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Research and optimization of air-cooled battery factors based on TOPSIS method and orthogonal analysis

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ABSTRACT. *In order to meet the operating temperature requirements of lithium batteries, air-conditioning parallel cooling battery packs are used when the ambient temperature is high in summer. Through the orthogonal analysis method, the study compared the influence of the diameter of the air inlet, the air temperature and the flow velocity on the cooling effect, and concluded that the cooling air temperature has the most significant effect and the flow velocity has the least significant effect. Through the TOPSIS method, three indicators of the module's maximum temperature, maximum temperature difference, and air conditioning power are selected, and the air temperature is comprehensively evaluated, and concluded that the optimal temperature of the cooling air is 291.15K.*

KEYWORDS: *Air-conditioning, Orthogonal analysis, TOPSIS method*

1. Extra heat generation rate

In previous studies,it was found that when lithium battery cells are discharged at a rate of 0.5C,the heat generation rate will fluctuate with the discharge time,but the overall range is small, with an average heat generation rate of 3400w/m^3.When using cooling air from the air conditioner evaporator, additional power and heat generation rate are generated.When the air conditioning efficiency (40%) and the lithium battery efficiency (95%) are basically stable, and the battery cell structure, the inclination of the bracket, the battery spacing and the number of battery cells in the module are fixed, the additional heat generation rate is only related to the diameter of the air inlet, the flow rate and temperature of the cooling air.The calculation formula is shown in formula (1)

$$Q = C * D^2 * v * (T_e - T) \quad (1)$$

C—Constants only related to battery modules;

D—The diameter of the air inlet;

v—the flow rate of the cooling air;

T_e—The outside air temperature in a high temperature environment, the summer environment temperature is higher at 35℃;

T—The temperature of the cooling air;

2. Orthogonal experiment

2.1 Factors and indicators

The experiment adopts the orthogonal design method. The orthogonal design can select a few schemes with strong representativeness among many schemes, which can greatly reduce the number of experiments and save computing resources while ensuring the overall experimental effect.

Because the additional heat generation rate is directly related to the diameter of the air inlet, the flow rate of the cooling air and the temperature, in order to ensure the cooling effect of the lithium battery and reduce the heat generation, it is necessary to study the impact of three factors on the battery cooling.

The orthogonal experiment sets 3 factors, and each factor has 3 levels. They are respectively A (the diameter of the air inlet hole), the level is 40, 50,60mm, B (the temperature of the cooling air), the level is 20,22.5,25℃, and the C (the flow rate of the cooling air), the level is 3,4,5 m/s.At the same time, there is a disturbance item factor D, ignoring the role of the first and second interaction items.

The cooling effect is characterized by the temperature of the battery and its equilibrium. Two indicators, the maximum temperature and the maximum temperature difference of the battery cells, are set. According to the number of factors and the principle of smaller tables, the orthogonal table of $L9(3^4)$ is selected for 9 simulation analyses.

2.2 Simulation solver

The cooling air flowing in the module at a certain speed causes the convective heat transfer coefficient everywhere inside the module to be not constant.Also, the distance between each battery cell and the air inlet is different, resulting in different cooling conditions for each cell, and the convective heat transfer coefficient cannot be simply specified.

Therefore, the simulation adopts fluid-heat coupling simulation, and the system automatically couples to solve it.Besides the overall temperature of module is low, the material basically has no thermal deformation, and the deformation of the small solid area has no effect on the fluid area. The simulation is completed in a one-way coupling in Fluent.

2.3 Model optimization

In the previous research, the battery cell spacing in the module is equal to 6mm. The result found that the cooling effect of the last four battery cells is poor and the temperature is higher due to the distance from the air inlet. Therefore, the distance between the four battery cells is increased to 8mm, which improves the air flow across the battery surface and balances the cooling effect of the entire battery pack.

The bracket of the battery pack is set with an inclination angle of 8°, and the air inlet is at the lower position. When the cooling air enters the module at a speed perpendicular to the inlet, it is below the first battery, resulting in almost no cooling air on the front of the first battery. It is necessary to design a secondary air inlet with a diameter of 20mm on the surface of the casing directly opposite the first battery. The air flow rate and temperature are consistent with those of main inlet in each experiment.

But the air velocity is not perpendicular to the inlet, the secondary air inlet velocity is at an angle of 45° to the horizontal and 37° to the front surface of the first battery. The inlet air flow is increased, and the diameter of the air outlet is designed to be 5mm larger than the diameter of the main air inlet to ensure that the air can flow in the module with small resistance.

