Structural Design and Numerical Simulation of FDM Molding Chamber Based on Thermal-Fluid-Structure Coupling

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Abstract. Four different design of FDM molding chamber with hot air circulation were proposed to meet the requirements of temperature uniformity of FDM rapid prototyping equipment. Fluid and solid domain model of FDM molding chamber was established by finite numerical simulation method in order to analyze the influence of the heating rod, blower, air inlet and outlet position on the temperature uniformity and air flow. The results show that the temperature uniformity and air velocity evenness are highest when the heating rod is located on both sides of the molding chamber, the blower is lied at the bottom, the air inlet is located above the left side, and the air outlet is above the right side. And the temperature uniformity is up to 99%. FDM molding chamber prototype was developed according to the simulation results. Air flows evenly, and temperature uniformity is as high as 97.66%, which verified the accuracy and effectiveness of the simulation results deeply.

1. Introduction
Fused deposition modeling (FDM) technology [1] is a kind of 3D printing technology, which refers to heating thermoplastic wire to molten state, using computer to control the moving of printing nozzle according the section profile and trajectory of forming parts, stacking molten wire on printing platform layer by layer, and finally the 3D part is realized. It has been widely used in industrial engineering, art, education and other fields to finish the prototype design and manufacturing, product function development verification, production of special complex parts [2]. As a new technology, it has the advantages of simple system, high material utilization ratio, low maintenance cost and easy to use [3].

FDM molding chamber is an important part of FDM rapid prototyping machine. Also, it is a key factor to maintain the temperature of wire condensing and prevent warpage of workpiece [4, 5], which can ensure the printing accuracy and obtain approving workpiece. Chen Yaping [6], coming from Huazhong University of Science and Technology, designed and explained the temperature control system using controllable silicon. Pang Xueqin [7], coming from Inner Mongolia University of Science and Technology, reconstructed the fused deposition rapid prototyping equipment based on numerical simulation results to meet the control of temperature. Zhang Xiaoping [8], coming from Tsinghua University, studied the principle, method and program design of temperature dynamic simulation during melt deposition.

In this paper, four different structures of FDM molding chamber are designed. Thermal-fluid-solid coupling calculation method is applied to simulate the four structures. The structure of FDM molding
chamber with uniform temperature and reasonable airflow is obtained. Finally, the accuracy and effectiveness of the design and simulation results are verified according to temperature uniformity analysis of the physical prototype.

2. Heat transfer principle and mathematical model

2.1. Heat transfer principle of FDM molding chamber

The FDM molding chamber can be regarded as a closed device, which is composed of molding chamber, inner wall, circulating air passage, outer wall, insulation and organ cover, as shown in Fig.1. The circulating air passage is provided with fan and heating rod, and the inner wall is provided with air inlet and air outlet. The heat generated by the heating rod enters the forming chamber through convection, conduction and radiation. A part of heat flows passing through the air outlet into the molding chamber in convection, because the fan drives air to circulate in the air passage; part of heat transfers through the inner wall into the molding chamber, thereby completing the heating process quickly, while reducing heat loss through the insulation layer to achieve the insulation process.

![Figure 1. Schematic diagram of FDM molding chamber.](image)

2.2. Finite element theory

The fluid inside the FDM molding chamber is self-circulating flowing air, which flows irregularly under the action of airflow and temperature difference. Considering it as an incompressible ideal air, using the turbulence model the expression is:

\[
\frac{\partial \rho k}{\partial t} + \frac{\partial}{\partial x_j} \left( \rho u_j k \right) = \frac{\partial}{\partial x_j} \left( \mu + \sigma_k \mu_t \right) \frac{\partial k}{\partial x_j} + P_k - C_{\mu} \rho c_k
\]

(1)

\[
\frac{\partial \rho \varepsilon}{\partial t} + \frac{\partial}{\partial x_j} \left( \rho u_j \varepsilon \right) = \frac{\partial}{\partial x_j} \left( \mu + \sigma_k \mu_t \right) \frac{\partial \varepsilon}{\partial x_j} + \frac{P_k}{k} C_{\varepsilon} \varepsilon - C_{\varepsilon} \rho c^2
\]

(2)

Where, \( \mu_t \) is turbulent viscosity coefficient, \( P_k \) is generation term of turbulent kinetic energy, the model constant \( C_{\alpha_1} = 1.44, C_{\alpha_2} = 1.92, C_{\mu} = 0.09, \sigma_{\varepsilon} = 0.5, \sigma_k = 0.5 \).

Make the following assumptions [9]:

1) Fluid inside the molding chamber conforms to mass conservation equation, that is, volume remains constant during the body motion, and its expression is:

\[
\frac{\partial (\rho u_x)}{\partial x} + \frac{\partial (\rho u_y)}{\partial y} + \frac{\partial (\rho u_z)}{\partial z} + \frac{\partial \rho}{\partial t} = 0
\]

(3)

Where, \( \rho \) is fluid density.

