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Simulation research on molten iron flow in blast furnace hearth based on Fluent

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Abstract: In order to simulate the hot metal flow and erosion behavior within blast furnace hearth, a 3D system simulation platform is established, which would be a great help to analyze all kinds of working condition due to arbitrary setting parameters about hearth structure and material properties. With the flexible parameterized control mechanism, the distribution about velocity field, pressure field, and temperature field can be simulated in this platform. The simulation results, which are mainly revolving round seven work conditions, show that the erosion degree about blast furnace hearth could be flexible and conveniently analyzed.

Keywords: Fluent; simulation; molten iron flow; blast furnace hearth

1. I
ntroduction

Hot metal flow in blast furnace (BF) hearth is one of the most important factors which affect the life-span of BF hearth. Hot metal flow in BF hearth has been deeply studied, but there are still some severe problems. For example, it is impossible to visualize the working conditions in BF hearth. Furthermore, it has become a more urgent problem for researchers to find deeper reasons which decrease the life-span of BF hearth and to analysis the transitive relation between mass, energy, and momentum within BF hearth. Through the previous research, great achievements have been obtained about erosion behavior and hot metal flow, which are based on methods of actual BF anatomy[1,2)] and sample analysis technique[3)]. However, the experiment cost is very high.

In recent years, simulation research about unsteady multi-parameter model, which is often used in BF engineering, could be worked very well with Fluent[4)], one of the most mature CFD software. That is because of the high-speed development of computational fluid dynamics and full-fledged computer with low price, which enable greater calculation accuracy and reliability to the CFD analysis model. So Fluent has been widely used in engineering to solve problems and hot metal flow and erosion behavior in BF hearth. Fluent has Pre-Processor(Gambit), which can create mesh model flexibly, and also has perfect post-processing function, that enable Fluent build nephogram and curve graph about the simulation result of velocity field, pressure field, and temperature field. So, it has been widely used in many researching work. One of the typical representatives is an experimental device and method, which is introduced in paper [5]. This device include cylindrical transparent container, sealing cap, air release hole, sold air enclosure,   and water outlet. A simulation system which is established based on the device can simulate hot metal flow in the bottom of BF hearth. In this simulation system, the sealing cap diameter can adopt with cylindrical transparent container, so the air release hole can be set in the sealing cap tightly. Under the sealing cap, a cold air enclosure is set, which have many evenly arranged air outlet. There are also ingenious designs about this device to achieve realistic simulation about hot metal flow in BF hearth. However, there are also some deficiencies about this system: 1) Dead-man state is not considered as a factor to influence hot mental movement; 2) This device can only simulate hot mental movement at bottom of BF, not the whole BF.

This paper tries to describe how to analysis working condition within BF through numerical simulation system about BF area. Users can obtain hot mental movement situation in BF, only need inputting process parameters and operating conditions. Furthermore, the temperature field distribution detail of side wall and bottom can also be easily obtained by this simulation system, in accordance with which can judge affect factors to BF smelting by process parameters and operating conditions.

Combining BF Technology with computer simulation, the BF simulation system can be taken as a research and development platform to improve process and operation parameters, and give more technical support for optimization of the BF iron making process.

2. A mathematical model of hot metal flow in BF hearth

2.1 Hypothetical condition of mathematical model

It's very complicated to judge the condition of hot metal flow in BF hearth. In order to establish the mathematical model of the hot metal flow in hearth, here give some assumptions and approximations.

(1) Only hot metal flow is considered in the mathematical model, and the iron mouth is considered as the internal unvocal area.

(2) Assume that the tapping process is steady, which means, the molten iron level remains constant through the whole tapping process.

(3) Ignore the effects of chemical reactions and heat transfer on the flow area.

(4) Assume that hot metal flows at a uniform velocity throughout the whole inlet interface.

(5) Dead-man state assumption. According to Guo[4)] and others study on the shape and position of dead-man, from simple to complex, this paper assumes that dead-man has seven states. As shown in **Fig. 1** (a)-(c) belongs to sitting states; (d)-(g) belongs to floating states.

2.2 Control equations for the mathematical model of hot metal flow

The distribution of molten iron flow field in the hearth is solved by the mass conservation equation and the momentum conservation equation. The Knozeny-Carman equation is used to describe the resistance that the dead material column as porous media on the flow of molten iron. The descent speed of molten iron surface in hearth can be calculated by the speed of molten iron on iron exit. Then the continuity equation, momentum equation and ergun equation can be obtained with cross section of hearth as the entrance.

