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MULTIPHASE FLOW NUMERICAL SIMULATION OF LADLE BOTTOM POWDER INJECTION

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Numerical simulations were performed on bottom injection of calcium oxide particles through double nozzle porous bricks into a 300 *t* hot metal ladle. The distribution characteristics of the calcium oxide particles in the ladle were predicted and analyzed. The modeling results show that, when the bottom blown porous bricks are located symmetrically off-centre by 1 / 2 ladle bottom radius and the injection speed of the calcium oxide particles is 7 *m / s*, an optimum distribution of the calcium oxide particles in the hot metal bath in the ladle can be achieved. This will provide a reference for evaluating the feasibility of applying bottom injection of the calcium oxide powder into hot metal ladles for desulfurization in the actual production process.

Key words: hot steel pretreatment, calcium oxide, desulfurization, bottom powder injection , numerical simulation

INTRODUCTION

With the progress of science and technology, the development of modern society requires steels with increasingly high quality and good performance. Sulfur is a major harmful element that deteriorates steel quality and performance and thus its content in the steel must be reduced to meet the process requirements.[1] Ladle hot metal pretreatment is the most economical and efficient means of desulfurization from the hot metal, which has become a nearly necessary step to produce steels with sulfur contents that meet technical specifications.[2] Top injection method and mechanical stirring desulfurization method are two major means that the steel producers have currently achieved,[3] while bottom injection desulfurization method has yet been to be developed and applied to the actual production processes. Therefore, it is important and necessary to conduct investigations on ladle bottom powder injection first through performing numerical simulations to find out appropriate injection parameters so as to provide a reference for evaluating the feasibility of applying bottom injection of the calcium oxide powder into hot metal ladles for desulfurization in the actual production process.[4]

MATHEMATICAL NUMERICAL MODEL DEVELOPMENT

In the present work, a CFD numerical model was developed based on the actual production conditions and experiments [5] on a 300 *t* hot metal ladle with two slot nozzle bottom blown porous bricks [6]. The dimensions of the ladle are given in Table 1. In order to establish the mathematical model, some basic assumptions are made as follows:

- The thermophysical properties are constant;
- Influences of temperature field and chemical reactions within the hot metal bath are disregarded;
- Effects of the slot nozzle plug internal structure on the distribution of calcium oxide particles in the hot metal bath are ignored;
- Effects of top slag layer on the fluid flow in the bath are also ignored;
- A lower than actual top space air height of 200 *mm* is considered in the mathematical model to reduce the computation amount.

In the present model, VOF (Volume of Fluid) method is adopted to simulate multiphase flows in the ladle and DPM (Discrete Phase Model) method to describe the motion of calcium oxide particles carried by nitrogen gas injected through the slot nozzle porous bricks installed at the ladle bottom. Standard $k - \varepsilon$ model is chosen to account for the fluid turbulence. The hot metal is treated as the main phase, whereas calcium oxide particles and nitrogen as well as air are as the second phases. Each phase mathematical model includes continuity equation, momentum equation, turbulent kinetic energy equation and turbulent dissipation equation.

As boundary conditions, the slot nozzles are set as velocity inlets through which nitrogen carrying calcium oxide particles is introduced into the hot metal bath at constant flow rates with the gas volume fraction being set as 1. According to the reference,[7] for calcium oxide particles of 1 mm diameter, a minimum injection speed of 3,57 m/s should be guaranteed for blowing the particles into the ladle, and the injection flow rate should also meet the technical requirements for stirring.

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Table 1 **Dimensions of 300 t hot metal ladle and slot nozzle plug**

Parameter	Value
Diameter of top / mm	3 942
Diameter of bottom / mm	3 438
Height / mm	5 196
Fluid level / mm	4 800
Diameter of porous brick / mm	57

From the reference,[5] the actual production process requires the gas flow rate to be in the range of 48,35 - 63,48 Nm3/h, corresponding to the inlet velocity of 5,26 - 6,91 m/s. To study the effect of different gas injection speeds on the distribution of calcium oxide particles in the hot metal bath, inlet velocities of 4 m/s, 5 m/s, 6 m/s and 7 m/s are used in the simulations. The outlet boundary is set as pressure outlet where gas phase volume fraction is set to 1. As initial conditions, the velocity of the entire computational domain is set to zero, and the initial depth of the hot metal bath is 4 800 mm, while the rest of the fluid domain is considered as air.

