Research on Optimization Strategy of Forced Convection Heat Dissipation for Super Capacitor Energy Storage Power Supply

Jun Zhang, Zhongcheng Jiang, Jixiong Jiang, JingJing Chen and Li Zhou

Abstract The service life of the super capacitor is very sensitive to the temperature. In order to obtain the optimization strategy of forced convection heat dissipation for super capacitor energy storage power, the main factors affecting the efficiency of forced convection heat dissipation are analysed based on the heat transfer theory, and the main direction of heat dissipation optimization are determined. The numerical heat transfer calculation model is established by the method of computational fluid dynamics. The internal flow field and temperature field distribution characteristics of super capacitor power supply are analysed. And the influence of cold air volume flow rate, air outlet layout and super capacitor heat dissipation structure on the heat dissipation effect is calculated and compared. The results show that the super capacitor heat dissipation structure and air outlet layout are most obvious to the improvement of heat dissipation. The maximum temperature of super capacitor is reduced to 32.62 °C from 68.69 °C through optimization in the same ventilation air volume flow rate and temperature. The improvement effect is very obvious.

Keywords Super capacitor · Forced convection · Heat dissipation
Computational fluid dynamics

1 Instruction

Super capacitor is a new energy storage component, which is different from conventional capacitance, its capacity can be thousands farad. It has the advantages of high power density of conventional capacitors and high energy density of battery, fast charge and discharge, and long service life, has developed into a new, efficient,

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practical energy storage device. In recent years, super capacitor has been applied in urban rail vehicles [1]. In order to achieve the long distance continuous operation, the super capacitor energy storage power supply complete charging in a short time at the stop by the high efficient charging and discharging performance.

The super capacitor will produce thermal loss due to its internal resistance during the working process. The heat generated by internal resistance causes the temperature rise. Forced ventilation cooling is usually used to dissipate heat from the super capacitor energy storage. Based on the heat dissipation of super capacitor energy storage power supply, the optimization direction and strategy of forced ventilation heat dissipation are studied in this paper.

2 Introduction of Super Capacitor Energy Storage Power Supply

In order to form a large energy storage capacity and a certain working current and voltage, a super capacitor module is usually connected in series and in parallel, as shown in Fig. 1. The super capacitor module is composed of super capacitor monomer, electrode connecting copper, module skeleton, single isolation strip, and module equalizer circuit board. A gap of 3 mm between each monomer is used for ventilation and is separated by isolation strips. The ventilation holes of copper and circuit board correspond to the gap between the module, and the air can pass up and down through these gaps.

Through the layer arrangement of the module, a complete super capacitor energy storage power supply is formed, as shown in Fig. 2. According to the working current and internal resistance of the super capacitor energy storage power, the total heating power is 681 W. The cold air of the air conditioning system in the vehicle passenger compartment is used as the forced convection cooling medium of the super capacitor energy storage power supply.

3 Theoretical Analysis

The air conditioning cold air is used in the ventilation cooling of super capacitor energy storage power supply, which is a typical physical process of forced convection heat transfer. Each super capacitor is a heat source. The cold air flows through the gap between each monomer. The heat of the super capacitor is removed through the convective heat transfer between the cold air and the surface of the super capacitor, which is the process of heat dissipation.

The heat calculation formula of convection is given by Newton cooling formula (1) [2].

