Fast Algorithm for Heating Injection Mold by Water

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Abstract. This paper puts forward a fast algorithm for heating injection mold by water accordance with these problems that the computing is enormous to simulate heating injection mold and there is a limitation for velocity of hot water that it should not be too larger otherwise simulating algorithm will be failure. The method does the similarity transformation to construct similarity model whose solution is the same with the mathematics model for the problem of heating injection mold by water, and the simulation time will be reduced greatly at the precondition of keeping precision using the similarity model. The first step of similarity transformation is time similarity transforming for the fluid governing equation describing the moving of hot water in the time area, i.e., actual heating time area for mold heating is transformed to heating time area of similarity model while keeping spatial domain unchanged. Meanwhile it does the same transformation for the heat conduction governing equation in the time area, also keeping spatial domain unchanged. In this way the similarity model of the origin mathematics model for fluid-solid coupling problem of heating mold by water is obtained. Simulating the similarity model could obtain mold temperature field after heating fast. The paper shows that the fast algorithm has good application value through examples.

Keywords: Fast algorithm; Mold heating; Similarity transformation; Mathematics model.

1. Introduction

The injection mold needs to be heated to a certain temperature of 80 ~ 90 ℃ before the injection production, and for rapid heat cycle molding it needs to be heated to a higher temperature. The common ways to heat the mold are electric heating, oil heating and water heating. The electric heating method has the advantages of fast heating and easy control, so it is widely used. Xie Zhiyin [1] applied Fluent to study the effects of factors such as the power of the electric heating rod, the distance between groups and the longitudinal distance on the cavity surface temperature response rate and surface temperature uniformity under fast heating conditions. Wu Kang and Zhou Hai [2, 3] study the influence of the gap between the electric heating rod and the mold mounting hole on the heating efficiency of the mold, and proposed a new type of electric heating method. By filling a thermal fluid between the electric heating rod and the mold, the contact condition between the electric heating rod and the mold is changed. Li Jinguo [4] studies the inverse problem of the heat source strength of the mold electric heating system, and gives out a multiple sources inversion algorithm for the heat conduction of the mold heating system. Considering the requirements of safety and environmental protection, the method of water heating has become main stream in recent years, and mold temperature controller is the ideal equipment for mold heating. The parameters of water heating include water temperature, velocity and flow rate. To heat a specific mold, it needs to determine the heating time for the mold to reach a given temperature under the specific conditions of water temperature and flow rate. Relying on experience and experiments in the past, the method is simple but requires repeated trials and the error of the results is large. With the popularization of computer technology and numerical simulation technology, CAE technology...
has been widely used in the field of molds. Hyuk-Jae Kwon [5] used the CAE method to study the design of aluminum alloy die-casting die, effectively optimized the die-casting system, and improved the design efficiency of aluminum alloy die-casting. Florian Wittemann [6] studied the injection molding simulation of short fiber reinforced thermostets with anisotropic and non-Newtonian flow behavior, and gave a new method of reaction injection molding simulation. Jia Pingping [7] puts forward a method for the simulation analysis of forming process of tube bends, which combines coordinate translation with mass scaling and is called the equivalent method. Examples show that this method could not only greatly raise simulation efficiency, but also has enough analysis precision.

But in the water heating simulation of injection mold, the research is still blank. The heating relies on flowing hot water to heat the mold; therefore, the problem is a highly nonlinear fluid-solid coupling problem. When using CFD software for mold heating simulation, an insurmountable problem was encountered. One is that the amount of calculation is enormous, and the size of the water pipeline in mold is much smaller than that of the mold, which results in a very dense calculation mesh. The other is that the boundary conditions are limited, that is, the water flow rate cannot be too large or the algorithm is prone to failure. How to overcome the limitation of this boundary condition and improve the calculation efficiency is an urgent problem to be solved in the water heating simulation of injection mold.

2. Fast Algorithm

Aiming at the existing problems of CFD simulation for water heating injection molds, this paper proposes an algorithm method of water heating simulation of injection molds that can not only break through the limitation of the flow rate of water, but also improve the simulation efficiency under the premise of ensuring the calculation accuracy.