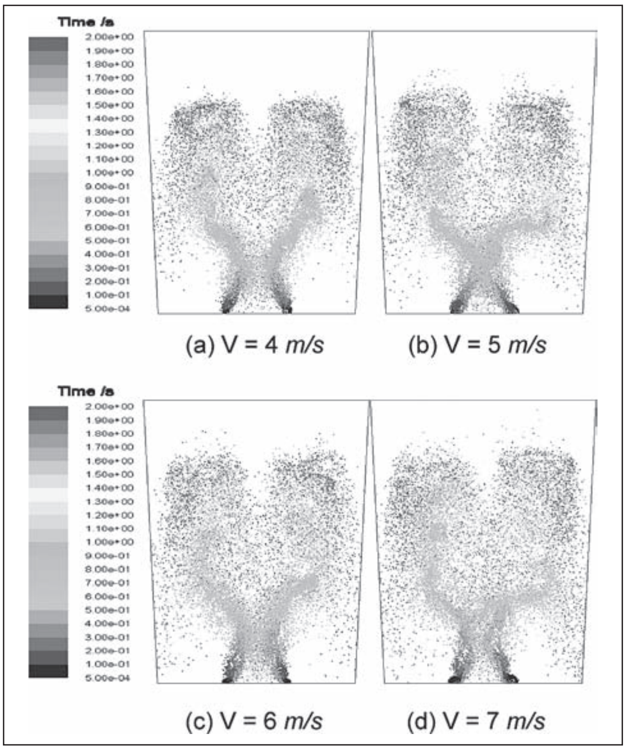

Figure 1 Calcium oxide particle distributions for double nozzle porous bricks at 1/3 bottom radius

RESULTS AND DISCUSSION

Effect of injection position on calcium oxide particle distribution

Due to the fact that for single nozzle injection the calcium oxide particles cannot be evenly distributed in the ladle resulting in poor desulfurization effect, in the present modeling work, calcium oxide particle distributions in a hot metal ladle installed with two injection slot nozzle porous bricks (double nozzle injection) in the ladle bottom were simulated.

Figures 1 to 3 show the simulation results for the ladles with double injection nozzles, each being located off-centre by 1/3, 1/2 and 2/3 of the ladle bottom radius, respectively. These figures depict distributions of the calcium oxide particles in the hot metal bath injected at four different speeds and after four seconds of injection. As seen from Figure 1, at four different injection speeds, the calcium oxide particle distributions exhibit similar patterns. As the particles initially go up a certain distance from the ladle bottom, the two particle plumes coming from the two injection inlets start to deviate towards the ladle axis and tend to merge there. Then, shortly after aggregating the particles disperse to the wall. Figure 1 indicates that few particles are dispersed to the ladle bottom region and thus none of the four distributions is ideal. It can be seen from Figure 2 that, at four different injection speeds, the calcium oxide particle distribution patterns also look similar but more uniform than those shown in Figure 1. The partial aggregation of the particle plumes does not occur. Figure 3 indicates that the calcium oxide particles injected at four different speeds generally exhibit similar distributions but, after the particles going up a certain distance, the two particle plumes first tend to deviate towards the ladle wall and then disperse towards ladle axis direction. This type of particle movement also leads to few particles dispersed in the bottom region and thus none of four distributions is ideal.