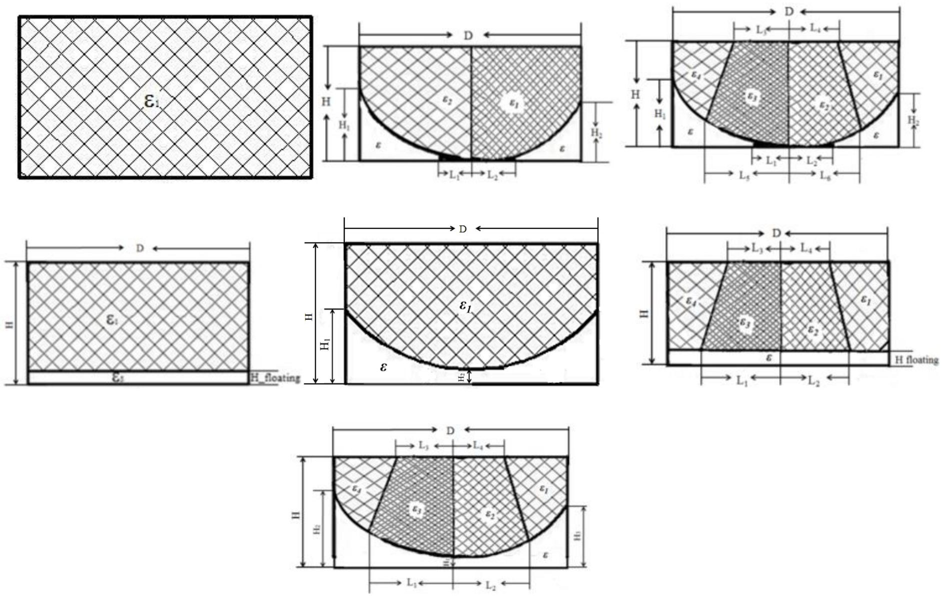


Fig. 1 States of dead-man，(a) Full Sitting，(b) Bottom center sink，(c) The bottom center is sinking and the middle is broken，(d) Flat bottom floating，(e) Pot bottom floating，(f) Flat bottom floating and the middle is broken，(g) Flat bottom floating and the middle is broken

The continuity equation is

$$\frac{\partial(\rho\mu_i)}{\partial x_i}=0\,, \tag{1}$$

where ρ is the fluid density, and its unit is kg/m^3. μ_{i} , which unit is m/s, denotes performance speed. ε is the voidage of dead material.

The momentum equation is

$$\frac{\partial\left(\rho\mu_i\mu_j\right)}{\partial x_j}=-\frac{\partial P}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial\mu_i}{\partial x_j}+\frac{\partial\mu_j}{\partial x_j}\right)\right]+\rho g_i+cS \tag{2}$$

In Eq. (2), μ_{i} and μ_{j} are the speed respective in x and y direction; P is pressure; c is coefficient, it's 1 in porous media region, others is 0; S denotes source.

The ergun equation is

$$\frac{\Delta P}{H}=150\cdot\frac{(1-\varepsilon)^2}{\varepsilon^3}\cdot\frac{\mu}{(\phi d)^2}\cdot\mu+1.75\cdot\frac{(1-\varepsilon)}{\varepsilon^3}\cdot\rho\cdot\mu^2 \tag{3}$$

In Eq. (3), $\Delta\mathrm{P}$ is Fluid pressure drop of porous media; ϕ is particle shape factor; H is bed height; d is diameter of coke particles.

2.3 Boundary conditions of hot metal flow in the hearth

The boundary condition is the premise of a certain solution for the control equation. The combination of the control equation and the corresponding boundary condition forms a mathematical description of a complete physical process. And the setting of the boundary condition affects directly the accuracy of the calculation result. This article sets the inlet boundary conditions, outlet boundary conditions, and hearth wall surfaces.

1)Inlet: speed entrance, calculated from the actual molten iron output daily;

2)Furnace wall surface: The non-slip boundary condition is adopted on the wall surface of the hearth, and the wall surface function method is used to calculate the fluid in the viscous bottom layer near the wall surface;

3)Outlet: outflow boundary conditions.

2.4. The basic steps of the simulation of hot metal flow in the hearth

1)Setting based parameters: set all based parameters in the model, mainly including hearth diameter, hearth height, iron notch depth, iron notch diameter, iron notch dips, and some related path(including work path, the install path of fluent and gambit and so on.).

2)Modeling and meshing: According to the model parameters, geometrical model can be established by calling gambit, at the same time, geometrical grid will be meshed automatic.

3)Setting boundary conditions: set boundary conditions, physical parameters, gird file imports fluent.

4)Simulated calculation: calling fluent simulates, setting iteration steps control iteration and constriction, middle calculation result can be checked by post-processor, and then judge that the result is reasonable or not.