2) Fluid inside the chamber conforms to momentum conservation equation, its expression is:

\[
\frac{dv}{dt} = F + \frac{1}{\rho} \cdot \nabla P
\]

(4)
Where, \( v \) is fluid velocity; \( F \) is mass force of unit mass fluid; \( \nabla \) is Hamiltonian; \( P \) is surface force per unit area.

3) Fluid inside the molding chamber conforms to energy conservation equation, its expression is:

\[
\frac{de_s}{dt} = F_{b1} \cdot v + \frac{1}{\rho} \text{div}(P \cdot v) + \frac{1}{\rho} \text{div}(k \cdot \text{grad}T) + q  
\]  

(5)

Where, \( e_s \) is total energy per unit mass; \( F_{b1} \) is mass force; \( \text{grad}T \) is conduction heat that transmitted from outside of unit mass fluid; \( q \) is radiant heat added to unit mass fluid per unit time.

2.3. Evaluation of temperature uniformity

In order to ensure the validity of measurement results, reference points are distributed uniformly at various positions inside the chamber. The temperature of each reference point is measured, the average temperature and temperature uniformity in the molding chamber are calculated. The expression is:

\[
\bar{T} = \frac{1}{n} \sum_{i=1}^{n} T_i  
\]

(6)

\[
\sigma = \left( \frac{1}{n} \sum_{i=1}^{n} (T_i - \bar{T})^2 \right)^{1/2}  
\]

(7)

Where, \( T_i \) is the temperature of each measuring point, \( n \) is the number of measuring points.

3. Structure design

The key point of controlling heat flow and achieving better temperature uniformity is to place heating rods, fans, air inlets and outlets reasonably in the FDM molding chamber. In the case that the overall size of the molding chamber is determined substantially, two different heating rods and fan positions are designed according to the range of heat radiation and conduction. One is that the heating rod is arranged at the bottom of circulating air passage, the fan is at the lower right; another is that the heating rod is arranged on the left and right sides of the circulating air passage, the fan is arranged at the bottom. According to the action characteristics of heat convection, two different air inlets and air outlets are designed. One is only the upper opening on the left and right sides of the molding chamber. At this time, heat entering generates from top to bottom by convection; the other is opening the left and right sides of the chamber. At this time, heat entering generates from left to right by convection.

Table 1 shows the structural design of the FDM molding chamber. The schematic diagram of heat transfer principle is shown in Fig. 2.

Table 1. Component locations of four structures

|        | Heating rods | Fans           | Air inlet | Air outlets |
|--------|--------------|----------------|-----------|-------------|
| Plan 1 | bottom       | lower right    | upper left| upper right |
| Plan 2 | bottom       | lower right    | left side | right side  |
| Plan 3 | both sides   | bottom         | upper left| upper right |
| Plan 4 | both sides   | bottom         | left side | left side   |

a) Plan 1  b) Plan2  c) Plan3  d) Plan4

Figure 2. The schematic diagram of heat transfer principle.
4. Numerical simulation analysis
According to the principle of single variable, numerical simulation of four structure under the same conditions is carried out to analyze air flow and temperature distribution in the FDM molding chamber, which provides a theoretical basis for the structure design.

4.1. Finite element model
The FDM molding chamber is a symmetrical structure in three-dimensional space. It is only necessary to establish a two-dimensional model of symmetrical section of the fluid domain to reflect the temperature and airflow inside the molding chamber in order to reduce calculation time, obtain higher meshing results. Since the asbestos insulation material is filled between the outer wall of the circulating air passage and the molding, it can be converted into heat flux applied to the outer wall of the circulating air passage, so that the part of the model structure can be omitted.

As shown in Fig.3, the two-dimensional model of symmetrical section of the four structures has an outer wall size of 1100×1250 mm, an inner wall size of 900×1150 mm, a heating rod diameter of 30 mm, and a single opening at the air inlet of 20 mm. The solid wall material is 45 steel, and the fluid domain material is air. The material parameters are shown in Table 2.

| Specific heat capacity [J/(kg*K)] | Thermal conductivity [W/(m*K)] | Density [kg/m³] | Young's modulus [Pa] | Poisson's ratio |
|----------------------------------|-------------------------------|----------------|----------------------|----------------|
| 45                               | 475                           | 44.5           | 7850                 | 200e9          | 0.33           |

4.2. Simulation result analysis
Fig.4 shows the airflow velocity distribution nephograms of four structures. It can be seen that in plan 1 and 3, the air inlet and outlet are placed respectively at the upper left and upper right of the molding chamber, air flows in the circulating air passage, and the velocity is uniform; in plan 2 and 4, the air inlet and outlet are disposed on the side wall of the molding chamber. In plan 2, most air flows upward inside the left passage, and little flows right through the left ventilation panel. In plan 4, most air enters the molding chamber from the left ventilation panel after contacting the heating rods, and then flows into the passage from the right ventilation panel, so that the air can only partially circulate at the bottom of the molding chamber, the heat cannot be effectively brought to the molding chamber to meet the temperature requirements.
Fig. 4. The nephograms of airflow velocity distribution.

