The Influence of Billet Spacing on Heating Efficiency is Studied Based on Simulation Analysis

Ning Guo and Fei He*
Nanjing University of Science and Technology, School of Mechanical Engineering, Industrial Engineering 402 Room, Jiangsu, Nanjing 210094, China
*Corresponding author

Abstract—In this paper, the heating process model of billets of different sizes with different spacing is simulated. Monte Carlo method is used to determine the observation factor matrix of the outer wall of the heating furnace, 3D finite-difference method is used to calculate the heat exchange between the furnace wall and the billet surface, and heat balance equation and 3D finite difference method are used to calculate the heat transfer inside the billet. Through the simulation research on the heating interval of the billet, the best heating efficiency interval and the relationship between the optimal spacing and billet size are found out, and the best standardized space coefficient is determined, which provides a theoretical basis for the actual production of reheating furnace and the production heat optimization and scheduling between processes.

Keywords—billet spacing; heating efficiency; heat exchange; heat conduction; normalized space coefficient

I. INTRODUCTION

The forging industry is characterized by high energy consumption. In the forging production process, the energy consumed by heating accounts for about 70% of the whole process, and reducing the energy consumption in the heating process has become the key research object of forging production. The research on reheating furnace by many experts and scholars at home and abroad includes flow combustion, furnace temperature, billet temperature field and oxidation burning loss. Liu Xin applied the finite difference method to get the matrix equation of temperature at each node of the billet. According to the time of the billet in each heating section, the temperature curves of the surface center point and the internal center point of the billet were obtained by solving and calculating [1]. Li Yanxia et al. developed the corresponding algorithm with VB language, calculated the temperature field of steel billets of different sizes and types, and compared and analyzed the data obtained from the field test and the data calculated by the established model [2]. Yu Wanhua et al. took the upper and lower surface temperature of billet measured by thermocouple as the boundary, simulated the billet temperature field by Matlab language programming, and verified the accuracy of the model by comparing the "black box" experimental data [3]. Moghaddam et al. used high eddy simulation and low Mach number methods to study the influence of turbulence and thermal radiation interaction on heat flow and heat flow in the channel under mixed convection-radiation heat transfer conditions [4]. Wick et al. established a temperature prediction model of billet heating process in the heating furnace, and applied Kalman filtering technology to estimate the dynamic state of heating system, but this model could only predict the surface temperature of billet [5]. Man Young Kim et al. established a two-dimensional mathematical model of a stepping heating furnace, simulated the heat transfer between the furnace wall and the billet in the heating process, and analyzed the effect of absorption coefficient and emission coefficient on the billet heating [6].

In order to improve the production capacity of furnace, saving energy consumption, increase production, make the optimal furnace heating efficiency, this article is based on the monte carlo view factor method for steel billet in the furnace the heat transfer process of numerical simulation and calculation, the purpose is to analyze different sizes of billet with different loading the effect of spacing to the furnace productivity, and obtain the optimal space distance.

II. HEAT TRANSFER PROCESS OF BILLET IN FURNACE

A. Differential Equation of Heat Conduction

Differential equation of heat conduction is an equation describing the general law of temperature field of heat conduction by mathematical method. The general form of the heat conduction differential equation can be expressed as:

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

(1)

On the left of the equal sign is the internal energy increment of the micro-element body within unit time, and on the right of the equal sign is the diffusion term caused by heat conduction, namely, the total heat flow into the micro-element body, the total heat flow out of the micro-element body and the internal heat source term. The heat imported is the heat imported along the x, y, and z axes. The heat derived is the heat imported along the x, y, and z axes through the x+dx, y+dy, and z+dz surfaces, as shown in Figure I.
The temperature gradient can be expressed as:

\[ \text{gradt} = \frac{\partial T}{\partial x} i_x + \frac{\partial T}{\partial y} j_y + \frac{\partial T}{\partial z} k_z \]  

(4)

The most widely used method to study the billet heating situation and the change of internal temperature field of the billet is to establish the mathematical model of the billet heating process in the furnace. The control equation is as follows:

\[ \rho C_p \frac{\partial T}{\partial t} + \frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \lambda \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( \lambda \frac{\partial T}{\partial z} \right) + S \]  

(5)

In the equation(5): \( \lambda \) is defined as thermal conductivity, W/(m·°C); \( \rho \) is defined as density, kg/m³; \( T \) is defined as temperature, °C; \( t \) is defined as time; \( S \) is the internal heat source term.