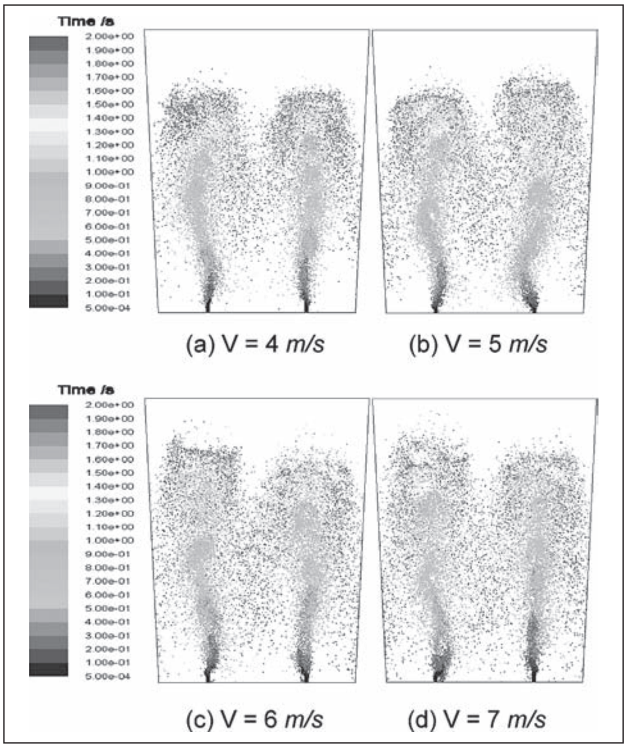

Figure 2 Calcium oxide particle distributions for double nozzle porous bricks at 1/2 bottom radius

Uneven distributions of the calcium oxide particles in the hot metal ladle as shown in Figs 1,3 are mainly

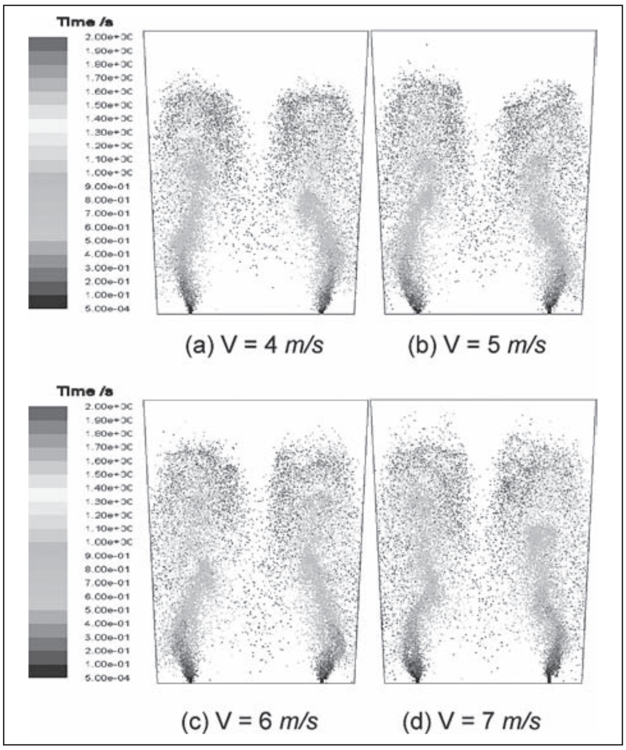

Figure 3 Calcium oxide particle distributions for double nozzle porous bricks at 2/3 bottom radius

