Structural Simulation and Optimization Analysis of Electric Heater Based on Chimney Effect

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Abstract. The natural convection heater is a commonly used electric heater, which belongs to the chimney structure heater. In this paper, a three-dimensional model is built and simulated by the finite element analysis software. The influence of chimney height, vent size and vent shape on chimney effect was studied by orthogonal experiment. The simulation results show that the electric heater with 85 mm chimney height, 6 mm equivalent diameter of the vent and square shape of the vent has the best heat transfer effect. The simulation work can play a guiding role for the customization of electric heater structure.

1. Introduction

With the rapid growth of China's economy, the environment and air quality has become worse and worse in recent years, which has seriously affected the sustainable development of China's economy [1-3]. The investigation shows that the large consumption of coal is the major cause of air pollution in China [4, 5]. China's coal is mainly used for heating [1, 4, 5]. Therefore, to solve the problem of air pollution in China, electric heaters can be used to replace coal heating.

Heaters can be divided into two categories: radiant heaters and convective heaters. Convective heaters can also be divided into natural convective heaters and forced convective heaters. Natural convection heater is becoming more and more popular because of its quiet, comfortable, rapid heating and other advantages. In order to improve the efficiency of natural convection, many scholars at home and abroad have carried out research. Zu-Guo Shen et al. studied the effect of aperture size on free convection and radiation heat transfer in isoflux upward-facing cylindrical cavities by numerical simulation and experiment [6]. Leonardo Micheli et al. reported general correlations among geometry, orientation and thermal performance of natural convective micro-finned heat sinks [7]. Zhang Min et al. carried out numerical simulation of natural convection in trapezoidal cavity with internal heat source. The effects of different aspect ratios and rotation angles of the internal heat source on the temperature field and flow field in a closed trapezoidal cavity with a certain area of the internal heat source are studied [8]. Yang Huizhu et al. studied the optimization of sawtooth fin height, fin spacing, fin thickness and fin pitch in heat exchangers [9].

In this paper, a three-dimensional model is built and simulated by the finite element analysis software. Three factors that influence the effect intensity of chimney, namely, chimney height, vent size and vent shape, were studied by orthogonal experiment.
2. Theoretical basis and model establishment

2.1 Theoretical basis
Take any infinitesimal hexahedron from the heat-conducting object as the research object, and make the following assumptions for simplified analysis:

1. Heat conducting object is isotropic continuum.
2. \( \rho \) is the density of microelement and \( c \) is the specific heat capacity of microelement. Both have nothing to do with temperature.
3. There is a uniformly distributed internal heat source in the body, whose value is \( \Phi \). It represents the heat energy produced or consumed per unit volume in unit time and its unit is W/m³.

According to the law of conservation of energy and Fourier's law, general form of three-dimensional unsteady heat conduction differential equation in Cartesian coordinates can be written as follows Eq.(1) [10]:

\[
\rho c \frac{\partial t}{\partial \tau} = \frac{\partial}{\partial x} \left( \lambda \frac{\partial t}{\partial x} \right) + \frac{\partial}{\partial y} \left( \lambda \frac{\partial t}{\partial y} \right) + \frac{\partial}{\partial z} \left( \lambda \frac{\partial t}{\partial z} \right) + \Phi
\]

(1)

Where \( \rho, c, \lambda \) and \( \Phi \) are variables.

In this paper, the heater studied is a device with three-dimensional, transient, internal heat source and constant physical properties. Its thermal conductivity differential equation is as Eq. (2).

\[
\alpha \left( \frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 t}{\partial y^2} + \frac{\partial^2 t}{\partial z^2} \right) + \frac{\Phi}{\rho c} = \frac{\partial t}{\partial \tau}
\]

(2)

Where \( \alpha = \frac{\lambda}{\rho c} \) is thermal diffusivity.

Combined with the boundary conditions, the differential equation of heat conduction and the temperature distribution characteristics can be obtained.

2.2 Model establishment
The chimney effect simulation of electric heater is carried out by finite element analysis software. To simplify the simulation, a chimney passage inside the electric heater is simulated. The reference model is shown in Fig. 1. The vent of the electric heater is square, the equivalent diameter is 4 mm, the height is 80 mm, and the material is Aluminum-3003. Between the two fins is the internal heat source, which is represented by a cuboid with a power of 20 W. Grid generation is shown in Fig. 2.

Fig. 1 Simulation model of single chimney channel
3. Orthogonal experiment design and results

3.1 Orthogonal experiment design
In this paper, orthogonal simulation experiments are used to study the combination of three variables: the height of the chimney H, the equivalent diameter of the vent D and the shape of the vent. The shape of the vent is shown in Fig. 3. According to the current situation of electric heaters sold in the market, the constraint range of D and H is determined as follows: 4 mm≤D≤10 mm, 80 mm≤H≤95 mm. Based on the data in the orthogonal table, the corresponding model is established, and the optimal combination of heat transfer parameters and the maximum temperature T at the air outlet of the electric heater can be obtained by substituting it into the simulation software. In the table, A, B and C represent the shape of the vent, the equivalent diameter of the vent and the height of the chimney respectively. The vent shapes represented by A1, A2, A3 and A4 are square, round, regular pentagon and trapezoid respectively.

