Research on the Key Factors of Improving Thermal Efficiency and Temperature Uniformity of Oven

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Abstract. As a convenient kitchen appliance, the oven is more and more popular. The thermal efficiency of the oven and the uniformity of the temperature field in the inner chamber are the key indexes to measure the product quality. In this paper, the existing oven in 3D hot air mode of low thermal efficiency and uneven temperature field were analyzed. The heat insulation, heat dissipation system and component structure of the oven were improved, and the effects of various improvement measures on the thermal efficiency and inner temperature field of the oven were simulated. The results show that the thermal efficiency and temperature uniformity of the oven can be greatly improved by increasing the thickness of the insulation cotton, pasting aluminum foil on the inside and outside of the side plate, reducing the speed of the back fan, optimizing the structure of the fan guide vane and the position of the back heating pipe.

1. Introduction
At present, some researches have been carried out on the thermal environment of oven equipment, such as Wu et al. [1] have optimized the internal flow field analysis and structure of forced convection oven. Zhang et al. [2] studied the optimization of the temperature field in the oven cavity under different modes, improved the structure of the oven cover plate and increased the fan speed, and optimized the uniformity of the temperature field in the oven. Wang et al. [3] studied the heat transfer mechanism of the oven at different working stages, and put forward guiding opinions on the structure of the oven by analyzing the internal heat transfer mode. Zinedine Khatir et al. [4] studied the small forced convection oven with bread, analyzed the air flow and temperature distribution in the oven, and demonstrated that the setting of boundary conditions and the selection of flow model had great influence on the temperature of the oven.

2. Establishment of the oven model
2.1. Simplified physical model
The simplified physical model of the research object is shown in Figure 1. The inner diameter of the oven is 450 mm length (L) × 340 mm width (W) × 340 mm height (H), and the baffle is 420 mm (L) × 390 mm (W). The oven is equipped with upper, lower and back heating pipes with radius of 3.3 mm, back fan radius of 75 mm and return air speed of 1.5 m/s.
2.2. Boundary conditions

The definition surface and boundary conditions of the model are shown in Table 1.

| Definition surface   | Boundary conditions                        |
|----------------------|--------------------------------------------|
| Upper heating pipe   | Heat flux $q=15969.2$ W/m$^2$, Emissivity 0.7 |
| Lower heating pipe   | Heat flux $q=17487.3$ W/m$^2$, Emissivity 0.7 |
| Back heating pipe    | Heat flux $q=16827$ W/m$^2$, Emissivity 0.7 |
| Oven door            | Heat transfer coefficient $k=1.8$ W/(m$^2$ K), $t=20$ °C, Emissivity 0.15 |
| Hot air fan          | Rotational speed $n=1300$ r/min, it is clockwise from the entrance |
| Other walls          | Heat transfer coefficient $k=1.6$ W/(m$^2$ K), $t=20$ °C, Emissivity 0.7 |
| Air inlet            | Pressure inlet, $t=250$ °C                 |
| Air outlet            | outflow                                    |

2.3. Numerical simulation method

Fluent software was used to simulate the temperature field in the inner chamber of the oven. The changes of the temperature field in the chamber under various improvement schemes were studied to find out the key factors affecting the thermal efficiency and temperature uniformity of the oven.

1. Tet/Hybrid is used for grid generation, and the total number of grids is 806742;
2. The gas flow pattern in the oven is three-dimensional incompressible turbulent flow;
3. The turbulence viscosity model adopts the standardized $\overline{k}−\overline{\varepsilon}$ model [5];
4. The radiation model adopts DO model;
5. Air is selected as material and Boussinesp model is adopted;
6. The second order difference of SIMPLEC is chosen as the algorithm.

3. Model validation

Aiming at the existing oven, the temperature field in the inner cavity of the oven was measured, and the test results were compared with the simulation results to verify the rationality of the numerical simulation simplification. According to the principle of nine point temperature measurement, the upper, middle and lower layers of the inner chamber of the oven were taken as the corresponding three reference planes. The distances between the upper, middle and lower layers of the test layers were 204 mm, 136 mm and 77 mm respectively. Nine measuring points were evenly arranged on each surface (as shown in Figure 2). The pre-heating temperature of the oven was set at 190 °C, and the temperature value of the measuring points were recorded every 10 seconds with the temperature recorder (OHR-F800).
Figure 2. Layout of three layer grill test points

It can be seen from Figure 3 that the simulated value of the average temperature in the inner cavity of the oven is 202.5 °C and the measured value is 186.8 °C. The simulated value is 15.7 °C higher than the measured value, and the temperature deviation of each measuring point is between 3% and 10%, the average deviation is 7.21%, and the maximum deviation is 9.82% < 10%, which is within the acceptable range. In addition, the distribution trend of the simulated temperature field is basically consistent with the measured value. Therefore, the model can be used.

Figure 3. Simulated and measured temperature fields of existing oven

4. Analysis of the key factors affecting the thermal efficiency of the oven

According to the knowledge of heat transfer, the heat transfer in the oven is mainly convection heat transfer and radiation heat transfer. Convection heat transfer mainly includes convection heat transfer between walls and air, and convection heat transfer between air and food; Radiation heat transfer mainly includes radiation heat transfer between walls and food, and radiation heat transfer between heating pipes and food [6].