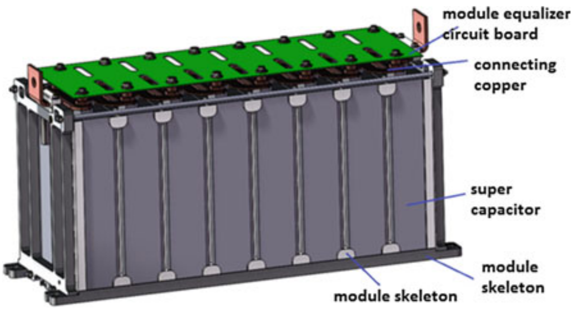

Fig. 1 Super capacitor module

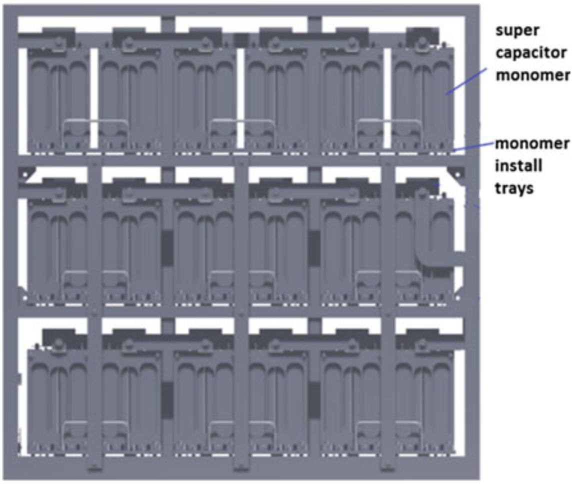

Fig. 2 Super capacitor energy storage power supply

$$q = h \cdot \mathrm{A} \cdot \Delta t \tag{1}$$

where q is the heat flow through an unit area in an unit time; h is convective surface heat transfer coefficient; Δt is the mean temperature difference between a solid surface and its surrounding fluid.

The convective surface heat transfer coefficient is a very important parameter. Newton cooling formula only gives its definition formula. Its value is related to many factors, including the physical properties, movement state, phase change, and the shape and size of the solid heat transfer surface [1]. Taking the single-phase forced convection heat transfer as an example, when the high speed flow is excluded, the surface heat transfer coefficient can be expressed as a function which is shown in the formula (1.2) [3].

$$h = f\left(u, l, \rho, \mu, \lambda, c_p\right) \tag{2}$$

where u is the velocity of fluid flow; l is a characteristic length of solid heat transfer surface; ρ is the density of the fluid; μ is the dynamic viscosity of fluid; λ is the coefficient of thermal conductivity of fluid; c_p is the specific heat capacity of fluid [4].

From the formula (1), it can be seen that increasing the heat dissipation area and the temperature difference between fluid and solid can improve the efficiency of convection heat dissipation. Because of the limits of the volume and weight of the super capacitor energy storage power supply, the method of enlarging the heat dissipation area will greatly increase the system complexity. Lowering the cooling air temperature can increase the temperature difference between fluid and super capacitor to enhance heat dissipation efficiency. Because the air conditioning system temperature is determined by the HVAC design, reducing the cold air will affect the comfort of passengers. These methods are not desirable.

It can be seen from the formula (2) that convection cooling efficiency can be improved by changing the physical properties of the fluid, increasing the flow velocity of the fluid and changing the geometry dimensions of the object. When the ambient temperature is certain, the physical parameters of the air are constant. If the parameters such as the thermal conductivity of the fluid can be improved by changing the cooling medium, the complexity of the cooling system will be increased, and the system design of the vehicle will be greatly affected. It is almost impossible. When the volume and weight of the energy storage power can not be changed, the characteristic length of convective heat transfer is constant. Therefore, the thermal efficiency of super capacitor can only be improved by increasing the velocity of air flow [5].

Improving the flow velocity of the surface air of the super capacitor can be realized by increasing the air flow and optimizing the local flow characteristics. In this paper, computational fluid dynamics method is used to calculate the three-dimensional temperature field of super capacitor energy storage power, and determine the optimization strategy of super capacitor heat dissipation.

4 Numerical Calculation Model

The fluid and solid calculation domain are discretized by hexahedral mesh. The turbulence model is used to simulate. And the commercial computational fluid dynamics software based on the finite volume method is used to calculate [6, 7].

Using the simplified geometric model, a very fine hexahedral calculation grid is established, and the calculation region is discretized. The overall schematic diagram of the grid is shown in Fig. 3, and the fluid domain body grid and partial surface mesh are hidden for visual convenience [8, 9].