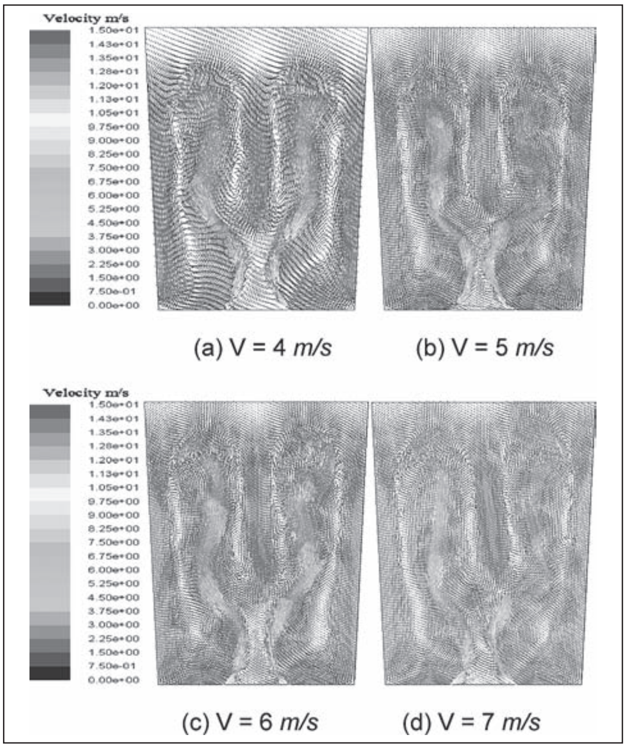

Figure 4 Velocity vector fields for double nozzle porous bricks at 1/3 bottom radius

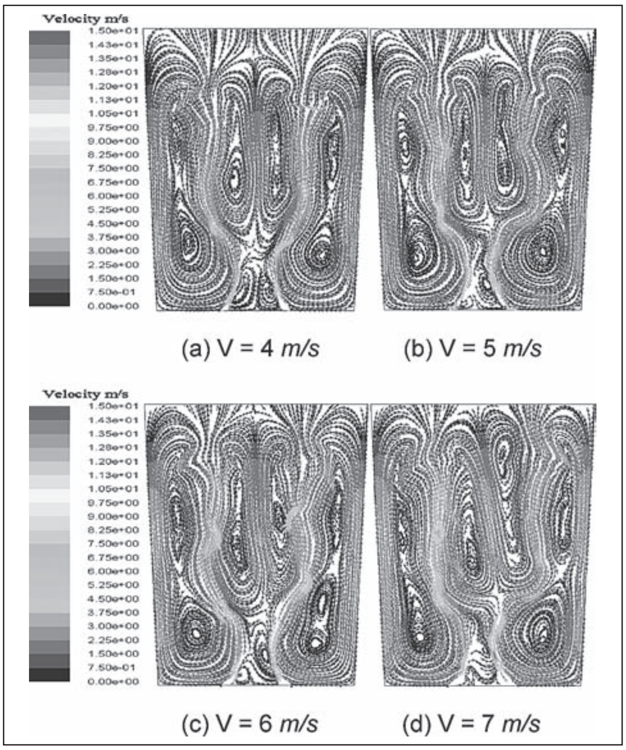

Figure 5 Streamline patterns for double nozzle porous bricks at 1 / 3 bottom radius

due to inappropriate internal flow fields in the ladle. Therefore, in this paper, flow patterns in the ladle with the injection nozzles located at 1/3 bottom radius are specially analyzed. Figure 4 shows velocity vector fields in the hot metal bath injected with calcium oxide particles at four different speeds and after four seconds of injection. It can be seen from this figure that the velocity vectors near the bottom inlets obviously deviate towards ladle axis direction, and the downward velocity vectors appear in regions close to the ladle wall forming two big vortices near the ladle bottom. Figure 5 depicts streamline patterns for injection nozzles at 1/3 bottom radius with four different injection speeds and after four seconds of injection. It can be seen from this figure that there are two very large vortices near the ladle bottom. It is these two large vortices that force the velocity vectors to deviate to the ladle axis, causing non-uniform distributions of the calcium oxide particles in the ladle.

When the double nozzle porous bricks are at 1/3 of bottom radius, since the two nozzle bricks are very close to each other, the left purging gas drives the liquid iron to flow from the left to the right, whereas the right purging gas drives the liquid iron to flow to the left. The two flows cancel each other, leading to two large whirlpools at the bottom. They force the liquid iron flows to deviate toward the ladle axis, resulting in uneven dispersions of the calcium oxide particles at the bottom of the ladle.

Effect of injection rate on calcium oxide particle distribution

Based on the above analysis, arranging the double nozzle porous bricks at 1/2 of bottom radius is the best injection location. Thus, the optimal injection rate at this injection location is further analyzed.

In this work, the ladle is evenly divided into ten surfaces in the horizontal (X) direction and the position of each surface is normalized by the ladle diameter (X/D).