The problem of water heating for mold is fluid-solid coupling, which involves several scientific issues such as fluid kinematics and heat transfer. The mathematical model of the water heating process consists of a mathematical model of heating water movement and a mathematical model of mold heating. The mathematical model of heating water movement can be described by the basic governing equations of fluid mechanics and corresponding boundary conditions. The general form of the basic equations is (1-3) [8]:

\[
\frac{\partial \rho_f}{\partial t} + \frac{\partial (\rho_f u_i)}{\partial x_i} = 0
\]

\[
\frac{\partial (\rho_f u_i)}{\partial t} + \frac{\partial}{\partial x_j} \left[ \rho_f u_i u_j - \frac{\partial p}{\partial x_j} + S_{ij} \right] = \nabla^2 u_i + \frac{\partial}{\partial t} \left( \frac{\partial (\rho_f T_f)}{\partial x_i} \right) + S_i
\]

Where, \(x, y, z \in \Omega_f, 0 \leq t \leq \beta; \Omega_f \) is the domain of heating water; \(\beta\) is the heating time; \(p, \rho_f, T_f, u\) represent the pressure, density, temperature and velocity of the water, respectively; \(S_w, S_T\) are generalized source term and viscous dissipation term; \(\mu, \lambda, C_p\) are the dynamic viscosity, thermal conductivity and specific heat capacity of the fluid.

The mathematical model of mold heating can be described by the basic equation of solid heat conduction and corresponding boundary conditions, as follows [9]:

\[
\frac{\partial T}{\partial t} = \frac{\lambda}{\rho_s c} \nabla^2 T + \frac{q_s}{\rho_s c}
\]

Among them: \(x, y, z \in \Omega_g, 0 \leq t \leq \beta; \Omega_g\) is the domain of the mold; \(T\) is solid temperature; \(t\) is time; \(\nabla\) is Laplace differential operator; \(q_s\) is heat source strength; \(\lambda\) is thermal conductivity; \(\rho_g\) is solid density; \(c\) is specific heat of solid.

Eq. 1-4 are generally solved by numerical methods, such as discrete solution of Eq. 1-3 using finite volume method, and discrete solution of Eq. 4 by finite element method. Since Eq. 1-4 include space coordinate variables and time coordinate variables, the numerical solution method is to establish a model by dividing mesh in the space domain and establish a recursive formula using the difference format in
the time domain. Because the size of the mold is much larger than the size of water pipeline of the mold, and the pipe diameter is small and the pipeline is long, the mesh for simulation analysis is very dense, which not only makes the simulation calculation amount huge, but also the flow rate of the water can easily affect the stability of the analysis, that is, the flow rate cannot be too large.

This paper proposes a fast algorithm method which uses a similar transformation to obtain a similar mathematical model for the mathematical model describing the water heating process of the mold, and simulates the similar model to quickly calculate the mold temperature after water heating. The establishment of a similar model includes the following steps: First, the time domain of the basic equation of the heated water flow described in Eq. 1-3 is transformed, that is, the similar transformation is a transformation for time variable, and the expression is as follows:

\[ t_1 = \alpha t \]  

(5)

Where \( \alpha \) is a transformation coefficient, and the transformation coefficient \( \alpha \) is dimensionless, which is a scaling factor for enlargement and reduction. Assuming that the mold heating time domain is \([0, \beta]\), the transformed time domain is \([0, \alpha \beta]\).

