THERMAL PERFORMANCE ANALYSIS AND OPTIMIZATION
DESIGN OF DRY TYPE AIR CORE REACTOR
WITH THE DOUBLE RAIN COVER

by

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In this paper, a fluid-thermal coupled finite element model is established according to the design parameters of dry type air core reactor. The detailed temperature distribution can be achieved, the maximum error coefficient of temperature rise is only 6\% compared with the test results of prototype, and the accuracy of finite element calculate method is verified. Taking the equal height and heat flux design parameters of reactor as research object, the natural-convection cooling performance of reactor with and without the rain cover is investigated. It can be found that the temperature rise of reactor is significantly increased when adding the rain cover, and the reasons are given by analyzing the fluid velocity distribution of air ducts between the encapsulation coils. In order to reduce the temperature rise of the reactor with the rain cover, the optimization method based on the orthogonal experiment design and finite element method is proposed. The six factors of the double rain cover are given, which mainly affect the temperature rise of reactor, and the five levels are selected, the influence curve and contribution rate of each factor on the temperature rise of reactor are analyzed. The results show that the contribution ratio of the parameter \(H_1\), \(L_1\), and \(L_2\) are obviously higher than the parameter \(H_2\), \(L_3\), and \(\theta\), so the more attention should be paid in the design of double rain cover. Meanwhile, the optimal structural parameters of rain cover are given based on the influence curves, and the temperature rise is only 43.25 \({}^\circ\text{C}\). The results show that the optimization method can reduce the temperature rise of reactor significantly. In addition, the temperature distribution of inner encapsulations coils of reactor are basically the same, the current carrying capacity of coils can be fully utilized, which provides an important guidance for the optimization design of reactor.

Key words: fluid-thermal coupled, dry type air core reactor, temperature rise, natural-convection cooling, rain cover, orthogonal experiment design

Introduction

The dry type air core reactor becomes the first type for large power reactor because of its simple structure, good linearity, light weight and high mechanical strength [1, 2]. It encoun-
tors overheating and even fire in the running process in recent years, and it has been confirmed that the partial high temperature of coils is one of the main reasons [3, 4]. Recently, the rain cover is often added at the top of reactor, to reduce the influence of external environment [5]. However, the heat dissipation conditions of coils gets worse after adding the rain cover, and partial encapsulation temperature rise may exceed the limit, which leads to the insulation and mechanical properties of the material changed, and consequently affects the safe and stable operation of the reactor in the power system. Thus, in order to reduce the influence of rain cover on temperature rise of reactor, the temperature distribution and heat dissipation characteristics of reactor should be analyzed when adding the rain cover, and the optimization methods about reactor are needed.

Currently, the research mainly includes:

- **The temperature distribution and heat dissipation characteristics:** In [6], the empirical formula is adopted to calculate the average temperature rise of the reactor. In [7], the average temperature rise method is introduced by calculating the resistance, which is widely used in industrial production, however, the accuracy is low and cannot reflect the heat dissipation characteristics. In [8], the finite difference method is used, the convection heat transfer coefficient along the axial direction of the coils is given based on the heat transfer criterion formula, and the temperature distribution of reactor can be obtained, but the calculation accuracy depends on the convection heat transfer coefficient, which limits its actual application. In [9], the temperature rise of transformer winding is given by establishing the Takagi-Sugeno model, but the computational process is complex. In order to obtain detailed and accurate temperature distribution of reactor, the finite element method is used. In [10, 11], the 2-D finite element model of reactor is established, and the detailed temperature field distribution is achieved. In [12], the 3-D temperature field simulation model of reactor is established, the influence of the rain cover is considered, the results of prototype experiment verify the correctness of finite element method. However, the heat dissipation characteristics of reactor have not been considered when adding the rain cover.