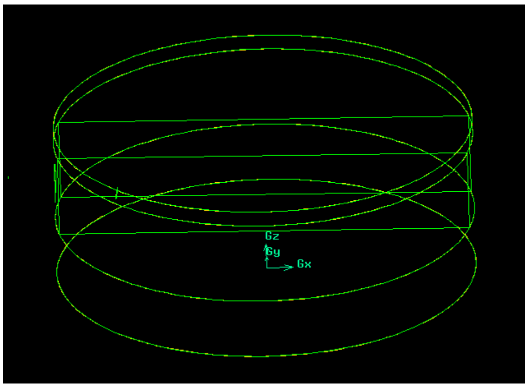
5)Analyze the iterative results and related documents generated, and determine the correctness of the simulation results.

3. Numerical simulation of hot metal flow in BF hearth

3.1 Geometric model establishment and meshing

Gambit, the Pre-Processor software of Fluent, is used to strictly establish and divide mesh model in accordance with the ratio of 1:1(shown in **Fig. 2**), which generates a gird file for Fluent. The impact parameters of the model are dynamically set by external software.

Fig. 2 shows the geometric model established in Gambit, in which the industry's common values are used to set its all control parameters. The result of meshing is shown in **Fig. 3**, and quad units are used as grid cell. Before meshing, boundary conditions need be set as: the entrance condition is set to mess-flow-inlet or pressure-flow-inlet, the outlet is set to outflow, the non-slip boundary condition is used on the wall of the hearth, and the wall function Method in the viscous bottom layer near the wall.



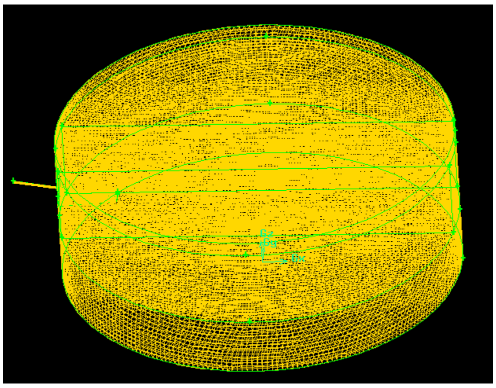


Fig. 2 Geometric model of Hearth hot metal flow **Fig. 3** Grid division of Hearth hot metal flow

3.2 Simulation of hot metal flow

The simulation model isn't created directly by the Fluent software, but by means of developing external software. In external software, all parameters can be set to control seven working states. So, it's necessary to develop an interface for data interaction between fluent and external software.

UDF(user-defined program), provided by Fluent, is an interface for secondary development, which provides a method that can interact with data in users and SOLVER by lots of macro definitions. It also can enhance the function of Fluent and the scope of application of the model, such as boundary conditions, modifying control equations, solving custom equations, and so on. In this article, journal log file are used to interact data between fluent and software.

3.2.1 Secondary development of Fluent

Gambit (Pre-Processor of Fluent) will generate the mesh grid file required by Fluent. Both Fluent and Gambit contain a complete set of journal log files that record every step of software execution. However there are differences between the two journal log files. Log file of the Gambit is used for geometric mesh modeling and generate mesh file for Fluent. Log files of Fluent is for hydrodynamic calculations. Physical parameters and boundary conditions are set in Fluent journal file, other parameters, such as hearth diameter and so on, are set in Gambit journal file. By the means of software interface, users can set parameters, modify their journal files before running fluent and gambit. Then the software automatically reads the journal file to model and calculate, and displays the calculation results. The whole process is shown in **Fig. 4**.

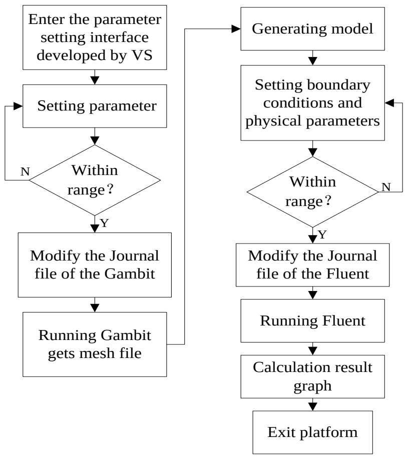


Fig. 4 System flow chart of simulation platform

3.2.2 The initial conditions of simulation

In this paper, initial values are based on the data of a steel BF hearth 3#. The height of the hearth is 5500mm. The diameter of the hearth is 14500mm. The inlet speed of molten iron is 0.00013m/s, The tap hole depth is 3800mm. The number of iron mouth is single iron mouth. The effect of molten iron flow in the BF hearth only contains dead-man state. Molten iron flow in the hearth is simulated under sit and float of dead-man.