The total heat generation rate of the battery cell is equal to the additional heat generation rate superimposed on the average heat generation rate during normal driving. The calculated total heat generation rates of 9 experiments are 4236 w/m^3, 4329 w/m^3, 4329 w/m^3, 5016 w/m^3, 5084 w/m^3, 4208 w/m^3, 6209 w/m^3, 4793 w/m^3, 4886 w/m^3.The experiment was carried out according to the design of orthogonal table, and the results are shown in Table 1.

Table 1 Orthogonal analysis table

Serial number	A	B	C	D	Maximum temperature /℃	Maximum temperature difference /℃
1	1	1	1	1	34.75	5.5
2	1	2	2	2	35.35	4.7
3	1	3	3	3	36.55	4.7
4	2	1	2	3	32.65	5.4
5	2	2	3	1	34.35	5.4
6	2	3	1	2	36.95	4.6
7	3	1	3	2	32.75	6.6
8	3	2	1	3	34.05	5.2
9	3	3	2	1	36.65	5.2

2.4 Result analysis

The minimum value of the maximum temperature is 32.65℃, and the minimum value of the maximum temperature difference is 4.6℃. The results adopt the analysis of variance method, which can distinguish data fluctuations caused by changes in conditions or experimental errors during the experiment. Check the F distribution to get $F_{0.10}(2,2)=9$, $F_{0.20}(2,2)=4$, The analysis of variance table is shown in Table 2.

Analyze the variance of the highest temperature and the result is $F_B > F_A > F_C$, Comparing the F value, it can be seen that the B factor has the greatest influence on the maximum temperature of the battery cell, the A factor is the second, and the C factor has the least influence. When the significance value is 0.10, F_B is greater than 9, indicating that the influence of factor B is super significant. Although factors A and C have an impact on the index, they are not significant.

Analyzing the variance of the maximum temperature difference result is also $F_B > F_A > F_C$, same as the maximum temperature result. When the significance value is 0.20, F_B and F_A are both greater than 4, and F_C is less than 4. It means that the influence of factor B is very significant, the influence of A is significant, and the influence of factor C is not significant.

In summary, factor B has the strongest influence both on the maximum temperature and maximum temperature difference of the battery cell, and factor C has the weakest influence on them. In the next research and optimization, the temperature of the cooling air can be further reduced to improve the cooling effect, and the flow rate of the cooling air can be reduced to decrease the heat generation rate and power.

Table 2 Analysis of variance table

·	Maximum temperature				Maximum temperature difference			
effect	sum of squares	Degree of freedom	Mean square error	F value	sum of squares	Degree of freedom	Mean square error	F value
A	1.976	2	0.988	1.78	0.802	2	0.401	6.94
B	17.102	2	8.551	15.42	1.609	2	0.804	13.92
C	0.736	2	0.368	0.66	0.436	2	0.218	3.77
error	1.109	2	0.554		0.116	2	0.058	
Total deviation	20.922	8			2.962	8		

3. Optimal design

As the temperature of the air has the greatest influence, lowering the temperature will help further reduce the temperature of the battery. Select the diameter of the air inlet to be 50mm and further reduce the air velocity to 2 m/s, The six discrete air temperatures are 283.15K, 285.15K, 287.15K, 289.15K, 291.15K, and 293.15K, respectively, for simulation experiments.

The battery cell temperature difference is caused by the characteristics of the battery itself. Reducing the air temperature will only increase the absolute value of the overall temperature difference of the module, but will not destroy the uniformity.

The thermal conductivity inside the battery is poor, which causes the heat to accumulate in the middle of the battery and cannot be quickly dissipated when heat is generated. The highest temperature appears in the core of the battery. The battery shell conducts heat well and is in direct contact with the cooling air, and the lowest temperature is in the battery shell, as shown in Figure 1.