- **The optimization methods about reactor:** In [13], the finite element method is used to reduce the temperature rise of reactor by adjusting the air ducts width and the thickness of the coils. In [14, 15], the genetic algorithm and particle swarm optimization algorithm are applied to the design of the reactor, but the large computation and long time is needed. In [16], the encapsulation-air ducts unit optimization method is proposed, but the effect of air ducts width on the thermal efficiency is not considered. In [17], the structure parameters of the rain cover is achieved based on the engineering experience, but the accuracy is low. In [18], the rain cover is equivalent to tilting baffle model, the influence factors of rain cover on temperature rise of the reactor are analyzed, and the optimal structural parameters are given based on the finite element method, however, it is only applicable to the tilting baffle model, which limits its practical application. In [19], the finite element method and Taguchi combined method is used to achieve the optimal structure parameters of sound arrester, but the situation of single rain cover is merely considered. In fact, the outline size of rain cover also has a great influence on the temperature rise. In [20], the double rain cover structure parameters are acquired in the forced air cooling conditions, it can realize the same fluid velocity distribution in the air ducts, and the heat dissipation efficiency can be improved.

However, the aforementioned method fails to elucidate the influence law of rain cover on temperature rise of reactor, and the optimal structure parameter cannot be obtained.

In this paper, according to the design parameters of reactor, a fluid-thermal coupled finite element model is established based on ANSYS simulation platform. The temperature field
simulation results are achieved, and the maximum temperature rise is 51.6 °C. Meanwhile, the prototype temperature rise test is done and the temperature rise is 49 °C, so the accuracy of finite element method is verified. In order to reduce the temperature rise of the reactor with the rain cover, taking the equal height and heat flux design parameters of reactor as research object, the six influence factors of the double rain cover on temperature rise of reactor are considered, and five levels are selected. Combined with the orthogonal experiment design and finite element method, it can be found the maximum temperature rise of inner encapsulations is higher after adding the rain cover, and the reasons are given by analyzing the fluid velocity distribution of air ducts. Meanwhile, the influence curve and contribution rate of each factor on the temperature rise are analyzed, and the optimal parameters of the rain cover are obtained. The results show that the optimization method can reduce the temperature rise of reactor significantly.

Temperature field simulation of reactor

The basic structure and parameters

The dry type air core reactor is mainly composed by the several coaxial encapsulation coils, which are parallel connected in electric, and the coils are composed by the metal conductor and insulating material. The sustaining bars locates the adjacent encapsulation coils, which acts as the insulation and heat dissipation channels. The upper and lower ends of the encapsulation coils are the spider arm, which plays a role of distributing current and strengthen coils. Figure 1 is the basic structure and equivalent model of dry type air core reactor in natural cooling conditions. The main electric parameters of reactor are the inductance is 3.1 mH. The rated current is 3150 A, the rated voltage is 220 kV. The main geometrical parameters of reactor are the height of coils is 1.75 m, the inner radius of coils is 0.3 m, the outside radius of coils is 1.1 m, the number of coils is 12 and the metal conductor material is aluminum. The double rain cover is added at the top of reactor, which includes the lower and upper rain cover. The heat generated by the encapsulation coils is dissipated through the bottom end of the lower rain cover and the central hole between the upper and lower rain cover, which has a better heat dissipation performance compared with the single rain cover.

Figure 1. The basic structure and equivalent model of reactor: (a) the basic structure nad (b) the equivalent model
Loss calculation

The spider arm and sustaining bar have little influence on the temperature rise of reactor, thus, only the loss of the encapsulation coils should be considered in the calculation of temperature field. The loss of reactor mainly includes resistance loss and eddy current loss, which is the precondition for the temperature field simulation calculation.

Resistance loss of coils: the resistance loss, $P_{0,i}$, can be written [21]:

$$P_{0,i} = I_i^2 \frac{\pi D_i W_i}{\kappa S_i}$$

(1)

where $I_i$, $D_i$, $W_i$, and $S_i$ are the current, diameter, turns number, and conductor cross-section area of the encapsulation $i$, respectively, $\kappa$ is the conductivity of metal conductor.

Eddy current loss of coils: the eddy current loss, $P_{ij}$, can be expressed as [22, 23]:

$$P_{ij} = \frac{\pi W_i D_i \kappa a_i b_i}{12} \left( a_i^2 B_{z,i}^2 + b_i^2 B_{r,i}^2 \right)$$

(2)

where $\omega$ is angular velocity, $a_i$ and $b_i$ are the radial width and single-turn axial height of the encapsulation $i$, $B_{z,i}$ and $B_{r,i}$ are the axial and radial component of the magnetic flux density. The magnetic flux density distribution of reactor depends on the diameter, height, turns number, and current of the encapsulation coils, which can be achieved by analytical calculation method. Thus, the total loss of each encapsulation can be written as the sum of resistance loss and eddy current loss.