(a) Square; (b) Round; (c) Regular pentagon; (d) Trapezoid

| Number | A   | B | C | T/℃ |
|--------|-----|---|---|-----|
| 1      | A1  | 4 | 80| 64.261 |
| 2      | A1  | 6 | 85| 46.917 |
| 3      | A1  | 8 | 90| 37.674 |
| 4      | A1  | 10| 95| 32.090 |
| 5      | A2  | 4 | 85| 58.943 |
| 6      | A2  | 6 | 80| 52.434 |
| 7      | A2  | 8 | 95| 34.934 |

Table 1 Orthogonal design L16 (4³)

Fig. 2 The mesh of model
3.2 Results

By taking the mean value of the orthogonal experimental results, the influence trend of three parameters A, B and C on T can be obtained, as shown in Fig. 4- Fig. 6.

### Table 1

| A  | B  | C  | T    |
|----|----|----|------|
| 8  | A₂ | 10 | 90   | 34.396 |
| 9  | A₃ | 4  | 90   | 51.980 |
| 10 | A₃ | 6  | 95   | 39.096 |
| 11 | A₃ | 8  | 80   | 45.372 |
| 12 | A₃ | 10 | 85   | 37.478 |
| 13 | A₄ | 4  | 95   | 43.662 |
| 14 | A₄ | 6  | 90   | 41.050 |
| 15 | A₄ | 8  | 85   | 39.988 |
| 16 | A₄ | 10 | 80   | 39.699 |

![Fig. 4 The relationship between average temperature and the shape of vents](image1.png)

![Fig. 5 The relationship between average temperature and D](image2.png)

![Fig. 6 The relationship between average temperature and H](image3.png)

4. Discussions

As can be seen from Fig. 4, when the vent is square, the average temperature of the electric heater vent is significantly higher than the other three vent shapes. In this structure, the square vent has the best heat transfer effect among the four vent shapes. However, by comparing the square vent with the best heat transfer effect and the trapezoid vent with the worst heat transfer effect, it can be found that the
average temperature difference between them is 4.136 ℃, and the temperature difference is not obvious, which shows that in this structure, the shape of vent has little effect on the heat transfer effect.

As can be seen from Fig. 5, when the diameter of the vent is 4 mm, the average temperature of the electric heater vent is significantly higher than the other three vents. When D increased from 4 mm to 6 mm, the average temperature of electric heater decreased rapidly from 54.712 ℃ to 44.874 ℃, which reduces 9.838 ℃ in total; when D increased from 6 mm to 10 mm, the temperature of electric heater decreased slowly, and the average temperature dropped 5.382 ℃ and 3.576 ℃ in turn. It shows that in a certain range, with the increase of the equivalent diameter of the vent, the temperature drops rapidly, and when it reaches a certain limit, the temperature drops slowly. By comparing the vent temperature with the best heat transfer effect and the worst heat transfer effect, it can be found that the average temperature difference between them is 18.796 ℃, indicating that in this structure, the vent diameter has a great influence on the heat transfer effect. In order to ensure the heat transfer effect of the electric heater and the mechanical strength of the electric heater, D = 6 mm.

It can be seen from Fig. 6 that with the increase of chimney height, the average temperature of the air outlet of electric heater keeps decreasing. When H increases from 80 mm to 95 mm, the average temperature of the air outlet of electric heater successively decreases by 4.61 ℃, 4.557 ℃ and 3.829 ℃. By comparing the vent temperature with the best heat transfer effect and the worst heat transfer effect, it can be found that the average temperature difference between them is 12.996 ℃, indicating that in this structure, the chimney height has a great influence on the heat transfer effect. In actual production, the increase of H will also increase the weight of electric heater and consumables, significantly increasing the cost of materials and transportation. Therefore, considering both cost and heat transfer effect, H = 85 mm.

According to the above analysis and discussion, it is not difficult to find out that the best parameter combination of heat transfer effect is A1B2C2, that is, the electric heater with 85 mm chimney height, 6 mm equivalent diameter of the vent and square shape of the vent has the best heat transfer effect. Obviously, this combination is the parameter of the second orthogonal experiment. At this time, T = 46.917 ℃, the temperature field distribution of electric heater is shown in Fig. 7.

![Fig. 7 Distribution of temperature field](image)

5. Conclusions
From the orthogonal experimental results, it can be concluded that the shape of vent has little influence on the heat transfer effect, while the size of vent and the height of chimney have great influence on the heat transfer effect. Considering from transportation cost, material cost, mechanical strength and heat transfer effect, the best parameter combination of heat transfer effect is A1B2C2, that is, the electric heater with 85 mm chimney height, 6 mm equivalent diameter of the vent and
square shape of the vent has the best heat transfer effect. The simulation work provides some guidance for the customization of electric heater structure.

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