The existing oven liner is a cold-rolled sheet with blackened enamel on its surface. The box body is made of double-layer hot-dip galvanized sheet, which is filled with insulation material and insulation cotton. The cabinet door assembly is composed of high borosilicate glass, Low-E glass and tempered glass from the inside to the outside, which can effectively reflect high-temperature radiation. At the same time, the three-layer glass forms a double-layer air insulation layer to prevent high-temperature penetration.

Through the detailed analysis of the internal heat transfer principle and the structure of the oven, the main factors affecting the thermal efficiency of the oven are the heat loss in the process of heat conduction and radiation, and the insufficient heat dissipation of the oven. In order to improve the
thermal efficiency of the oven, the heat insulation and heat dissipation system of the oven are optimized. Combined with the follow-up experiments, the following reasonable improvement schemes are proposed.

![Figure 4. Thermal efficiency improvement scheme](image)

5. **Analysis of the key factors affecting the temperature uniformity of the oven**

After the numerical simulation and experimental test of the original oven, it was found that the internal temperature field of the original oven was significantly uneven in 3D hot air mode, and the temperature standard deviation reached 4.6 ℃. According to the velocity streamline and temperature contour, the main causes of temperature inhomogeneity in the oven include the existence of central vortex and insufficient heating of inlet air by back heating pipe.

5.1. **Optimization of guide vane structure of back fan**

Because of the large circumferential velocity component at the outlet of the back fan, the vortex in the center of the oven is very obvious. By reasonably improving the structure of the guide vane of the back fan, the circumferential velocity component of the fan outlet was reduced, so as to suppress the formation of the vortex in the oven chamber. Based on the straight plate folding guide vane structure of the original oven, the actual processing technology of the oven blade and mathematical modeling, two kinds of guide vane structures, namely straight guide vane and twisted guide vane, were designed and analyzed with Fluent software.

It can be seen from Figure 5 that the speed loss caused by the straight guide vane structure is relatively large, the change of streamline direction is relatively limited, and the vortex inside the oven is still relatively obvious. The temperature uniformity of the inner cavity of the twisted guide vane structure is better than that of the first two guide vane structures, and there is no big vortex, especially in the middle region. According to the results of numerical simulation, the ratio of radial velocity component to circumferential velocity component is 1.05, 1.41 and 2.89 respectively. The average temperature in the inner chamber of the oven is 182.4 ℃, 186.8 ℃ and 184.3 ℃, and the temperature standard deviation is 3.8 ℃ and 4.6 ℃, and 2.6 ℃ respectively. Therefore, the twisted structure can be used to optimize the guide vane structure of the back fan.
5.2. **Position optimization of back heating pipe**

In 3D hot air mode, because the heating pipe of the original oven is located at the periphery of the fan inlet, only the peripheral air is heated in actual work, which results in long heating time and poor heating effect in the oven. In order to further improve the temperature uniformity of the oven, the back heating pipe was optimized in the numerical simulation. It is mainly to adjust the space position of the back heating pipe, as shown in Figure 6 that is, the heating pipe moves to the tail of the fan, so that the semi-phase outlet air of the fan is directly opposite to the heating pipe, so as to improve the heating effect.

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**Figure 5.** Velocity streamline (x=170 mm plane) and temperature contour (z=170 mm plane) of three different guide vane structures

**Figure 6.** Temperature contour (z=170 mm plane) of oven chamber under different heating pipe positions
According to the temperature contour, the temperature uniformity of the oven after changing the position of the heating tube is better than that of the original heating tube. The average surface temperature of the oven is 185.0 ℃, and the temperature standard deviation is reduced by 1.8 ℃.

6. Results and Discussion
On the basis of the existing numerical simulation results, the thermal efficiency, the actual temperature distribution in the inner chamber of the oven were analyzed experimentally when the pre-heating temperature was set at 190 ℃, so as to obtain the improvement effects of various improved structures on the uniformity and thermal efficiency of the oven. According to the principle of nine point temperature measurement, the temperature distribution of the three-layer grill in the inner cavity of the oven and the improved oven was measured as shown in Figure 6 and Figure 7.

Under the above experimental conditions, the average time for the original oven to reach 190 ℃ is 268s, while the average time for the new type of oven with improved structure to reach 190 ℃ is 184s. Combined with the evaluation method of the thermal efficiency of the new oven, the thermal efficiency of the new type of oven has been significantly improved, and the thermal efficiency has increased by 31.3%. After the inner cavity temperature of the original oven reaches 190 ℃, the average temperature of the three-layer grill fluctuates greatly and finally stabilizes at ± 4.63 ℃. However, the average temperature fluctuation of the three-layer grill is small and finally stabilizes at ± 1.81 ℃. Obviously, the temperature uniformity of the improved oven has been greatly improved.

7. Conclusion
In this study, the heat insulation and heat dissipation system and components structure of the oven were improved, and the effects of various improvement measures on the thermal efficiency and temperature field of the oven were simulated. The performance test was completed by combining with the experimental test. The study results show that:

(1) 10 mm thick insulation cotton can reduce heat conduction and improve the thermal efficiency of the oven;

(2) The heat conduction can be reduced and the thermal efficiency of the oven can be improved by pasting aluminum foil on the inside and outside of the side plate, replacing Low-E glass and low emissivity oven liner;

(3) Reducing the speed of the back fan by 400 r/min, replacing the back fan with a small circumferential velocity component, and adjusting the position of the back heating pipe can make the heat efficiency and temperature uniformity of the oven greatly improved.
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