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Optimization for Cooling System of Batteries Having Porous Material Using Design of Experiments

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A hybrid power composed of fuel cell and batteries has become the reasonable strategy for hybrid electric vehicles. On the contrary, the produced heat by batteries can affect the total performance of hybrid electric vehicles significantly. In this paper, analysis methods and optimization strategy were constructed for obtaining the high performance cooling system for batteries having porous material. At first, a numerical method for obtaining the temperature distribution of battery pack including porous material was developed by using CFD technique. In the following step, the cooling systems for batteries with porous material or not were compared for showing the merit of the cooling system for batteries having porous material. Ultimately, an optimization strategy based on D-optimal DOE method was obtained through a real optimal design process. There was 13.3% reduction on the view of the root mean square temperature between batteries compared with the original cooling system for batteries as shown in the optimization result. The constructed analysis method and optimization strategy can be used to improve the performance of the cooling system for batteries, and these works have made the theoretical basis for simulation and optimization of the cooling system for batteries.

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NOMENCLATURE

D_{eff} = D-optimal assessment index
M = moment matrix

1. Introduction

With the increasing concern of energy consumption and environment conservation, the interest about hybrid electric vehicle has been greatly increased.

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

Air cooling type or water cooling type can be applied for designing the cooling system of batteries. Air cooling type has the goodness of low cost, easy application and etc. The drawback of air cooling type is difficult to adjust the temperature distribution of batteries. The temperature distribution can be adjusted by changing the parameters of the cooling system of batteries.

Many researchers have studied the effects of the design variables to the flow distribution for adjusting the temperature distribution. Bajura and Jones have researched the phenomena of the flow distribution which has set up a theoretical basis for designing a cooling system of batteries.[9] Choi has studied the effect of area ratio to the flow distribution using numerical methods when cooling the electronics devices.[10] Jones and Lior have researched the effect of the uniformity of the channel flow to the performance of the solar energy collector.[11] Tonomura has studied the geometry effect of the micro devices to the flow distribution.[12] Hu has researched the temperature distribution of batteries using CFD (computational fluid dynamics), and showed a new cooling method for batteries.[13] Based on CFD method, Xuan and Li developed the optimization strategies using thermal analysis database and response surface method.[14,15] On the contrary, the previous studies described above have not showed a significant cooling system and an efficient optimization method for obtaining the high performance cooling system of batteries.

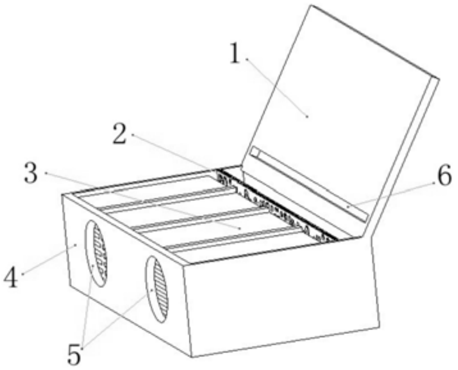

Fig. 1 Cooling system for batteries having porous material (1: Cover; 2: Porous material; 3: Batteries; 4: Case; 5: Outlet; 6: Inlet)

In this paper, an air cooling type cooling system for batteries having porous material was recommended 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 having porous material was constructed using CFD technique. In the following step, the performance of cooling system of batteries with porous material or not were compared using the constructed analysis method. Finally, the cooling system for batteries including porous material was optimized using an D-optimal DOE (design of experiments) method.

2. Numerical Model and Analysis Conditions

In order to improve the performance of the cooling system for batteries, porous material was applied to the cooling system for batteries as shown in Fig. 1.

The cooling system for batteries having porous material can be used to improve the uniformity of temperature distribution of batteries because relatively uniform flow distribution can be expected by making the cooling air through porous material film.

The width, the length and the depth of a battery were 100 mm, 200 mm and 5 mm 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 5 mm. Also, there was a cartridge between the columns, and the length, the width and the height of a cartridge was 200 mm, 10 mm and 95 mm respectively. The length, the width and the depth of the cooling system were 440 mm, 230 mm and 105 mm respectively. The length and the width of the 2 inlets were 440 mm and 10 mm as shown in Fig. 1, and the diameters of the 2 outlets were 90 mm. The distance between the centers of the 2 outlets was 220 mm. The distance between the outlets and the batteries were 10 mm, and the distance between porous material to batteries were also 10 mm. The thickness of the porous medium was 1 mm.