Transform the Eq. 1-3 in the time domain for time variable, and transform these basic equations expressing fluid motion into equivalent fluid motion equations. The transformed basic equation is:

\[
\frac{\partial \rho_{fi}}{\partial t_1} + \frac{\partial (\rho_{fi} u_{fi})}{\partial x_i} = 0
\]

(6)

\[
\frac{\partial (\rho_{fi} u_{fi})}{\partial t_1} + \frac{\partial}{\alpha^2 \partial x_i} \left( \frac{\partial (\rho_{fi} u_{fi} u_{fi})}{\partial x_i} \right) = \frac{1}{\alpha^2} \nabla^2 \mu u_{fi} - \frac{\partial p}{\partial x_i} + S_{fi}
\]

(7)

\[
\frac{\partial (\rho_{fi} T)}{\partial t_1} + \frac{\partial (\rho_{fi} u_{fi} T)}{\partial x_i} = \frac{\partial}{\alpha^2 \partial x_i} \left( \frac{\lambda}{C_{pi}} \frac{\partial T}{\partial x_i} \right) + S_{f1}
\]

(8)

Secondly, the same similar transformation is used for the basic heat conduction equation of the mold. After the transformation:

\[
\frac{\partial T}{\partial t_1} = \frac{\lambda}{\rho_s c_1} \nabla^2 T + \frac{q_i}{\rho_s c_1}
\]

(9)

Here the similarity transformation (5) only transforms the time domain. Since the time domain of the fluid problem (1-3) is the same as the time domain of the solid problem (4), the similarity transformation (5) is to transform the time domain of the two problems from \([0, \beta]\) to \([0, \alpha \beta]\)at the same time. Since the similarity transformation (5) does not transform the spatial domain, the spatial domain of the two problems is unchanged.

In order to facilitate the distinction in the transformation calculation, the subscripts f and g denote fluid and solid variables, while the variables of similar models use subscript 1 to distinguish them from the variables of the original model.

For the fluid domain, as long as the Reynolds number \( \text{Re} \) is not changed, consistency of solutions between the original model and the similar model can be guaranteed, such as Eq. 10. For similar transformation of fluid velocity and fluid density, see Eq. 11 and Eq. 12; where the Eq. 11 indicates that the heated water flow rate after similar transformation is less than 1; in the Eq. 10, \( U \) is a mode of the water flow rate, and specifically see the Eq. 13.

\[
\text{Re} = \frac{\rho_f UL/\mu}
\]

(10)

\[
u_{fl} = \alpha u_{fi}
\]

\[
\rho_{fi} = \frac{\rho_f}{\alpha}
\]

(12)

\[
U = \sqrt{u^2 + v^2 + w^2}
\]

(13)

After the transformation, the solid density, thermal conductivity, heat flow, and heat source remain unchanged, and the specific heat capacity of the solid changes, i.e. \( c_1 = \alpha c \).
After transformation, a similar mathematical model equivalent to the original mathematical model of the problem is obtained. The solid and fluid domains of the two models are unchanged (which are molds and water pipelines), and the heating time, water flow rate and water density are different, but the temperature fields of the two models are the same. If the transformation coefficient is less than 1, it can be seen from Eq. 5 and Eq. 11 that since the time domain of the similar model become smaller and the water velocity becomes smaller, the solution of the similar model has stronger analysis stability. And the heating time is effectively reduced and the amount of simulation calculation is greatly reduced. Therefore, the temperature solution of the original problem can be obtained quickly by solving similar model, which is much more efficient than directly solving the original model. The procedure of the fast algorithm could be described as follows:

![Figure 1. Procedure of fast algorithm for water heating simulation of injection mold.](image)

3. Specific Implementation Examples

The following two examples are used to further illustrate the effectiveness of the fast algorithm for water heating simulation of injection molds described in this paper. The comparison of simulation time is used to illustrate the difference in calculation efficiency between the proposed algorithm and the original algorithm.

Example 1, water heating for mold 267:
The problem is described as follows: mold temperature 25°C, ambient temperature 25°C, hot water temperature 90°C, water velocity 2.7m/s, heating time β=1800s. The calculation steps using the fast algorithm in this paper are as follows:
Step 1: Similar transformation of the basic fluid mechanics equations for the motion of heated water. According to experience requirements, that is, the water flow speed should be less than 1, taking the similarity transformation coefficient $\alpha=1/6$, the heating time of the similarity model is $\alpha \beta=1800/6=300$, and the similarity transformation of the water speed and density is as follows (the density of water before transformation: $\rho_f=1$): $\rho_f=6 \times 10^{-9} kg/m^3$; $u_1=\alpha u=0.45m/s$.
Step 2: Perform a similar transformation on the basic solid heat conduction equation of the mold. Transform with the same similarity transformation coefficient in step 1, where the similar specific heat capacity parameter of the solid is calculated as: $c_1=c/6$.
Step 3: the result of simulation shows that the mold temperature reached by the last mold heating is 88°C.