The super capacitor energy storage power supply is installed inside the passenger compartment. Both inside and outside of the box are cold air provided by the air conditioning system, the temperature difference between inside and outside is very small. In order to simplify the calculation, the temperature difference between

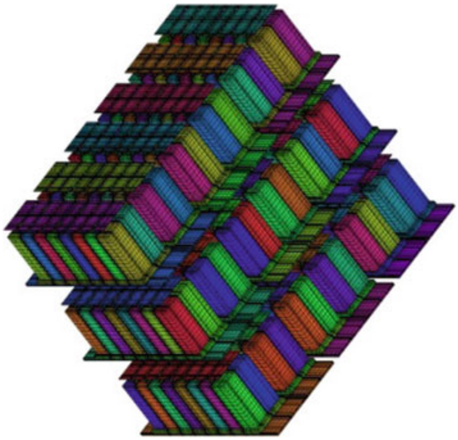

Fig. 3 Mesh model of numerical calculation

the inside and outside of the box is ignored, so the convective heat transfer of the inner air and the super capacitor energy storage power supply box wall can be ignored.

The ideal gas is used to calculate, considering the change of air density with the change of temperature, the other physical properties of air are approximately determined as constant. The super capacitor monomer is approximated to be a homogeneous heating body, and its equivalent thermal physical properties are shown in Table 1.

The air inlet of the ventilation system is set to the velocity inlet boundary condition. The inlet velocity is calculated according to the ventilation air flow volume. The inlet air temperature is 20 °C. Pressure export boundary conditions are used for air outlet of the ventilation system. The pressure is 1 ATM. The wall of box is set as no slip adiabatic wall boundary.

Ignoring the transient process of super capacitor temperature, all simulation calculations are steady-state calculation.

5 Calculation Results and Analysis of Initial Scheme

For the initial scheme, the cold air temperature is 20 °C, the cold air volume flow rate is 400 m^3/h. The air inlet size is 250 mm × 100 mm, the size of each air outlet is 110 mm × 110 mm. The layout of the four air outlets is shown in Fig. 4.

Table 1 Equivalent physical properties of super capacitor monomer

Physical properties	Density kg/m^3	Specific heat capacity J/(kg K)	Thermal conductivity W/(m K)
Value	810	2265	0.7

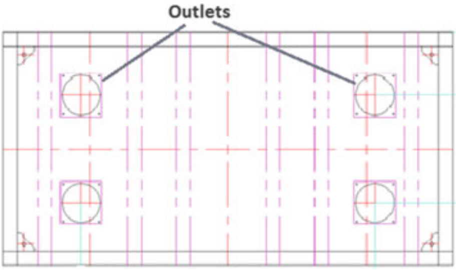

Fig. 4 The layout of the four air outlets

The simulation model is established, and the numerical solution and post-processing are carried out. The maximum temperature of the super capacitor is 68.69 °C. The highest air temperature is 59.29 °C. The average outlet air temperature is 24.82 °C. Figure 5 is the temperature distribution cloud picture at the symmetrical section. Figure 6 is the velocity distribution cloud picture at the symmetrical section. Figure 7 is the air flow trace picture.

As shown in Fig. 5, the internal temperature distribution in the super capacitor box is very uneven. The highest temperature of the middle two of the third layer module is 68.69 °C. This is obviously not the best working temperature for the super capacitor. The initial scheme should be improved.

As shown in Figs. 6 and 7, the air flow velocity distribution uniformity is very poor. The air velocity is high between the super capacitors in the first layer of super capacitor module, which is low in the second and the third layer. The gap between the super capacitor installation trays is relatively large; the air flow velocity through this gap is very high. In particular, the air velocity between the tray and the wall