The face permeability of porous film was $2.2 \times 10^8\,m^2$, and the other material properties 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 0.020 kg/s and 300 K; The mass flow rate was increased from original 0.015 kg/s for the basic cooling system with no porous material under the condition of considering the pressure drip due to porous material. The generated heat flux of a battery was assumed as 30000 W/m^3.

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

In order to estimate the performance of the cooling system for batteries having porous material, a numerical simulation model was set up using a commercial CFD code - FLUENT which is based on one of the most popular numerical methods.[16-18]

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. 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 2 fluid volumes. 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. For porous material film, porous jump boundary condition was used with the characteristics given above. The boundary condition of the cooling system's case was wall boundary condition with heat transfer coefficient of convection (5 W/m^2.K). For simulation, about 300000 unstructured grids were used.

3. Comparison of the Cases Having Porous Material or Not

In order to show the merit of the cooling system for batteries having porous material, the comparison between the two cases having porous material or not was carried out using the developed analysis model described in the previous chapter. The difference is that the interface between two fluid volumes was porous jump or interior boundary condition.

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.

Table 2 and 3 show the temperature distributions of the two cases having porous material or not. As shown in Table 2 and 3, the symmetry trend can be found for the two cases, and the regions of the center show smaller temperature due to the positions of the inlets and the outlets.

The Table 4 shows the comparison between the two cases having porous material or not. As shown in Table 4, the root mean square temperature have been decreased due to the effect of porous material.

Table 2 Temperature distribution of batteries for case having porous material

No.	Column 1 (K)	Column 2 (K)	Column 3 (K)	Column 4 (K)
1	307.8	308.9	308.5	307.6
2	307.4	306.9	306.6	307.1
3	305.2	304.8	304.8	305.2
4	304.2	304.1	304.1	304.3
5	304.0	303.9	303.9	304.0
6	304.0	303.9	303.9	304.0
7	304.3	304.1	304.1	304.3
8	305.1	304.8	304.9	305.2
9	307.0	306.7	306.9	307.2
10	307.4	308.6	308.8	307.6

Table 3 Temperature distribution of batteries for case with no porous material

No.	Column 1 (K)	Column 2 (K)	Column 3 (K)	Column 4 (K)
1	308.7	310.4	310.0	308.5
2	308.4	307.9	307.6	308.1
3	306.1	305.7	305.6	306.0
4	305.1	304.9	305.0	305.1
5	304.9	304.7	304.8	304.9
6	304.9	304.7	304.8	304.7
7	305.1	305.0	305.0	305.1
8	305.9	305.7	305.8	306.0
9	308.0	307.7	307.9	308.2
10	308.3	310.1	310.2	308.5

Table 4 Comparison of cases having porous material or not

Case	Mean Temperature (K)	Root Mean Square Temperature (K)
Having porous material	305.7	1.69
With no porous material (Original)	306.6	1.83

4. Optimization Method

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 D-optimal DOE method was used to reduce the optimization time.

4.1 Concepts of D-optimal DOE method

Desgin of Experiments is a method for selecting reasonable experimental points for obtaining the response value.[19,20]

The orthotropic design, the central composite design, the random design, the Box-Benken design, D-optimal design and etc. were included into Design of Experiments.

For problems that have complicated constraints or when the design space is not rectangular, the conventional DOE methods such as the orthotropic design and the central composite design can not be applied, and computer-aided DOE methods are the only candidates. D-optimal design is one of these popular computer-aided DOE methods. D-optimal design can obtain reasonable approximation with minimum experimental points.