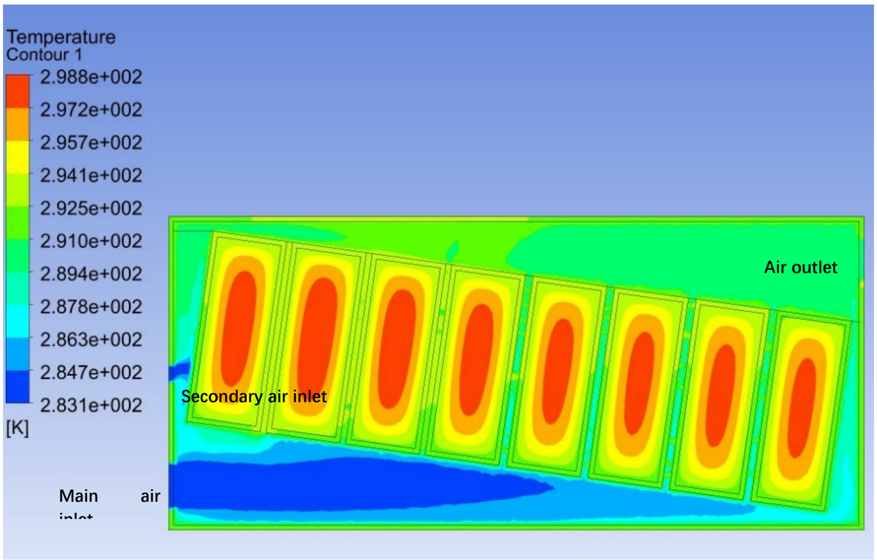

Figure 1 Battery module temperature distribution and air inlet and outlet diagram

In addition, what needs to be considered is that lowering the temperature will further increase the heat generation rate, and it is very possible that a too low temperature can fail to achieve the expected cooling effect but only consume energy. Therefore, when selecting the sensible temperature, it is necessary to comprehensively consider the power generated by the air conditioner, the maximum temperature of the module, and the maximum temperature difference to determine a reasonable temperature. The formula for calculating the power generated by the use of air conditioners is equation (2)

$$P = \frac{Q*V}{1-\eta} \quad (2)$$

V—Total volume of heat generating part of battery pack;

η—Lithium battery efficiency, 95%;

4. TOPSIS method

4.1 data processing

The TOPSIS method, also known as the superior-inferior solution distance method, is a multi-objective decision-making method in systems engineering. It does not require an objective function and passes the corresponding test,namely the restriction requirements are greatly reduced and the scope of application is wider.

Air conditioner power, module maximum temperature, and maximum temperature difference are all cost indicators. So the data of the original decision-making matrix A_{nxm} (n evaluation objects, m indicators) should be normalized and transformed into efficiency indicators. for the purpose of eliminating the incommensurability between the three indicators, the normalized matrix is then standardized to remove the influence of each indicator’s different dimensions.

4.2 Weight determination

Compared with the maximum temperature difference that affects the working performance of the battery, the maximum temperature is directly related to the safety of the battery. Too high temperature is prone to dangerous situations such as thermal runaway leading to combustion or even explosion. At the same time, the cruising range has always been an essential factor restricting the development of electric vehicles, and the power and energy consumed by the use of air conditioning also need to be seriously paid attention to.

Consequently, the weights of the three indicators, the maximum temperature of the module, the maximum temperature difference of the module, and the air conditioner power, are set to 0.4, 0.2, and 0.4 respectively. The weighting coefficients are multiplied by the standardized matrix to obtain the weighted standard matrix.

4.3 Result analysis

Find out the worst and optimal solutions, calculate the Euclidean distances between each evaluation object and the optimal and worst solutions,then calculate the relative closeness of each evaluation object to the optimal solution as the basis for evaluating the merits, The calculation formula is shown in formula (3).

$$S_i = \frac{D_i^-}{D_i^+ + D_i^-} \quad (3)$$

D_i^-—The distance from the solution to the negative ideal solution;

D_i^+—The distance from the solution to the positive ideal solution;

S_i—Unnormalized score;

Table 3 TOPSIS method matrix and results

temperature /T	weighted standard matrix			D_+	D_-	Normalized score	Rank
	temperature	temperature difference	power				
283.15	0.4027	0.0000	0.0000	0.9068	0.6712	0.13611	6
285.15	0.3232	0.0682	0.0539	0.6724	0.600	0.15090	5
287.15	0.2436	0.0910	0.1079	0.5709	0.5740	0.16045	4
289.15	0.1641	0.1365	0.1618	0.5039	0.6673	0.18233	3
291.15	0.0845	0.1592	0.2157	0.5524	0.7696	0.18630	1
293.15	0.0000	0.1819	0.2697	0.6712	0.9068	0.18391	2

Normalize the result. The larger the result, the better the effect. The results are shown in Table 3. It can be concluded from the table that when the inlet diameter is 50mm and the wind speed is 2m/s, the optimal temperature of the cooling air is 291.15K. At this time, the maximum temperature of the module is 33.25℃, the maximum temperature difference is 5℃, and the power is 195W. The result is ideal.

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