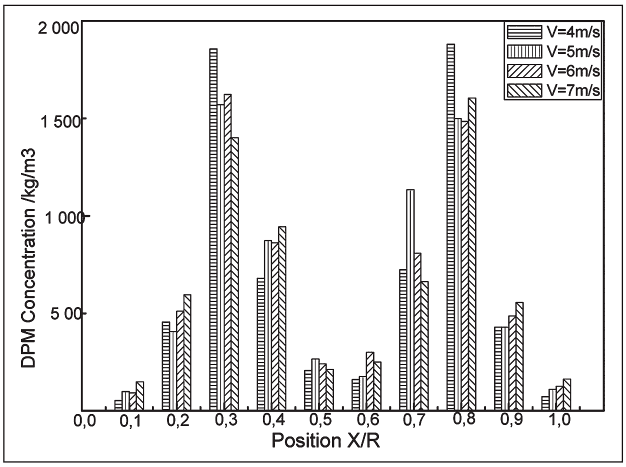

Figure 6 Calcium oxide concentrations on ten surfaces for double nozzle porous bricks at 1/2 bottom radius

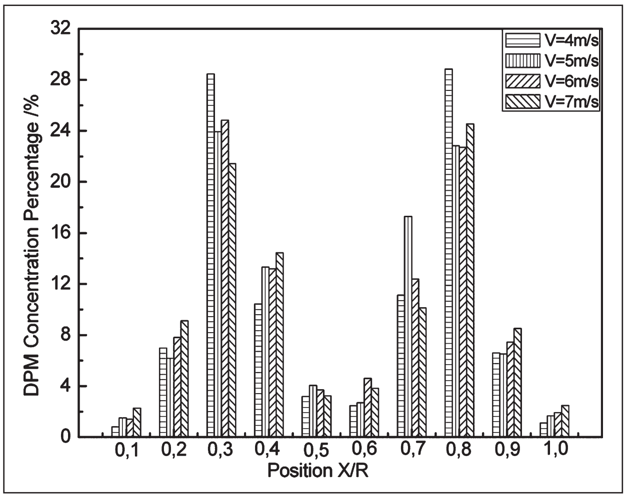

Figure 7 Percentage of calcium oxide concentration in total calcium oxide concentration in ladle on ten surfaces for double nozzle porous bricks at 1/2 bottom radius

The calcium oxide particle concentration (in *kg/m³)* at each surface is calculated for different injection speeds, as shown in Figure 6. In addition, the percentage of the particle concentration at each surface in the total calcium oxide particle concentration in the whole ladle is also calculated for different injection speeds, as shown in Figure 7 In order to achieve uniform distribution, the calcium oxide particle concentrations at the surfaces close to ladle wall (X/D = 0,1; 0,2; 0,9; and 1,0) should be higher enough while those concentrations at the surfaces in the injection regions (X/D = 0,3 or 0,8) should be lower enough.Figures 6 and 7 both indicate that when the injection speed is 7 *m/s* relatively more uniform distribution of the calcium oxide particles in the ladle can be realized. Therefore, among the four injection velocities examined, the optimal injection velocity is 7 *m/s*.

CONCLUSION

Though the present numerical simulation study, the following conclusions can be drawn:

(1) In the injection speed range (4 *m/s* to 7 *m/s*) examined, when injecting calcium oxide particles through the bottom double nozzle porous bricks into the hot metal ladle, the injection location has a larger effect than the injection speed on the distribution of the calcium oxide particles in the ladle.

(2) When the double nozzle porous bricks are located at 1/3, 1/2, and 2/3 of the bottom radius, it is found that injection at 1/2 of the bottom radius gives the optimal calcium oxide particle distribution in the ladle.

(3) When the double nozzle porous bricks are located at 1/2 of bottom radius, among the four injection speeds examined (4 *m/s*, 5 *m/s*, 6 *m/s* and 7 *m/s*), the optimal injection speed is 7 *m/s* that can enable best particle distributions in the ladle.

Acknowledgments

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Note: Wei Ye is responsible for English language, Anshan, China