III. VIEW FACTOR MATRIX BASED ON MONTE CARLO METHOD

Monte Carlo method can usually get more accurate results and is suitable for off-line research. The basic idea of Monte Carlo method is to simulate the emission, absorption and scattering of micro element and the emission, absorption and reflection of boundary wall. The emission, absorption, scattering and reflection of each energy beam are tracked by probability simulation until absorption, and the number of absorbed energy beams of each micro element is counted to calculate the radiation heat exchange. Monte Carlo method avoids the complicated multiple integral calculation of radiative exchange area by region method, and is flexible and easy to deal with complicated boundary conditions. Therefore, this paper will study the billet heating process through Monte-Carlo view factor matrix.

The calculation of thermal radiation transfer between billet surfaces can be divided into energy part and geometry part. The heat radiation exchange part of the furnace wall surface mainly determines a view factor matrix \( F \), and \( F_{ij} \) represents the elements of the view factor matrix, which reflects the proportion of the total heat radiation released by surface \( A_i \) absorbed by surface \( A_j \), including multiple reflections [9].

The Monte Carlo method is particularly suitable for studying the conduction of thermal radiation because the energy generated by thermal radiation travels along a straight line in the form of discrete photon beams when interacting with the surface of an object. Under the premise of determining the view factor, a large number of \( N_i \) photons are emitted from the \( A_i \) surface, and these photons follow the probability density function distribution. The path of each photon can be tracked, including possible reflections, until they are absorbed at the surface of the furnace wall. In the model, the emission and reflection of photons are regarded as gray and diffuse reflection, thus determining the view factor in the furnace, which means that sampling from the photon emission point to the absorption point (including multiple reflections) is random, and the emission and tracking of photons are based on statistical probability. After a large number of \( N_i \) photons are reflected from the surface \( A_i \), the view factor \( F_{ij} \) can directly determine the thermal radiation energy absorbed by the surface \( A_j \) by counting the number of photons \( N_{ij} \).
The emission of single photon from surface $A_i$ depends on the emission point $X_E$ and emission direction $\mathbf{e}$, as shown in Figure III.

\[
F_{i,j} = \lim_{N_j \to 0} \left( \frac{N_{i,j}}{N_j} \right) \approx \frac{N_{i,j}}{N_j}, N_j > 1
\]  

(6)

According to the actual size of billet, the simulation model was established in Fluent, including mesh division, setting of boundary conditions and initial conditions, etc. The solution type is transient thermal analysis, and the calculation time is set at 14,400 seconds (4 hours). The simulated calculation results are post-processed in Tecplot, as shown in Figure IV.

\[
X_E = a \times R_1 + b \times R_2
\]  

(7)

Direction of launch is determined by the Angle $\theta$ and $\Phi$. In this model, gray diffusive emission and reflection are assumed to be approximate. In this case, $\theta$ and $\Phi$ can use two random Numbers $R_3$ and $R_4$ to determine:

\[
\theta = \sin^{-1} \left( \sqrt{R_3} \right)
\]  

(8)

\[
\Phi = 2\pi R_4
\]  

(9)

TABLE I. COMPARISON OF SIMULATION AND MEASUREMENT

| Time (s) | Billet Surface Temperature (°C) | Error (%) | Billet Center Temperature (°C) | Error (%) |
|---------|--------------------------------|-----------|--------------------------------|-----------|
|         | Measured | Simulating | Measured | Simulating | Measured | Simulating |
| 1800    | 367      | 336        | 8.45     | 169        | 166      | 1.8       |
| 3600    | 573      | 514        | 10.3     | 422        | 376      | 10.9      |
| 5400    | 759      | 717        | 5.53     | 605        | 572      | 5.45      |
| 7200    | 884      | 870        | 1.58     | 797        | 735      | 7.78      |
| 9000    | 1070     | 1090       | 2.80     | 964        | 913      | 5.29      |
| 10800   | 1210     | 1130       | 6.61     | 1140       | 1070     | 6.14      |
| 12600   | 1200     | 1190       | 0.83     | 1210       | 1180     | 2.48      |
| 13800   | 1220     | 1223       | 0.25     | 1220       | 1200     | 1.64      |
| 14400   | 1230     | 1227       | 0.24     | 1220       | 1206     | 1.15      |