Temperature field simulation

In order to obtain the detailed and accurate temperature distribution, the finite element method is selected considering the complex structure and heat dissipation process of the reactor with the rain cover. The temperature field simulation process mainly includes simulation model establishment, control equation, heat source loading, boundary conditions and grid generation.

Model establishment

According to the structural characteristic of reactor, the spider arm and sustaining bar, which interrupt the heat flow of coils, are relatively small compared with the total heat dispersing surface of coils [12], thus, the actual reactor with the encapsulation coils and double rain cover can be equivalent to 2-D symmetrical axis model. The simulation model is established based on ANSYS simulation platform, as shown in fig. 2. Some simplification and equivalent are done, only considering the steady-state thermal process, the encapsulation coils of reactor and double rain cover are equivalent to 2-D axisymmetric model, the size of coils and double rain cover are basically identical to actual design parameters. Considering both the com-
putation time and accuracy, the whole computational domain adopts the 2.5 times radial length and 3 times axial height of reactor in the model.

The physical properties of metal conductor can be obtained according to the actual aluminum, the outer insulating material of metal conductor and rain cover are set as the same, as shown in tab. 1. The region which around the coils and the rain cover is defined as the air, the physical properties can be achieved according to the corresponding pressure and temperature.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density [kgm$^{-3}$]</th>
<th>Thermal conductivity coefficient [Wm$^{-1}$K$^{-1}$]</th>
<th>Specific heat capacity [Jkg$^{-1}$°C$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal conductor</td>
<td>2707</td>
<td>217</td>
<td>880</td>
</tr>
<tr>
<td>Insulation materials</td>
<td>980</td>
<td>0.5</td>
<td>1125</td>
</tr>
</tbody>
</table>

Control equation

The heat generated by the encapsulation coils of reactor is mainly dissipated outward by three ways, heat conduction, heat convection and heat radiation [24-26].

Heat conduction: In the steady-state, the energy transmits in the metal conductors and insulation material is by the way of heat conduction, the control equation can be described:

$$\frac{1}{r} \frac{\partial}{\partial r} \left( \lambda r \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z} \left( \lambda \frac{\partial T}{\partial z} \right) + q = 0$$

(3)

where $T$ is the temperature, $q$ – the heat generating rate per unit volume, $r$ and $z$ are the length of radial and axial direction, and $\lambda$ – the thermal conductivity.

The interface between the insulating material and the metal conductor in the inner of encapsulation coils is satisfied:

$$\lambda_1 \frac{\partial T_1}{\partial n} = \lambda_2 \frac{\partial T_2}{\partial n}$$

(4)

where $\lambda_1$ and $\lambda_2$ are the thermal conductivity, $T_1$ and $T_2$ – the temperature of insulating materials and metal conductors, respectively, and $n$ – the interface normal.

Heat convection: The energy transmits, including the encapsulation surface and surrounding air, rain cover and surrounding air, are mainly by the way of heat convection, the control equation can be represented by continuity, momentum and energy equation, the detailed equation can be found in [18].

Heat radiation: The radiation of inner encapsulation coils can be ignored due to the temperature difference between the adjacent encapsulation coils is small, thus, only the radiation of internal surface of encapsulation 1 and external surface of encapsulation 12 are considered.

Heat source loading

Supposing the total heat source of each encapsulation coil is equal between the actual parameter of reactor and simulation model, so the equivalent current density, which applied to the metal conductor surface in the model:
where $J_a$ is the equivalent current density, $S_{tot}$ – the total area of metal conductor in the model, $J_i$, $S_i$, and $W_i$ are the current density, conductor cross-section area and turns number of the actual encapsulation $i$.

**Boundary setting and grid generation**

The boundary conditions are essential to calculate the temperature field of reactor, the detailed setting refers to the reference [27]. The grid density directly affects the calculation accuracy and time, considering the temperature field simulation results mainly focuses on the region that nearing the encapsulation coils and rain cover, thus, the grid is relatively dense when nearing the encapsulation coils and rain cover, and relatively sparse when the region is far away the encapsulation coils and rain cover, as shown in fig. 3.