3.2.3 Fluent simulation

After setting the relevant parameters in the software interface(shown in **Fig. 4**), hearth molten iron flow can be simulated by calling Fluent software, and mesh grid file generated by Gambit and journal files(including boundary parameters, physical parameters, .c file path, etc.) will be read automatically. Because of the reason that the number of iterations affects the convergence of the iteration results, the number of iterations is important. In this paper, the number of iteration is set in software before calling fluent, which is set dynamically. The results of iteration contain velocity field, temperature field, with which the software can generate automatically the appropriate documents for further analysis.

3.3 The result of simulation

The velocity distribution of the molten iron calculated by the Fluent iteration is shown in **Fig. 5** and **Fig. 6**. It can be seen that, the velocity of molten iron at the side wall is smaller at the condition of dead-man sitting than that of floating. Also, the velocity of molten iron at the bottom of the furnace is smaller at the condition of sitting than that of floating. These results show that, at the condition of floating, molten iron flows faster in the non coke layer, and at the condition of sitting, the flow of iron is faster on both sides of the dead-man. When there is a low liquid permeation zone in dead-man, the velocity of the bottom and the side wall is greater than $1.3\times10^{-5}\,m/s$, and the degree of dissolution and erosion is more serious in the area of high temperature. When there is no coke layer in the bottom of the hearth, and the scorch area (small porosity) occupies the vast majority of the space, the erosion of the whole bottom and the side wall would be very serious, also the adhesive layer is easy to be eroded. That will cause direct contact between molten iron and brick lining, and further more, lead to erosion of brick lining.

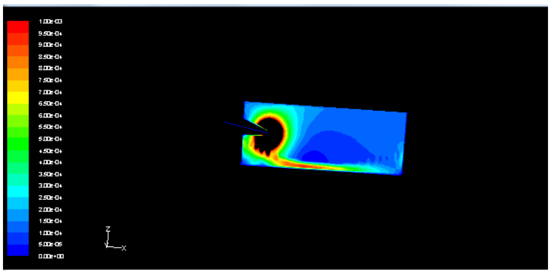


Fig. 5 Flow rate of molten iron-sitting

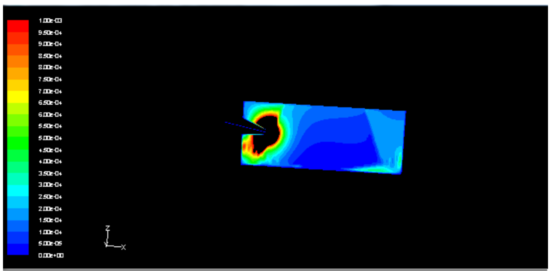


Fig. 6 Flow rate of molten iron-floating

In the actual smelting of BF hearths, the flow rate of molten iron is fast at 1.5 m-1.8 m from the tip of the iron gate. Based on the above simulation results, the flow rate of molten iron is shown in **Fig.7** when the dead-man sinks or floats away from the iron port.

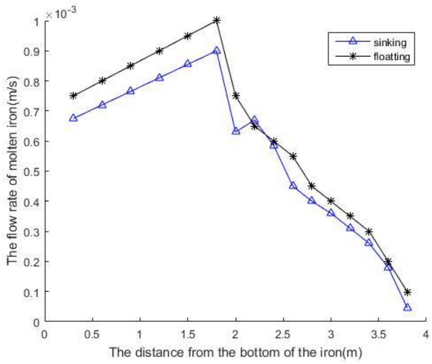


Fig.7 The flow rate of molten iron changes with the value of the distance from the bottom of the iron

It can be seen from the figure that whether the dead-man is in a sinking or floating state, when the distance from the iron gate is getting farther, the speed of the molten iron flow gradually becomes larger at first, and when the distance from the iron gate is 1.5m-1.8m, the flow rate of molten iron reaches a maximum, and then the velocity gradually decreases until it approaches zero. Therefore, the simulated results are consistent with the state of the molten iron flow rate in the actual BF production, which also explains the reliability and authenticity of the simulation.

4. Conclusion

Based on Fluent, a simulation platform is established to analysis molten iron flow in BF hearth, mainly about BF No.1 in Baosteel. The basic research data from BF No.1 provided requisite analysis and validation cases for the simulation platform. With this platform, all kinds of working condition could be analyzed around the condition of dead-man, especially the two conditions of sinking and floating, which are frequently taken as research emphasis in molten iron flow in BF.

This platform can simulate the molten iron flow in BF hearth, and can provide very convenient ways for BF workers who are not very familiar with Fluent to carry out BF hearth molten iron flow. The common platform can be used as a means of research and changing the experimental platform of technology and operation, which improves the efficiency of the BF staff, and provides technology support for optimization and innovation of the future BF iron-making process.

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