B. Simulation Results and Analysis

In this paper, three kinds of billets of different sizes are simulated, and their sizes are 180mm*180mm*500mm, 220mm*220mm*500mm and 300mm*300mm*500mm.

In order to determine the influence of spacing on heating efficiency, it is necessary to define heating efficiency. Since heating efficiency cannot be directly reflected, radiant heat flux absorbed by billet is taken as the standard to measure heating efficiency.

The simulation result data and the model calculation formula were iteratively processed, and the space distance were set between 0 and 20cm, respectively obtaining the heat flux values absorbed by the billets of three specifications with different
spacing. The specific data were shown in Table II. For different spacing points in each model, the view factor matrix F is used to calculate the value of billet heating process in the furnace. In addition, the heating time of billet reaching the heating standard under different spacing is simulated for several times. Figure V is the fitting curve calculated by B-spline function according to the data in the Table II.

**TABLE II. THE BILLET ABSORBS THE TOTAL HEAT FLUX AT DIFFERENT SPACING**

| Spacing (mm) | 0.01 | 0.03 | 0.04 | 0.05 | 0.06 | 0.07 | 0.08 | 0.09 |
|--------------|------|------|------|------|------|------|------|------|
| 180          | 751  | 768  | 783  | 795  | 810  | 822  | 832  | 842  |
| 220          | 739  | 745  | 755  | 762  | 763  | 764  | 767  | 767  |
| 300          | 771  | 775  | 780  | 785  | 792  | 796  | 792  | 793  |
| 80            | 0.1  | 0.11 | 0.12 | 0.13 | 0.14 | 0.15 | 0.16 | 0.17 |
| 180          | 833  | 826  | 818  | 805  | 794  | 782  | 756  | 729  |
| 220          | 809  | 801  | 790  | 784  | 776  | 767  | 762  | 755  |
| 300          | 776  | 780  | 785  | 792  | 793  | 791  | 782  | 770  |

As can be seen from the heating time curves of Figure V (a), (b) and (c), when the space spacing of billets is 0, the heating time is the longest. It takes about 5 hours for a 180mm billet, 7 hours for a 220mm billet and 9 hours for a 300mm billet. In this case, the main reasons for the slow billet heating are the small heat exchange area (only the upper surface) and the low bottom temperature (indirect heating through forging) with the heat released by the furnace gas and the furnace wall. When the gap between billets increases, the heating time will also be shortened, and finally tends to be stable in a certain range.

**V. CONCLUSION**

The simulation model of forging billet heating process established in this paper considers the calculation of thermal radiation of furnace wall and heat exchange between billets, and the simulation results of the simulation model are in good agreement with the test data of thermocouple in practical industrial furnace. The following conclusions can be drawn from the result analysis:

(1) The effect of space spacing between billets on heat absorption is significant. There is an optimal space spacing between billets of different specifications, which makes them have the highest heating efficiency. The larger the size of billets is, the larger the optimal space spacing required will be.

(2) The optimal heating spacing of 180mm billets is 75mm-85mm, 100mm-110mm for 220mm and 130mm-140mm for 300mm;

(3) The billets of three sizes have roughly uniform standardized space, that is, the ratio of billet thickness to the optimal space spacing. The best standardized space coefficient of 180mm billet is 0.42-0.47; The best standardized space coefficient of 220mm billet is 0.45-0.5; The best standardized space coefficient of 300mm billet is 0.43-0.47. This is consistent with the best standard space coefficient of 0.3-0.7 proposed by experts, which further confirms the reliability of the results.

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