**Temperature field simulation and test results**

According to the parameters of reactor, the simulation model is established, and the temperature field simulation results are obtained by the material parameter setting, heat source loading, boundary condition setting and grid generation, as shown in fig. 4.

In fig. 4, it shows that the maximum temperature rise is 51.6 °C. At the same time, the grid-independence result test is carried out, the temperature rise under different grids are given in tab. 2, it can be deduced that the temperature rise reached a stable value when the nodes number is 338432.

<table>
<thead>
<tr>
<th>Number of nodes</th>
<th>116026</th>
<th>152799</th>
<th>200790</th>
<th>259341</th>
<th>338432</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature [°C]</td>
<td>70.9</td>
<td>71.0</td>
<td>71.3</td>
<td>71.6</td>
<td>71.6</td>
</tr>
</tbody>
</table>

![Figure 3. The grid generation of reactor](image)

![Figure 4. Temperature field simulation results](image)
The temperature rise test of prototype is done at the rated current, in the test, the thermal resistance is selected to measure the temperature rise of the reactor, it is attached to the surface of the wrapping coils, and the placement position of thermocouple is given in fig. 5.

The data of the maximum temperature rise is recorded every half hour, the prototype and temperature rise test results of reactor are given in fig. 6, and the maximum temperature rise is gradually increased with the rise of the time, and tends to be stable within 12 hours.

In fig. 6, the measurement results show that the maximum temperature rise is about 49°C, the maximum error coefficient of temperature rise between the simulation results and test results is 5.3%, thus, the correctness of finite element method is verified.

Figure 5. The placement position of thermocouple

Figure 6. The prototype and temperature rise test results of reactor; (a) prototype of reactor and (b) test results

Thermal characteristics analysis and optimization design of the double rain cover

The equal height and heat flux design method can realize the same temperature rise distribution for inner encapsulation without the rain cover, the carrying current capacity of reactor can be fully utilized [28, 29], thus, this method is selected as research object to analyze the influence of rain cover on temperature rise. The main parameters of air core reactor are the rated inductance is 20.9 mH, rated current is 875.5 A, the encapsulation height is 1.75 m, the air ducts width are 0.025 m, encapsulation number is 12, and the inner radius of reactor is 0.3 m, the metal conductor material is Al.
Temperature field simulation results
with the different rain cover

According to the structure characteristic of the double rain cover, the main factors affecting the temperature rise of the reactor are six, they are $L_1$, $L_2$, $L_3$, $H_1$, $H_2$, and $\theta$, thus, the previous six factors are selected as the variables. Meanwhile, the accuracy will be reduced when the number of determined level is small, and the amount of computations is large and the computation time is long when the number of determined level is large. In order to balance the calculation accuracy and time, combined with the engineering experience, the five levels for each factor are selected, as shown in tab. 3.

Table 3. The five level of each factor

<table>
<thead>
<tr>
<th>Level</th>
<th>$L_1$ [m]</th>
<th>$L_2$ [m]</th>
<th>$L_3$ [m]</th>
<th>$H_1$ [m]</th>
<th>$H_2$ [m]</th>
<th>$\theta$ [$^\circ$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.90</td>
<td>0.20</td>
<td>0.60</td>
<td>0.100</td>
<td>0.30</td>
<td>10.0</td>
</tr>
<tr>
<td>2</td>
<td>0.95</td>
<td>0.25</td>
<td>0.65</td>
<td>0.125</td>
<td>0.35</td>
<td>12.5</td>
</tr>
<tr>
<td>3</td>
<td>1.00</td>
<td>0.30</td>
<td>0.70</td>
<td>0.150</td>
<td>0.40</td>
<td>15.0</td>
</tr>
<tr>
<td>4</td>
<td>1.05</td>
<td>0.35</td>
<td>0.75</td>
<td>0.175</td>
<td>0.45</td>
<td>17.5</td>
</tr>
<tr>
<td>5</td>
<td>1.10</td>
<td>0.40</td>
<td>0.80</td>
<td>0.200</td>
<td>0.50</td>
<td>20.0</td>
</tr>
</tbody>
</table>