Fig. 5 shows the temperature distribution nephograms of four structures. It is obviously that in plan 1 and 2, it is far away from the heating platform when the heating rod is placed at the bottom of the molding chamber, as a result, there is a certain temperature difference between the upper and lower parts of the molding chamber, and the heating efficiency is very low; in plan 3 and 4, the overall temperature difference is small when the heating rod is disposed on both sides, because in this plan, a part of heat is solid conducted, and a part is driven by the airflow to realize the heat flow circulation.

Fig. 5. The nephograms of temperature distribution.

As shown in Fig. 6, in order to further characterize temperature uniformity, seven paths, a (y=0.33), b (y=0.56), c (y=0.79), d (y=1.02) at transverse direction, e (x=0.3), f (x=0.55), g (x=0.8) at longitudinal direction, were set uniformly inside the molding chamber. The intersection of each path is the point we will measure according to numerical simulation results. Measurement results are shown in Table 3.

Fig. 6. Schematic diagram of the measurement path
Table 3. Temperature measurement results.

| Point  | Plan 1 (K) | Plan 2 (K) | Plan 3 (K) | Plan 4 (K) |
|--------|------------|------------|------------|------------|
| 1      | 363.77     | 360.71     | 369.90     | 368.30     |
| 2      | 361.14     | 355.12     | 370.64     | 370.30     |
| 3      | 359.10     | 351.43     | 370.62     | 370.27     |
| 4      | 357.00     | 348.98     | 369.70     | 368.81     |
| 5      | 364.50     | 361.92     | 369.51     | 367.38     |
| 6      | 361.52     | 356.19     | 370.21     | 369.27     |
| 7      | 359.16     | 352.18     | 370.17     | 369.54     |
| 8      | 356.95     | 349.40     | 369.42     | 368.66     |
| 9      | 363.76     | 360.71     | 369.90     | 368.30     |
| 10     | 361.14     | 355.12     | 370.64     | 370.30     |
| 11     | 359.10     | 351.43     | 370.62     | 370.27     |
| 12     | 357.00     | 348.98     | 369.70     | 368.81     |

Table 4. Average temperature and temperature uniformity of four structures.

|         | Average temperature(K) | Temperature uniformity (%) |
|---------|-------------------------|----------------------------|
| Plan 1  | 360.35                  | 99.24                      |
| Plan 2  | 354.35                  | 98.66                      |
| Plan 3  | 370.09                  | 99.88                      |
| Plan 4  | 369.18                  | 99.73                      |

Calculate the average temperature and temperature uniformity of four structures. As shown in Table 4, it is obvious that when the heating rod temperature is 100 °C, that is, 373.5 K, the average temperature is 354.35 K in plan 1, 360.35K in plan 2, which is quite different from the setting temperature. The average temperature and temperature distribution in plan 3 and 4 are similar, but the average temperature of plan 3 is 370.09K, and the temperature distribution uniformity is 99.88%, which is slightly higher than plan4. Therefore, plan 3 can be initially selected.

5. Model verification

A prototype was developed according to plan 3. After installation and commissioning, set the molding chamber temperature to 100 °C under the condition that ambient temperature is 20 °C. After 15 minutes of heating, the temperature distribution of the same points were measured. The average temperature is 369.39K, and the temperature uniformity at each measuring point is 98.14%.

Obviously, the temperature distribution in the chamber is uniform, the actual results are basically consistent with numerical simulation results, which further verified the accuracy of simulation results.

6. Conclusion

According to the characteristics of the molding chamber in FDM rapid prototyping equipment, four different air circulation structures were designed. Thermo-fluid-solid coupling simulations were carried out to verify the air flow and temperature uniformity of these four structures, the main conclusions are as follows:

1) For the plan 3, when the heating rods are on the left and right sides, the fan is on the bottom, the air inlet is on the upper left side, and the air outlet is on the upper right side, the average temperature in the molding chamber can reach 370.09K, the internal temperature uniformity can reach 99.88%, and the hot air flows the most regular.

2) Based on the simulation results, a prototype of the molding chamber was developed. The actual test showed that the internal air flows stably and the temperature uniformity reached 98.14%. The accuracy and validity of the simulation results are verified by the actual results.
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