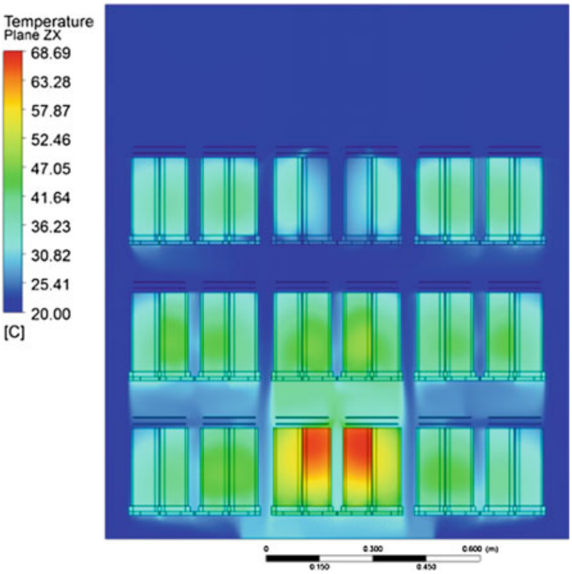

Fig. 5 The temperature distribution cloud picture at the symmetrical section

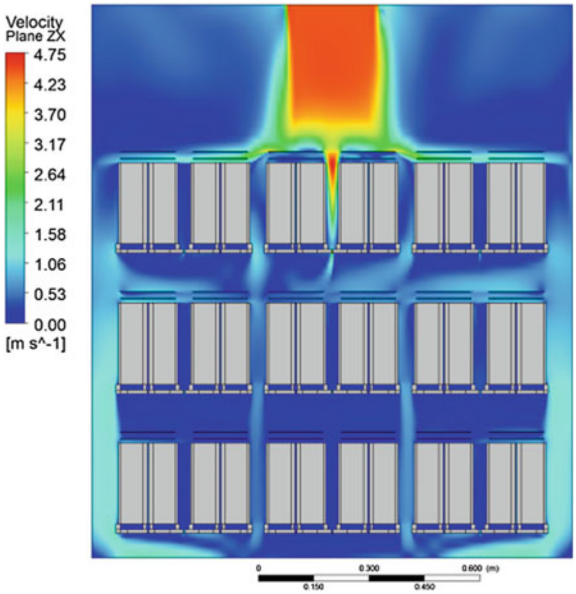

Fig. 6 The velocity distribution cloud picture at the symmetrical section

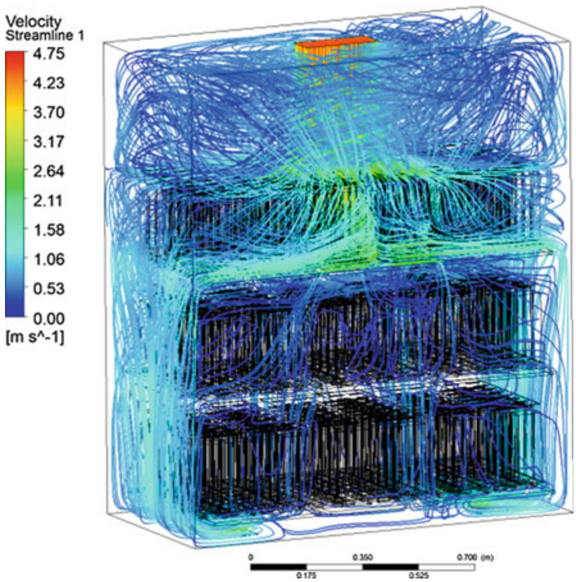

Fig. 7 The air flow trace picture

surface of the box is very large. Figure 7 is the trace of 500 random selected massless particles from the inlet through the entire fluid domain driven by the velocity vector field. As shown in Fig. 7, the particles flow between the super capacitor monomers in the second and third layer modules are very few and the flow velocity is very low.

Because the four outlets are located at the bottom of the left and right trays of the third layer module, there is almost no particle flow through the middle tray in the third layer module. The arrangement of the outlet is also the cause of the high temperature of the super capacitor in the third layer module.

According to the mechanism of forced convection heat transfer, the higher the flow velocity on the surface of the high temperature object, the greater the heat transfer in the unit time. The cooling efficiency of the super capacitor can be improved by increasing the flow velocity at the surface of the super capacitor.

According to the analysis of the above calculation results, in order to improve the ventilation and heat dissipation effect of the super capacitor box, reduce the maximum capacitance temperature, can be optimized from the following aspects.

The first, increase the air volume flow rate: by increasing the total air volume flow rate of the heat dissipation, the air velocity in the super capacitor box can be increased, so as to accelerate the convective heat transfer and reduce the maximum temperature of the super capacitor.

The second improve outlet arrangement: Add two air outlets below the intermediate tray in the third layer module. Improve the cooling effect of the intermediate super capacitor in the third layer, thereby reducing the maximum temperature of the super capacitor.