Table 4. Simulation results with the different rain cover

<table>
<thead>
<tr>
<th>Case</th>
<th>$L_1$ [m]</th>
<th>$L_2$ [m]</th>
<th>$L_3$ [m]</th>
<th>$H_1$ [m]</th>
<th>$H_2$ [m]</th>
<th>$\theta$ [$^\circ$]</th>
<th>Temperature rise</th>
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</thead>
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<td>–</td>
<td>–</td>
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<td>–</td>
<td>–</td>
</tr>
<tr>
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<tr>
<td>19</td>
<td><strong>1.05</strong></td>
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<td><strong>0.65</strong></td>
<td><strong>0.200</strong></td>
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<td>10.0</td>
<td>53.68</td>
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</tbody>
</table>
In tab. 3, it exists 15625 (5^6 = 15625) different structural parameters of the double rain cover by permutation and combination method, in order to reduce the calculation amount and time, the orthogonal experimental design method is adopted in this paper, it is a method to study multi-factors and multi-levels by selecting some representative horizontal combinations, and finally find out the optimal horizontal combination based on the test results.

Meanwhile, the orthogonal table, $L_{25}(5^6)$, is used based on the previous factors and levels, and the simulation results with different structure parameters of double rain cover are given in tab. 4. Where, the Case 0 is defined as the temperature rise of reactor without the rain cover.

In tab. 4, it shows that the structure parameters of double rain cover have a great influence on temperature rise of reactor, in Case 1, the maximum temperature rise is 72.57 °C, but in Case 19, the temperature rise is 53.30 °C, they are significantly higher than the situation without the rain cover.

In order to analyze the reasons that the temperature rise of reactor is higher and different when adding the rain cover, the equivalent model and simulation results of Cases 1 and 19 are selected, as shown in figs. 7 and 8.
The extracted path of reactor is given based on the aforementioned simulation results, as shown in fig. 9.

The temperature and axial fluid velocity distribution of the air ducts along the radial direction was extracted with the different case, as shown in fig. 10.

In fig. 10, it can be seen that the maximum temperature rise of inner encapsulation coils are basically the same, so the carrying ability can be efficiently utilized. Meanwhile, the maximum fluid velocity in the air ducts is 1.1 m/s in Case 0, however, when adding the double rain cover, the fluid velocity becomes the 0.5 m/s and 0.8 m/s in Cases 1 and 19, respectively, so it can be concluded that the fluid velocity change leads to the temperature rise of the reactor increased.

Table 5. Performance statistics analysis of the double rain cover

<table>
<thead>
<tr>
<th>Case</th>
<th>$L_1$ [m]</th>
<th>$L_2$ [m]</th>
<th>$L_3$ [m]</th>
<th>$H_1$ [m]</th>
<th>$H_2$ [m]</th>
<th>$\theta$ [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$PS_1$</td>
<td>304.74</td>
<td>299.13</td>
<td>294.15</td>
<td>298.29</td>
<td>298.59</td>
<td>293.70</td>
</tr>
<tr>
<td>$PS_2$</td>
<td>286.66</td>
<td>288.10</td>
<td>286.68</td>
<td>292.60</td>
<td>287.16</td>
<td>285.47</td>
</tr>
<tr>
<td>$PS_3$</td>
<td>279.80</td>
<td>282.68</td>
<td>285.30</td>
<td>282.87</td>
<td>280.75</td>
<td>283.36</td>
</tr>
<tr>
<td>$PS_4$</td>
<td>278.16</td>
<td>281.27</td>
<td>279.46</td>
<td>280.30</td>
<td>280.61</td>
<td>278.77</td>
</tr>
<tr>
<td>$PS_5$</td>
<td>276.39</td>
<td>274.57</td>
<td>280.16</td>
<td>271.69</td>
<td>278.64</td>
<td>284.45</td>
</tr>
<tr>
<td>$R_j$</td>
<td>28.35</td>
<td>24.56</td>
<td>14.69</td>
<td>26.60</td>
<td>19.95</td>
<td>14.93</td>
</tr>
</tbody>
</table>
In tab. 5, the calculation procedure of $PS$ can be explained by an example, $PS_1$ is equal to the sum of temperature rise in Level 1, which locates the row from Cases 1-5.

