewall (wall II and wall III) are shown in Figure 4.

Figure 6(A) shows the maximum cell surface temperature under different air inlet location conditions, and Figure 6(B) depicts the temperature distribution of DC-DC converter at different air inlet positions.

As shown in Figure 6(A), in Case 2(f), the maximum surface temperature of cells 2 and 3 is about 310 K, which is significantly higher than that of other inlet locations. In Figure 6(B), Case2(c) showed the DC-DC converter’s best surface heat dissipation performance, indicating a maximum surface temperature of 344.99 K. The reasoning behind this observation is that the air inlet location is close to the fan will lead to an air short circuit phenomenon. Thus, less cooling air flows to the channels in the cells and the DC-DC converter, leading to the DC-DC converter’s heat transfer performance being worse. Also, when the air inlet location is away from the DC-DC converter, more cooling air flows to up space of the battery pack, and there is also less cooling air blowing over the DC-DC converter. Therefore, Case 2(c) is an optimal location of the air supply inlet.

4.3 | Air inlet size

Air inlet size dramatically impacts the cooling effect and temperature uniformity due to the airflow velocity and direction. The air short circuit phenomenon between battery cells is explored, shown in Figure 7(A). The influence of the air inlet size on the heat dissipation performance of the battery pack is discussed with the constant airflow...
FIGURE 4  Progressive optimization of battery pack structure
rate. Four different inlet dimensional measures are concerned with the constant airflow rate in this paper, as shown in Figure 4.

Figure 7(B) shows the temperature field of the battery pack under different air inlet size conditions. The thermal behaviors of cell No. 4, cell No. 8, cell No. 12, and cell No. 16 are not good compared with the other cells. When the air inlet size decreases, the inlet air path is more greatly affected by fan 1, and most of the inlet air flows to the front of the battery pack. Thus, little air flows to the back of the battery pack, resulting in the high-temperature area generated on cells 4 and 16. However, if the air inlet size is too large, the air velocity will be smaller, and the cooling efficiency will also be affected. Case 3(b) shows the best thermal performance of the battery pack, where the maximum cell surface temperature is 297.09 K.

4.4 | Gap size between the battery cell and the back wall

The gap size \(D_0\) also has a significant influence on the heat dissipation of the cells; the blowing scope is enlarged as the \(D_0\) value increases. In order to evaluate the influences of the \(D_0\) value on heat dissipation performance of the battery pack, four different \(D_0\) values (8, 14, 20, and 26 mm) are selected, as shown in Figure 4.

Figure 8(A) shows the maximum cell surface temperature with different \(D_0\) values. Figure 8(B) demonstrates the temperature contours of the DC-DC converter with different \(D_0\) values.

From Figure 8(A), at 20 and 26 mm values, the surface temperature of the cells presents a better uniformity, and the maximum cell surface temperature is relatively low. When \(D_0\) increases, the air flows into the upper space from the inlet III in the wall I rise, and the blowing scope increases. The relation between the two flow mechanisms is very complicated, which leads to an optimal solution for \(D_0\) value.

From Figure 8(B), the increase in \(D_0\) is beneficial to decreasing the maximum temperature of a DC-DC converter. The results present little change when it increases to a particular value. Considering the temperature distribution of the cells and the DC-DC converter, \(D_0 = 20\) mm delivers the best thermal performance.

Eventually, the optimization of the heat dissipation of the battery pack is completed. The maximum temperature of the cells reaches 297.51 K, and the maximum temperature of the DC-DC converter reaches 339.93 K. Moreover, the maximum temperature difference between cells is 4.5 K. All the above indexes are meet the design requirements.

5 | CONCLUSION

This work focuses on the heat dissipation performance of lithium-ion batteries for the container storage system. The
FIGURE 6  Temperature distribution at different air inlet positions. (A) Maximum cell surface temperature under different air inlet location conditions. (B) Temperature distribution of DC-DC converter at different air inlet positions.
FIGURE 7  Different airflow and temperature distributions at different air inlet sizes. (A) Air short circuit phenomenon. (B) Temperature distribution of battery pack at different air inlet sizes
FIGURE 8 Temperature distribution with different $D_0$ values. (A). Maximum cell surface temperature with different $D_0$ values. (B). Temperature distribution of the DC-DC converter
CFD method investigated four factors (setting a new air inlet, air inlet position, air inlet size, and gap size between the cell and the back wall). The effects on cooling effectiveness are studied, and the optimized battery pack structure is obtained. The conclusions can be drawn as follows:

1. A new rectangular inlet (410 mm × 75 mm) on the wall I of the battery pack increases the intensity of ventilation and heat dissipation. (2) The inlet location in the middle of the battery pack sidewalls (wall II and wall III) presents good thermal performance, which is mainly conducive to the heat dissipation of the DC-DC converter. (3) The inlet size of 100 mm × 35 mm shows the best thermal performance, where the maximum cell surface temperature is 297.09 K. Air short circuit phenomenon will be generated when the inlet size is too small. (4) When $D_o$ increases, the air flows into the upper space from the inlet III in the wall I rise, and the blowing scope increases. And 20 mm is the optimal value of $D_o$. (5) The optimized model satisfies the design requirements. The maximum temperature of the cells reaches 297.51 K, and the maximum temperature of the DC-DC converter reaches 339.93 K.

**NOMENCLATURE**

- $D_o$: gap between the battery cell and the back wall (mm)
- $T$: temperature (K)
- $t$: time (s)
- $\Delta T$: temperature difference (K)
- $p$: coolant fluid flow pressure (Pa)
- $V$: coolant fluid flow velocity (m/s)
- $c_p$: specific heat of coolant (kJ/kg.K)
- $\dot{q}$: volumetric heat generation rate (W/m³)
- $\phi$: universal variable
- $\rho$: density
- $\mu$: dynamic viscosity of coolant (kg/m s)

**ORCID**

Hong Shi [https://orcid.org/0000-0002-2534-1501](https://orcid.org/0000-0002-2534-1501)

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