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

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***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 finit-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 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 beat 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:

$$\rho c\frac{\partial t}{\partial \tau}=\frac{\partial}{\partial x}\left(\lambda\frac{\partial t}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial t}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda\frac{\partial t}{\partial z}\right)+\dot{\Phi} \tag{1}$$

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.

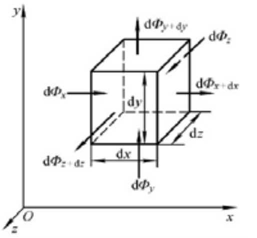

FIGURE I. THREE-DIMENSIONAL HEAT CONDUCTION DIAGRAM

B. Model of Heat Transfer in Furnace

Because the temperature in the heating furnace is too high, the calorific value of radiation heat transfer is far greater than that of convection heat transfer, so most of the heat transfer process is dominated by radiation heat transfer, the heat transfer process mainly includes flame radiation, furnace wall radiation, furnace gas medium radiation, etc. The following equation describes the radiant heat transfer process in the heating furnace [7].

$$\frac{di_\lambda}{ds}=-\alpha_\lambda i_\lambda s+\alpha_\lambda i_{\lambda b}s-\sigma_{s\lambda}s+\frac{\sigma_{s\lambda}}{4\pi}\int_{\omega_i=4\pi} i_\lambda(s,\ \omega_i)\Phi(\lambda,\ \omega,\ \omega_i)d_{\omega_i} \quad (2)$$

$$i_\lambda k_\lambda=i_{\lambda 0}\exp\text{-}k_\lambda+\int_0^{k\lambda} I_\lambda k_\lambda,\omega\exp\left[-\left(k_\lambda-k_\lambda^*\right)\right]dk_\lambda^* \quad (3)$$

In the equation(2) and equation(3): i_λ is defined as radiation intensity, unit is W/ (m2·Sr);s is defined as radiative range; α_λ is defined as radiation absorption coefficient; $\sigma_{s\lambda}$ is defined as radiant scattering coefficient; ω_i is defined as solid space angle; $\Phi(\lambda,\ \omega,\ \omega_i)$ is defined as radiation phase function; k_λ is defined as coefficient of radiation attenuation; λ is defined as wavelength.

C. Internal Heat Conduction Model of Billets

The heat transfer process of billet is actually the process of temperature change inside the billet, namely the temperature field, which describes the temperature distribution of all points in a certain instant space. The temperature gradient is a vector along the vertical direction of the isothermal surface, that is, only through the isothermal surface can the temperature difference change. As shown in Figure II, the rate of temperature change of P in a certain direction at a certain point in the object [8].

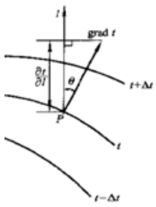

FIGURE II. THE TEMPERATURE GRADIENT UNDER THE ISOTHERM

In 3d modeling, the temperature gradient can be expressed as:

$$\text{gradt}=\frac{\partial t}{\partial x}i+\frac{\partial t}{\partial y}j+\frac{\partial t}{\partial z}k \quad (4)$$

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:

$$\rho C_P\frac{\partial T}{\partial \tau}=\frac{\partial}{\partial x}\left(\lambda\frac{\partial t}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial t}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda\frac{\partial t}{\partial z}\right)+S \quad (5)$$

In the equation(5): λ is defined as thermal conductivity, W/ (m·°C); ρ is defined as density,kg/m^3;T is defined as temperature, ° C; τ 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 $F_{i\text{-}j}$ 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 $F_{i\text{-}j}$ can directly determine the thermal radiation energy absorbed by the surface A_j by counting the number of photons $N_{i\text{-}j}$.

$$F_{i\to j}=\lim_{N_i\to\infty}\left(\frac{N_{i\to j}}{N_i}\right)\approx\left(\frac{N_{i\to j}}{N_i}\right)_{N_i\gg 1} \tag{6}$$

The emission of single photon from surface A_i depends on the emission point X_E and emission direction e, as shown in Figure III.

