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Optimal Design for Cooling System of Batteries Using DOE and RSM

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A hybrid power composed of fuel cell and batteries has become the good strategy for HEV. On the contrary, the produced heat of batteries can affect to the total performance of HEV significantly. In this study, simulation methods with optimization were developed for obtaining the high performance cooling system of batteries. At first, a numerical method for obtaining the temperature distribution of batteries was developed by using CFD. In the following step, several parameters were investigated for selecting design variables with the important effect on the performance of the cooling system of batteries. Finally, an optimization method based on DOE and RSM was obtained through a real optimal design. There was 21.1% reduction on the view of the root mean square temperature between batteries as shown in the optimization result. The developed analysis with optimization can be used to improve the performance of the cooling system of batteries, and these works have made the theoretical basis for simulation and optimization of the cooling system of batteries.

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NOMENCLATURE

c = coefficient of the response surface
x = design variable

1. Introduction

With the heightened concern for energy consumption and environment conservation, the interest on fuel cell HEV (hybrid electric vehicle) has been greatly increased.

Recently, a hybrid power composed of fuel cell and batteries has become the good strategy for HEV. On the contrary, the produced heat of batteries can affect to the total performance of HEV significantly.[1-4] So, the cooling system of batteries should be designed well for adjusting the temperature distribution of batteries.[5-8]

Air cooling type or water cooling type can be used for designing the cooling system of batteries. Air cooling type has the merits of low cost, easy application and etc. The drawback of air cooling type is difficult to control the temperature distribution of batteries. The temperature distribution can be controlled by adjusting the parameters of the cooling system of batteries.

Many researchers have studied the effects of the parameters on the flow distribution for controlling the temperature distribution. Bajura and Jones have studied the characteristics of the flow distribution which has constructed a basis for designing a cooling system of batteries.[9] Choi has researched the effect of area ratio on the flow distribution using numerical methods when cooling the electronics devices.[10] Jones and Lior has studied the effect of the uniformity of the channel flow on the performance of the solar energy collector.[11] Tonomura has researched the geometry effect of the micro devices on the flow distribution.[12] Hu has studied the temperature distribution of batteries using CFD (computational fluid dynamics), and recommended a new cooling strategy for batteries.[13] On the contrary, the previous studies described above have not recommended an efficient optimization method for obtaining the high performance cooling system of batteries.

In this study, a general air cooling type cooling system for batteries was researched for obtaining the optimal performance of the cooling system for batteries. At first, an analysis model for calculating the temperature distribution of the cooling system for batteries was constructed using CFD. In the following step, several design variables were investigated for choosing the important parameters for optimization using the developed model. Finally, the cooling system for batteries was optimized using DOE (design of experiments) and RSM (response surface method).

2. Parameter Study Using CFD

In order to estimate the performance of the cooling system of batteries, a numerical simulation model was set up using a commercial CFD code – FLUENT which is based on one of the most popular numerical methods.[14-16] Also, parameter studies were carried out for choosing some important design variables of the cooling system of batteries for optimization. The candidated parameters included the operating condition, the material of the component and the geometry parameters of the cooling system of batteries. The outputs for investigation were the mean temperature of batteries and the root mean square temperature between batteries. The mean temperature of batteries is the total average temperature about the average values of every batteries, and the root mean square temperature is the root mean square calculated under the condition of setting the temperature of each battery as the average value. In a word, the mean temperature and the root mean square temperature express the levels of the temperature rise and the uniformity of temperature distribution.

2.1 Numerical Model and Analysis Conditions

For developing an analysis model of obtaining the temperature distribution of batteries, a general air cooling type cooling system of batteries was selected.

Fig. 1 shows the shape of a baseline cooling system for batteries, and Fig. 2 shows batteries and the cartridges. 1, 2 and 3 express the case, the inlets and the outlets of the cooling system respectively. Also, 4 and 5 express batteries and the cartridges respectively.