For comparison, at the same time, the original model is calculated by simulation. The comparison of the mold temperature distribution at the end of heating is shown that the results are consistent. The calculation time of the original model for heating mold 267 is 2.7 hours, while the fast algorithm is 0.27 hours. The simulation calculation time is greatly shortened, and the calculation efficiency is greatly improved.

Example 2, water heating for mold 295:
The problem is described as follows: mold temperature 25°C, ambient temperature 25°C, hot water temperature 90°C, water velocity 3.68m/s, heating time β=1800s. The calculation steps using the fast algorithm in this paper are as follows:
Step 1: Similar transformation for the motion of heated water. Taking $\alpha=1/6$, $\alpha \beta=1800/6=300$, $\rho_f=6 \times 10^{-9} kg/m^3$; $u_1=\alpha u=0.45m/s$.
Step 2: Perform a similar transformation for the mold, where: $c_1=c/6$.
Step 3: The comparison of the mold temperature distribution at the end of heating is shown that the results are consistent. Simulation time: 6.2 hours for the original algorithm and 0.62 hours for the fast algorithm.

4. Conclusion
This paper proposes a fast algorithm for water heating simulation calculation of injection molds. Based on the similarity transformation, a similar model equivalent to the original model is constructed, and the similar model is simulated, which greatly shortens the simulation time on the premise of ensuring accuracy. This method can not only solve the problem quickly, but also has no limitation on the flow velocity of the heated water. The paper shows that the method is adaptable and has a good engineering application prospect through calculation cases.

References
[1] Xie Zhiyin, Chen Shiqiang, Tan Lijuan, etc. Study of temperature distribution of mold under temperature gradient in rapid heating process [J]. China Plastics, 2019, 33(4), 59-65. (in Chinese)
[2] Wu Kang, Zhou Hai, Wang Baolong, etc. Numerical Simulation and experiments of a new rapid mold heating method for rapid heat cycle molding [J]. Engineering Plastics Application, 2017, 45(2), 77-81. (in Chinese)
[3] Wu Kang, Zhou Hai, Wang Baolong, etc. Effect of gap on thermal response efficiency in heating process of RHCM [J]. Engineering Plastics Application, 2017, 45(7), 73-79. (in Chinese)
[4] Li Jinguo, Liu Hong, Lin Kang, etc. Theory and experimental research on the multiple source heat conduction inversion of the polymer curing reaction Mould Heating System[J], Journal of mechanical engineering, 2016, 52(14), 174-181. (in Chinese)
[5] Hyuk-Jae Kwon, Hong-Kyu Kwon. Computer aided engineering (CAE) simulation for the design optimization of gate system on high pressure die casting (HPDC) process. Robotics and Computer-Integrated Manufacturing [J], 2019, 55, Part B, 147-153.
[6] Florian Wittmann, Robert Maertens, Luise Kärger, Frank Henning. Injection molding simulation of short fiber reinforced thermosets with anisotropic and non-Newtonian flow behavior. Composites Part A: Applied Science and Manufacturing [J], 2019, 124, Article 105476.
[7] Liu Hong, Jia Pingping. Method of rising simulation efficiency for tube bends [J]. Computer Simulation, 2015, 32(10), 234–238. (in Chinese)
[8] Wang Fujun. Computational Fluid Dynamics method [M], Beijing: Tsinghua Publishing House, 2004.9. (in Chinese)
[9] Yang Shiming, Tao Wenquan. Heat Transfer [M], Beijing: Higher Education Publishing House, 2006.8. (in Chinese)