In D-optimal design, the moment matrix can be defined as follows.

$$M = \frac{X^T X}{k} \tag{1}$$

Table 5 Lower and upper bounds for each design variable

Design Variables	Maximum	Minimum
X_1 (Cartridge Width)	12 mm	8 mm
x_2 (Distance between Batteries)	5.5 mm	4.5 mm
x_3 (Mass flow rate of air)	0.022 kg/s	0.018 kg/s

Table 6 Analysis results of the selected experimental points

No.	X_1	x_2	X_3	Mean Temperature (K)	Root Mean Square Temperature (K)
1	0	1	0	305.7	2.85
2	0	0	0	306.8	1.69
3	1	0	0	306.2	2.43
4	1	0	-1	305.9	2.38
5	-1	0	0	305.6	2.30
6	1	0	1	305.5	2.28
7	1	-1	0	305.4	1.72
8	0	-1	0	305.1	1.59
9	-1	1	-1	306.5	3.02
10	1	1	1	307.9	3.66
11	0	-1	1	305.1	1.73
12	0	-1	-1	306.3	2.33
13	-1	-1	-1	305.6	1.69
14	1	1	-1	307.4	3.44
15	-1	-1	1	305.6	2.15

D-optimal design maximizes the determinant of the moment matrix when selecting the experimental points. The meaning of maximizing the determinant of the moment matrix is decreasing the total elements of the $(\boldsymbol{X}^T\boldsymbol{X})^{-1}$. Generally, D_{eff} can be used as a judgement index of D-optimal design, and it can be expressed using the nondimension value between -1 and 1 for each design variable as follows.

$$D_{eff} = \frac{|M|^{1/p}}{k} \tag{2}$$

Where $p = k + 1$, and D-optimal design selects the experimental points under the condition of maximizing (D_{eff}).

4.2 Optimization using D-optimal DOE method

Not only the temperature rise of batteries but also the temperature difference between batteries should be considered for improving the total performance of hybrid electric vehicles. In this work, the optimal design was achieved to decrease the root mean square temperature between batteries using D-optimal DOE method under the condition of neglecting the effect of the mean temperature of batteries because the design variables affect the mean temperature of batteries a little as shown in Table 2 and 3.

Table 5 shows the design variables selected in this study, and the lower and upper boundaries of each design variables were also described.

For compensating the drawback of the method based on trial and error for optimization, 15 experimental points were selected as shown in Table 6. Table 6 also shows the analysis results for the selected experimental points. As shown in Table 6, the case 8 were the optimal case.

For checking the merit of the optimal case, the original case with no porous material was compared with the optimal case. As shown in Table 7, the root mean square temperature was significantly decreased due to the effect of porous material.

Table 7 Comparison of optimal and original cases

Case	Mean Temperature (K)	Root Mean Square Temperature (K)
Optimal case	305.1	1.59
Original case	306.6	1.83

Table 8 Temperature distribution of batteries for optimal case

No.	Column 1 (K)	Column 2 (K)	Column 3 (K)	Column 4 (K)
1	307.7	308.1	307.8	307.6
2	306.0	306.1	305.9	306.0
3	304.4	304.4	304.4	304.4
4	303.8	303.8	303.9	303.8
5	303.7	303.7	303.7	303.7
6	303.6	303.8	303.8	303.7
7	303.8	303.9	303.8	303.8
8	304.3	304.4	304.3	304.4
9	306.0	306.1	306.0	305.9
10	307.7	308.0	308.0	307.7

Table 8 shows the temperature distribution of batteries for the optimal case. As shown in Table 8, relatively uniform temperature distribution of batteries have been accepted.

Unnecessary iterative analysis time can be reduced by using the D-optimal DOE method.

The mean temperature of batteries should be considered as a constraint when the design variables affect the mean temperature of batteries significantly.

The cooling system for batteries having porous material will be used to develop high performance hybrid electric vehicles due to its acceptable temperature rise and uniformity of the batteries.

Also, 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 having porous material were constructed for designing the high performance cooling system of batteries. The detailed descriptions are as follows: (1) For achieving the performance of the cooling system of batteries with porous material, a numerical model was set up using a commercial CFD code; (2) The cooling systems for batteries including porous material or not were compared for showing the merit of the cooling system for batteries having porous material; (3) Using D-optimal DOE method, an efficient optimization method was constructed for obtaining the high performance cooling system for batteries. The developed analysis and optimization methods would be widely used for designing the high performance cooling system for batteries.

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