The width, the length and the depth of a battery were 100mm, 200mm and 5mm respectively, and 40 batteries had been divided into 4 columns as shown in Fig. 1. There were 10 batteries in a column, and the distance between batteries was 5mm. Also, there was a cartridge between the columns, and the length, the width and the height of a cartridge was 200mm, 10mm and 95mm respectively. The length, the width and the depth of the cooling system were 440mm, 220mm and 105mm respectively. The length and the width of the 2 inlets were 440mm and 10mm as shown in Fig. 1, and the diameters of the 2 outlets were 90mm. The distance between the centers of the 2 outlets was 220mm.

The material properties of batteries and the cartridges were as shown in Table 1. The operating conditions were as follows: The mass flow rate of one inlet and the temperature of cooling air were 0.015kg/s and 300K; The generated heat flux of a battery was assumed as 30000W/m^3.

In order to analysis the cooling system of batteries, heat conduction and heat convection should be solved. In this study, the steady simulations were carried out using a commercial CFD code. The standard k-ε turbulence model was used for the simulation of heat convection, and 3 dimensional heat conduction was included.

The model was composed of 40 volumes of batteries, 3 volumes of the cartridges and a fluid volume. The source terms of the volumes of batteries were the generated heat flux given above. The boundary conditions of the inlets were mass flow inlets with a given value above, and the boundary conditions of the outlets were outflow conditions. The boundary condition of the cooling system's case was wall boundary condition with heat transfer coefficient of convection (5W/m^2.K). For simulation, about 300000 unstructured grids were used.

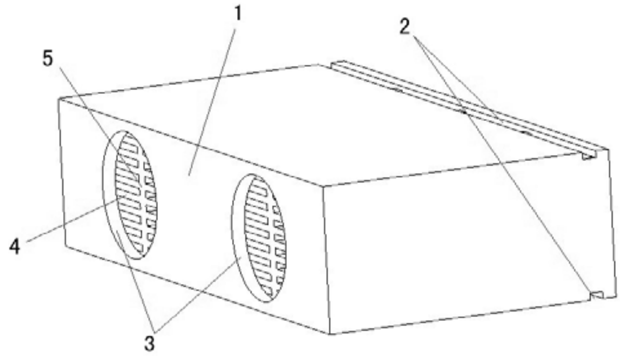

Fig. 1 Cooling system for batteries

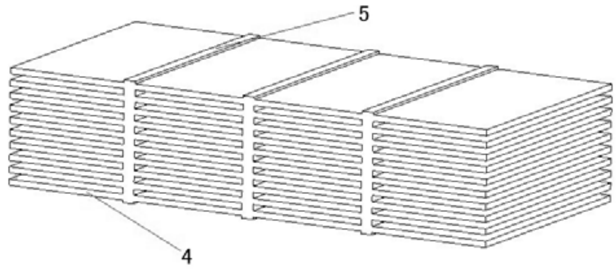

Fig. 2 Batteries and cartridges

Table 1 Material properties

Item	Density (kg/m^3)	Thermal Conductivity (W/m.K)	Specific Heat (J/kg.K)
Battery	2414	2.2	1011
Cartridge(ABS)	1014	0.25	1206

Table 2 Temperature variation with different heat flux of battery

Heat Flux	20000W/m^3	30000W/m^3 (Baseline)	40000W/m^3
Mean Temperature(K)	304.3	306.4	308.5
Root Mean Square(K)	0.51	0.76	1.02

2.2 Parameter Study

In order to choose several important design variables for optimizing the cooling system of batteries, some parameters were investigated.

At first, the heat flux of battery was changed for researching the effect on the performance of the cooling system for batteries. Table 2 shows the results of the selected 3 cases. The mean temperature was increased with increasing the heat flux of battery, and the root mean square temperature between batteries was also increased with increasing the heat flux as shown in Table 2.