The third, adjust the gap between the trays: by adjusting the gap between the tray and the gap between the tray and the wall of the box, solve the problem of uneven internal velocity distribution, so that the air flow velocity between the super capacitor monomer can be increased under the same air volume flow rate, so as to accelerate the convective heat transfer.

6 Effect of Increasing Air Volume Flow Rate

When the air volume flow rate is increased by half to 600 m^3/h, the maximum temperature of the super capacitor box is 60.94 °C. The highest air temperature is 57.75 °C. The average outlet air temperature is 23.33 °C. The calculation results show that the heat dissipation efficiency can be improved by increasing the air volume flow rate. But the maximum temperature of the super capacitor is still relatively high. Super capacitor cooling efficiency can still be further improved.

7 Effect of Improved Air Outlet Layout

Add two air outlets below the intermediate tray in the third layer module. The added outlets is in the middle of the original outlets, as shown in Fig. 8.

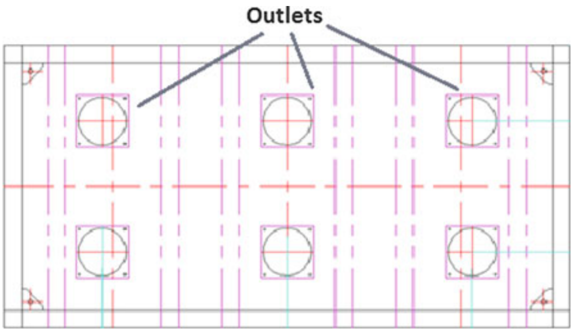

Fig. 8 Improved air outlet layout

For the improved air outlet layout scheme, the cold air temperature is 20 °C, the cold air volume flow rate is 400 m^3/h. Through calculation, the internal maximum temperature of the super capacitor is 54.36 °C. The highest air temperature is 50.67 °C. The average outlet air temperature is 25.12 °C. Figure 9 is the temperature distribution cloud picture at the symmetrical section.

Figure 9 shows that the overall temperature distribution is much more uniform than Fig. 4 (initial scheme). And the maximum capacitance of super capacitor also decreased about 14 °C, indicating that the improved outlet layout has obvious effect on heat dissipation. The scheme is better than adding half of the air volume flow rate, and the scheme does not increase the load of the air conditioning system. It is suggested to adopt this improved outlet layout scheme in the project.

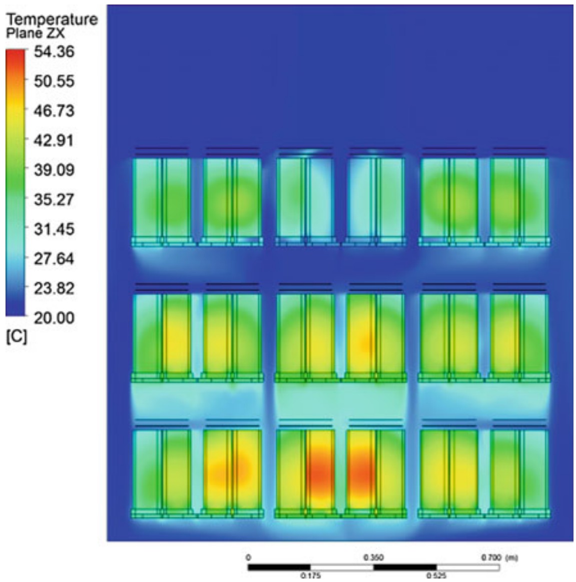

Fig. 9 The temperature distribution cloud picture at the symmetrical section

8 Effect of Improvement of Internal Flow Field

In order to improve the uniformity of the velocity field, adjust the gaps to 5 mm between the trays. The gaps between the module trays and the walls are canceled. Improved six outlets layout scheme is adopted. The cold air temperature is 20 °C, the cold air volume flow rate is 400 m^3/h.

Through calculation, the internal maximum temperature of the super capacitor is reduced to 32.62 °C. The highest air temperature is 30.90 °C. The average outlet air temperature is 25.04 °C. Figure 10 is the temperature distribution cloud picture at the symmetrical section. Figure 11 is the velocity distribution cloud picture at the symmetrical section.