The parameter, $R_j$, is defined \[ (6) \]
\[
R_j = \max\left(PS_k\right) - \min\left(PS_k\right), \quad L = 1, 2, 3..., 5
\]
where $j$ is the stands for the six undermined factors and $L$ – is the corresponding level of each parameter.

The total range is:
\[ \sum R_j = R_{11} + R_{12} + R_{13} + R_{14} + R_{15} + R_{16} \quad \theta \\
\]  

The contribution ratio is defined as the eq. (8), which indicates the influence degree of each parameters on temperature rise of the reactor:
\[ \theta \]
\[
Co_j = \frac{R_j}{R_{\text{sum}}}
\]

From the eq. (8), the contribution rate of each parameters can be plotted, as shown in fig. 11.

In fig. 11, it can be found that the contribution ratio of parameter $H_1$, $L_1$, and $L_2$ are obviously higher than $H_2$, $L_3$, and $\theta$, thus, the more attention should be paid in the design of double rain cover.

**Optimization design of the double rain cover**

According to the simulation results in tab. 3, the curves is plotted, which reflects the effect of structural parameter variation on temperature rise of reactor, as shown in fig. 12.

In fig. 12, it can be seen that the maximum temperature rise of reactor gradually decreased with the rise of the parameter $H_1$, $L_1$, $L_2$, $L_3$, $H_1$, $H_2$, and $\theta$, the mainly reason is that the effect of the rain cover on the fluid velocity in the air ducts is decreased with the rise of the aforementioned parameters, the reactor has a better heat dissipation conditions and lower temperature rise. Meanwhile, it exists an inflection point in the parameter $\theta$, when the value of $\theta$ continues to increase, it will hinder the fluid-flow between the lower and upper rain cover. Thus, the optimal parameter of double rain cover can be obtained when the temperature rise obtains the minimum in the curve, as shown in tab. 6.

According to the initial design parameters of reactor and the optimal structure parameter of the double rain cover, the temperature field simulation model is established, and the results is shown in fig. 13.

In fig. 13, the maximum temperature rise of reactor is only 52.43 °C, it is the minimum among the 25 different double rain cover structure parameter, thus, the simulation results verify the correctness of the optimization method. Meanwhile, the temperature distribution is extracted according to the simulation result, as shown in fig. 14. It can be seen that the temperature rise distribution of inner encapsulations coils are basically the same under the optimal parameter of double rain cover.

**Conclusions**

In this paper, a fluid-thermal coupled finite element model is established, the test results verified the accuracy of temperature field simulation calculation. Meanwhile, the or-
orthogonal experimental method is adopted to analyze the influence laws of double rain cover on temperature rise of rain cover, and the following conclusions can be obtained.

- When adding the rain cover, the maximum temperature rise is changed from 46.32-72.57 °C, and the reasons are given by analyzing the fluid velocity distribution of air ducts between the encapsulation coils, the maximum fluid velocity of air ducts is changed from 1.1-0.5 m/s without and with the rain cover.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$L_1$ [m]</th>
<th>$L_2$ [m]</th>
<th>$L_3$ [m]</th>
<th>$H_1$ [m]</th>
<th>$H_2$ [m]</th>
<th>$\theta$ [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>1.1</td>
<td>0.4</td>
<td>0.8</td>
<td>0.2</td>
<td>0.5</td>
<td>17.5</td>
</tr>
</tbody>
</table>

Table 6. The optimal parameters of the double rain cover
The influence curve and contribution rate of each factor on the temperature rise are analyzed, the contribution ratio of the parameter $H_1$, $L_1$, and $L_2$, are obviously higher than the parameter $H_2$, $L_3$, and $\theta$, so the more attention should be paid in the design of double rain cover. Meanwhile, the maximum temperature rise of reactor is only 52.43 ℃ based on the optimal structural parameters of double rain cover, so the optimization method can obviously reduce the temperature rise of reactor.

According to the simulation results, the temperature rise distribution of inner encapsulation coils are basically the same under the optimal parameters of double rain cover, the current carrying capacity of coils can be fully utilized, which provides an important guidance meaning for the optimization design of reactor.

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