In the following step, the material of the cartridge and the cartridge width were studied for improving the performance of the cooling system for batteries. Table 3 shows the results of the selected 3 different cases. The cases made of Al and Fe were better

Table 3 Temperature variation with different material of cartridge

Material	ABS(Baseline)	Al	Fe
Mean Temperature(K)	306.4	305.6	305.5
Root Mean Square(K)	0.76	0.55	0.55

Table 4 Temperature variation with different cartridge width

Width	8mm	10mm(Baseline)	12mm
Mean Temperature(K)	307.2	306.4	306.3
Root Mean Square(K)	1.01	0.76	0.77

Table 5 Temperature variation with different distance between batteries

Distance	4.5mm	5.0mm(Baseline)	5.5mm
Mean Temperature(K)	306.7	306.4	306.8
Root Mean Square(K)	0.63	0.76	1.60

Table 6 Temperature variation with different distance from the wall face to outlets

Distance	8mm	10mm(Baseline)	12mm
Mean Temperature(K)	306.4	306.4	306.6
Root Mean Square(K)	0.77	0.76	0.87

than the baseline case made of ABS, and the case made of Al was the same level with the case made of Fe as shown in Table 3. Table 4 shows the results of the 3 cases having different cartridge width. The case having the cartridge width of 12mm was the same level with the baseline case, and the baseline case was better than the case having the cartridge width of 8mm on the view of the performance of the cooling system for batteries as shown in Table 4.

Finally, the distance between batteries and the distance between the wall face to the outlets and batteries were investigated for obtaining better performance of the cooling system of batteries. Table 5 shows the analysis results with different distance between batteries. The 3 cases were the same level on the view of the mean temperature of batteries, but the case having the distance between batteries of 4.5mm was the best one of the selected cases on the view of the root mean square temperature between batteries. Table 6 shows the numerical results with different distance between the wall face to the outlets and batteries. Larger distance between the wall face to the outlets and batteries means that batteries and the cartridges were near to the outlets. The investigated cases were the same level on the view of the mean temperature of batteries. The case having the distance between the wall and batteries of 8mm was nearly the same with the baseline, and the baseline was better than the case having the distance between the wall and batteries of 12mm on the view of the root mean square temperature between batteries as shown in Table 6.

3. Construction of Response Surface

If the optimal design is carried out based on trial and error, the optimization time would be very long. Many optimization problems can not be easily solved specially for that the analysis is performed based on CFD. In this study, the RSM (response surface method) was used to reduce the optimization time.

Table 7 Lower and upper bounds for each design variable

Design Variables	Maximum	Minimum
x_1(Cartridge Width)	12mm	8mm
x_2(Distance between Batteries)	5.5mm	4.5mm
x_3(Distance from the wall face to outlets)	12mm	8mm

Table 8 Analysis results of the selected experimental points

No.	x_1	x_2	x_3	Mean Temperature(K)	Root Mean Square Temperature(K)
1	0	0	0	306.4	0.76
2	0	1	0	306.8	1.60
3	1	0	–1	306.3	0.75
4	1	0	0	306.3	0.77
5	1	0	1	306.5	0.86
6	–1	0	0	307.2	1.01
7	0	–1	0	306.7	0.63
8	1	–1	0	306.6	0.64
9	1	1	1	306.6	1.49
10	–1	1	–1	306.7	1.55
11	0	–1	1	306.7	0.66
12	–1	–1	–1	306.7	0.66
13	0	–1	–1	306.6	0.68
14	1	1	–1	306.4	1.27
15	–1	–1	1	306.9	0.67

3.1 Concepts of DOE and RSM

The RSM is a widely used tool in the quality engineering field.[17,18] The RSM comprises regression surface fitting to obtain approximated responses, DOE to obtain minimum variances of the responses, and optimizations using the approximated responses. For most of the response surfaces, the functions for the approximations are polynomials because of their simplicity, although the functions are not limited to the polynomials. In this study, the response surface was composed of the quadratic polynomials in Eq. (1) to set up a smooth curved surface:

$$C_m(x_i) = c_0 + \sum_{i=1}^{k} c_i x_i + \sum_{i=1}^{k} c_{ii} x_i^2 + \sum_{i=1}^{k-1} \sum_{j=2}^{k} c_{ij} x_i x_j \tag{1}$$

where $C_m(x)$ is the objective function, c_i is the coefficient to be defined, and K is the number of design variables. When the response model is defined as a quadratic polynomial, the number of coefficients c_i can be calculated using (k + 1)(k + 2)/2.

The adjusted coefficient of the multiple determination (R^2_{adj}) is used to judge the goodness of the approximation of the response surface. The R^2_{adj} has a maximum value of 1 and a minimum value 0. The value is closer to 1 for a good response surface.