As shown in Fig. 10, the temperature distribution of each super capacitor module is very uniform. The temperature of the first layer super capacitor is the lowest. The temperature of the second and third layer modules increased slightly in turn. The highest temperature is only 32.62 °C. And the improvement effect is remarkable compared with the initial scheme. As shown in Fig. 11, the flow velocity distribution is also very uniform.

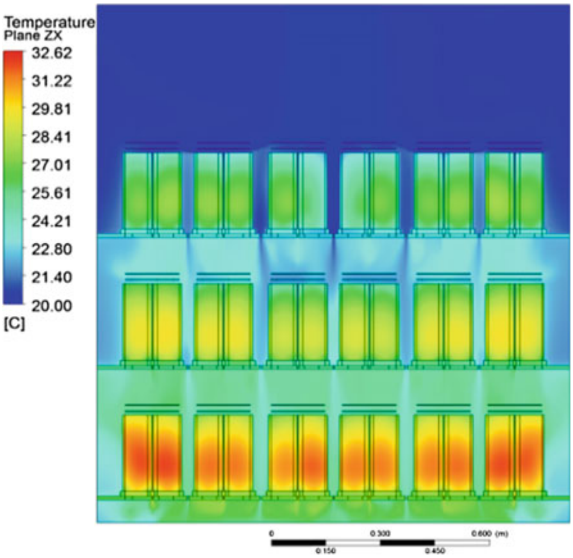

Fig. 10 The temperature distribution cloud picture at the symmetrical section

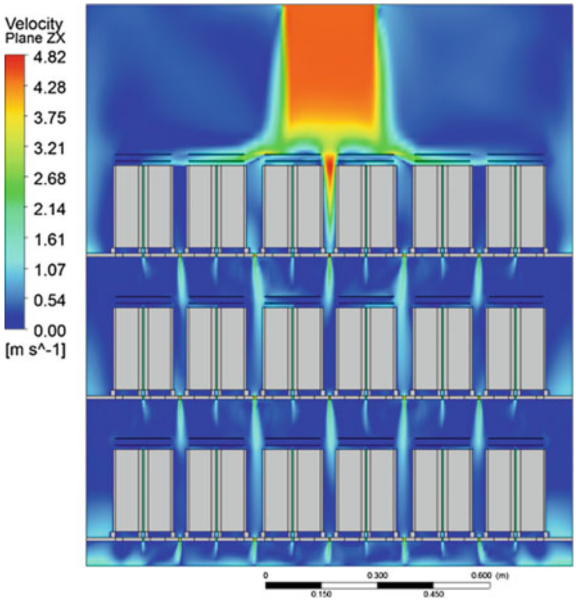

Fig. 11 The velocity distribution cloud picture at the symmetrical section

9 Conclusions

The Comparisons of different forced convection condition are listed in Table 2. Through the research in this paper, it is found that increasing the flow velocity on the surface of super capacitor is an effective way to improve the efficiency of forced ventilation cooling of super capacitor energy storage power. It is not obvious to enhance the heat dissipation efficiency of super capacitors by simply adding the air volume flow rate method. Through optimizing the internal arrangement of the super

Table 2 Comparisons of different forced convection condition

Convection condition	Maximum temperature °C	Improving temperature difference °C	Remarks
Initial scheme: flow rate 400 m^3/h	68.69	–	High temperature, uneven distribution
Increasing air volume flow rate to 600 m^3/h	60.94	7.7	HVAC higher load; uneven temperature distribution
Improved air outlet layout Flow rate 400 m^3/h	54.36	14.33	Lower temperature More uniform distribution
Improved internal flow field Flow rate 400 m^3/h	32.62	36	Lowest temperature More uniform distribution

capacitor to change the air flow, and guide more air flow through the super capacitor surface and the gap between the super capacitor monomers, forming more effective air flow is a good way to improve the heat efficiency of super capacitor. In another aspect, through the improvement of the arrangement of the air outlets, changing the uniformity of cooling air flow velocity field has a good effect on the uneven distribution of the temperature field of the super capacitor energy storage power supply.

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