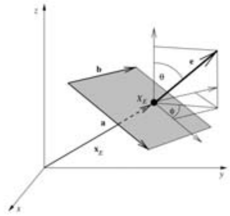

FIGURE III. FPHOTON EMISSION

The photon emission model is uniformly distributed in the interval [0,1] and generated randomly.The probability of A_i emission on the rectangular surface is evenly distributed over the whole surface.Therefore, the emission point X_E can be determined by multiplying vectors a and b by two random Numbers R_1 and R_2:

$$X_E=a\times R_1+b\times R_2 \tag{7}$$

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

$$\theta=\sin^{-1}(\sqrt{R_3}) \tag{8}$$

$$\Phi=2\pi R_4 \tag{9}$$

Photon tracking algorithm is used to track the emission or reflection path of each photon. A photon can interact with one of the intercepted geometric surfaces in its divergent path. When the photon interacts with the geometric surface, a new random number R_i is generated. If $R_i\le\varepsilon_k$, we can assume that in the model, the photon is absorbed at the surface A_k, otherwise the photon will reflect. If a reflection occurs, the intercept point is treated as the reflection point.

IV. Modeling and Analysis of Billet Heating Process

A. Verification of simulation model

In this paper, the billets with regular shape are placed in a certain interval in a heating furnace, and the heating time and efficiency are solved through different spacing. In order to measure the experimental data, the towed thermocouple is mounted on a test billet to measure the surface temperature and the internal temperature of the billet. The standards for putting billets of the three sizes into and out of the heating furnace are the same. The criterion is that the billet temperature should be at least 1200℃, and the temperature difference between the upper and lower surface of the billet should be less than 20℃.

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.

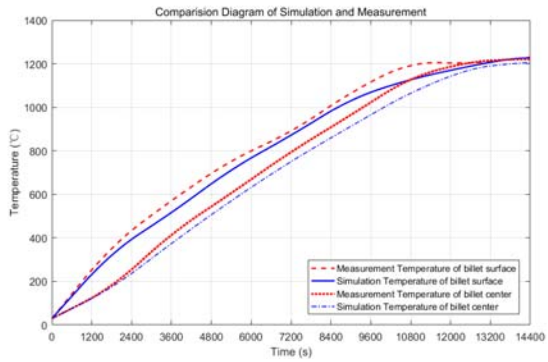

FIGURE IV. THE SIMULATION RESULTS ARE COMPARED WITH THE TEST RESULTS

Table I shows the comparison results of simulation results and experimental data, in which the maximum error is controlled within 11%, proving that the simulation model has good reliability.

TABLE I. COMPARISON OF SIMULATION AND MEASUREMENT

Time (s)	Billet Surface			Billet Center		
	Temperature（℃）		Error (%)	Temperature（℃）		Error (%)
	Measured	Simulation		Measured	Simulation	
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	1040	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

	0	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
180	751	768	783	795	810	822	832	842	844	843
220	730	745	755	762	763	764	767	775	787	796
300	711	725	732	740	744	749	756	760	763	770
	0.1	0.11	0.12	0.13	0.14	0.15	0.16	0.17	0.18	0.19
180	833	826	818	805	794	782	765	753	742	736
220	800	801	800	790	784	776	767	762	755	752
300	776	780	785	792	793	791	782	770	758	752

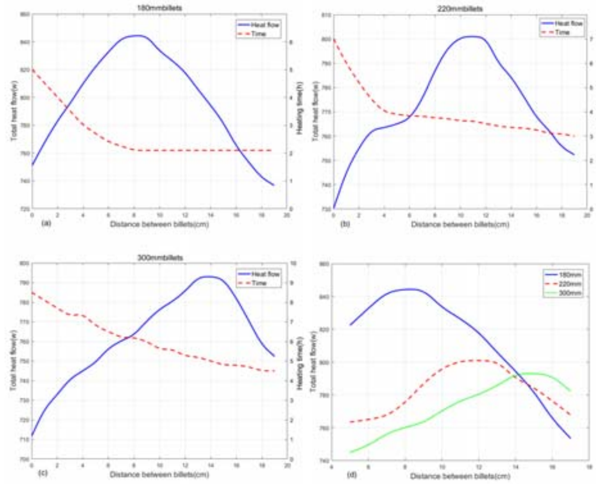

FIGURE V. THREE KINDS OF BILLETS ABSORB HEAT FLOW AND HEATING TIME AT DIFFERENT INTERVALS

Figure V (a), (b) and (c) show that the optimal heat absorption rate is 180mm billet with spacing of 80mm, 220mm billet with spacing of 110mm and 300mm billet with spacing of 140mm.It can be seen from the curve comparison in Figure V (d) that the larger the billet size is, the larger the optimal spacing is. The reason is that the shielding effect between the two surfaces of the billet size is high when the billet size is heated in the furnace, so a larger spacing is required to ensure that the radiated photon beam can be transmitted to the surface of the billet.

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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