For problems that have complicated constraints or when the design space is not rectangular, the conventional DOE methods such as the orthotropic designs can not be applied, and the computer-aided DOE methods are the only candidates. D-optimal design is one of those popular computer-aided DOE methods. In this study, the D-optimal design was used in the process of choosing experimental points for setting up the response surface.

3.2 Response Surface

In this study, the design variables were the cartridge width, the distance between batteries and the distance between the wall face to the outlets and batteries. Table 7 shows the lower and upper

Table 9 Coefficients for the constructed response surface

Item	Coefficient for Root Mean Square Temperature
C_0	0.843618E+00
C_1	-0.995553E-01
C_2	0.458646E+00
C_3	0.778110E-01
C_{11}	0.220223E-01
C_{22}	0.246568E+00
C_{33}	0.214647E-01
C_{12}	-0.100721E+00
C_{13}	-0.413516E-01
c_{23}	0.963516E-01

boundaries of the design variables. For improving the reliability of the response surface, 15 experimental points were selected using the D-optimal DOE method as shown in Table 8; this is 1.5 times the number of the unknown coefficients. The values of -1, 0 and 1 in the column 2, 3 and 4 of Table 8 mean the minimum, middle and maximum values of each design variable. Only the root mean square temperature between batteries was constructed as a response surface because the design variables affect to the mean temperature of batteries a little as shown in Table 8. The calculated unknown coefficients for the root mean square temperature between batteries are listed in Table 9 which are the constants for the unknown coefficient expressed in Eq. (1). As an evaluation standard for the reliability of the response, the value of R^2_{adj} in the constructed response surface was larger than 0.97.

4. Optimal Design Using RSM

Not only the temperature rise of batteries but also the temperature difference between batteries should be considered for improving the total performance of HEV. In this work, the optimal design was achieved to decrease the root mean square temperature between batteries using the constructed response surface under the condition of neglecting the effect of the mean temperature of batteries because the design variables affect to the mean temperature of batteries a little as shown in Table 8. The constraint was that the design variables should be satisfied their lower and upper boundaries shown in Table 7 respectively. In this study, the SQP (sequential quadratic programming) optimization algorithm was used in DOT (design optimization tools) software.[19]

Table 10 shows the comparison of the baseline case and the optimum case using the constructed response surface of the root mean square temperature between batteries. To confirm the data from the constructed response surface, an analysis of the optimal case should be carried out.[20] Table 11 shows the verification of the data from the response surface. From Table 10 and Table 11, it can be found out that there was 21.1% reduction on the view of the root mean square temperature between batteries with 3.3% computational error.

Unnecessary iterative analysis time can be reduced by using the response surface method and optimization techniques.

The mean temperature of batteries should be considered as a constraint by constructing another response surface for the mean

Table 10 Optimal results using RSM

Item	Baseline	Optimum
x_1(Cartridge Width)	10.00mm	10.58mm
x_2(Distance between Batteries)	5.00mm	4.56mm
x_3(Distance from the wall face to outlets)	10.00mm	10.28mm
Root Mean Square Temperature	0.76K	0.60K

Table 11 Verification of data from response surface

Item	Data from response surface	Data from analysis
x_1(Cartridge Width)	10.58mm	10.58mm
x_2(Distance between Batteries)	4.56mm	4.56mm
x_3(Distance from the wall face to outlets)	10.28mm	10.28mm
Root Mean Square Temperature	0.62K	0.60K

temperature of batteries when the design variables affect to the mean temperature of batteries significantly.

The developed optimization method can be widely applied to optimize the cooling system of batteries with minimum computational effort.

5. Conclusions

An analysis model and an optimization method for the cooling system of batteries were developed for designing the high performance cooling system of batteries. The detailed descriptions are as follow: (1) For obtaining the performance of the cooling system of batteries, a numerical model was constructed based on a commercial CFD code; (2) Several parameters including the operating condition, the material of the component and the geometry of the cooling system were investigated for selecting the important design parameters used for optimal design of the cooling system; (3) Using DOE and RSM, an efficient optimization method was developed for obtaining the high performance cooling system. The developed simulation and optimization methods will be widely used for designing the high performance cooling system of batteries.

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