Mathematical Simulation on Slag Entrainment in Bottom-blowing Gas Ladle with Immersed Cylinder

De-hui ZHANG, Ming-gang SHEN, Chao WU, Qing-hua QI, Qing XU, Zhen-shan ZHANG
(School of Materials and Metallurgy, University of Science and Technology Liaoning, Anshan 114051, Liaoning, China)

Abstract: A flow field mathematical model of the molten steel in a 150 t bottom blowing gas ladle has been established. The ladle blowing argon process was simulated by mixture multiphase model. The flow of the liquid steel and the phenomenon of slag entrainment on the surface of the liquid steel in bottom blowing gas ladle with immersed cylinder were studied. On the basis of the effects of the gas flow rate and the way of blowing on the flow state of the top slag and mixing of molten steel, the critical gas flow rate with the immersed cylinder was determined. The results show that the flow distribution of the liquid steel tends to be uniform, the liquid surface velocity decreases, the critical gas flow of slag entrainment increases and the mixing time is shortened in the ladle when an immersed cylinder is applied.

Key words: ladle; bottom-blowing argon; immersed cylinder; slag entrainment

Stirring operation by bottom blowing argon can improve the materials transmission and the reaction rate between slag and molten steel[1-3] and be beneficial to the removal of non-metallic inclusion. With the increasing demand worldwide for cleaner steel and high quality metal products, the important function of the ladle refining of steel has been growing focused[4-6]. Non-metallic inclusions in the steel have an extremely negative effect on the internal continuity of steel products, which can lead to serious defects in the final product[7-9]. It is well known that gas injection can effectively remove non-metallic inclusions from molten steel and thereby improve the quality of steel. The mixing rates of the temperature and composition of the liquid steel can be increased by bottom blowing argon stirring[10-12]. The stirring intensity can be improved by increasing the gas flow. While, slag entrainment could be induced by the excess gas flow rate[13-15]. Recently, it has been generally considered that three-dimensional (3-D) models is a powerful tool in respect of stirring[16,17]. In the paper, the immersed cylinder was inserted in steel ladle. Then, slag entrainment in liquid steel was restrained; the critical gas flow rate of bottom blowing increased and stirring efficiency of molten steel was improved. Mathematical model of flow distribution of liquid steel in the ladle with immersed cylinder was established. The influences of ladle slag behavior and the critical gas flow rate of bottom blowing gas were analyzed. Then, the feasibility of improving the refining efficiency and shortening the mixing time were discussed.

1 Mathematical Model

1.1 Geometric model

First, the three-dimensional geometric model of the 150 t bottom blowing gas ladle was built and further meshed with GAMBIT software. The grid is shown in Fig. 1.

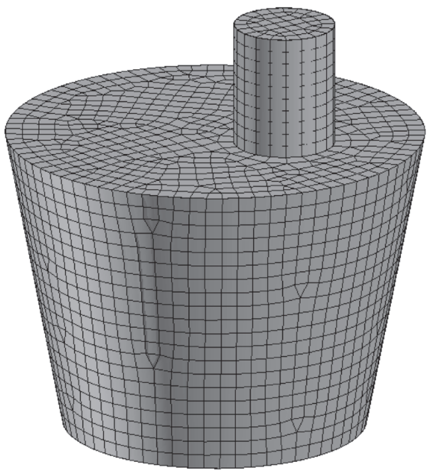

Fig. 1 Grid generation

1.2 Calculation model

The mixture (mixed) model is selected as the multiphase flow model, meanwhile, liquid steel and the argon is respectively set as phase 1 and phase 2. The diameter of gas bubble is set as 10 mm. The drag force is selected as the interaction force between the gas and liquid phase. Realizable model is selected as turbulence model. The initial conditions: select the entrance in the initialization, the initial values of field variables should be determined by entrance conditions. The entire flow field is considered as molten steel[18-20]. The solutions are set as follows: standard pressure, and pressure-velocity coupling by SIMPLEC, as well as first-order upwind momentum, turbulence kinetic energy and turbulence dissipation rate.

Biography: De-hui ZHANG, Doctor Candidate, Senior Engineer; **E-mail:** zhangdehui2000@126.com
Corresponding Author: Ming-gang SHEN, Doctor, Professor; **E-mail:** lnassmg@163.com

1.3 Boundary conditions

1.3.1 Initial conditions

In the initial time of refining process, the bath is full of liquid steel; meanwhile, the liquid steel is static. The gas fraction α=0.

1.3.2 Boundary conditions

(1) Solid wall

For the ladle sidewalls and solid wall of the bottom, the velocity and pressure use no moving boundary condition. The turbulent kinetic energy κ and turbulent kinetic energy dissipation rate ε are set as zero. That is,

$$u = v = \omega = 0 \tag{1}$$

$$\frac{\partial u}{\partial \chi_j} = \frac{\partial v}{\partial \chi_j} = \frac{\partial \omega}{\partial \chi_j} = 0 \tag{2}$$

$$\kappa = \varepsilon = 0 \tag{3}$$

where, u, v, and ω are the velocity components of χ_j.

(2) Entrance

Set Ar blowing entrance as the entrance. The velocity at the entrance is calculated by the inlet flow and inlet area.

$$v = \frac{G}{60 \times \rho \times \pi \times r^2} \tag{4}$$

where, ρ is the density of argon gas and r is the radius of the entrance in the formula.

(3) Export

Set the ladle liquid surface as export. The argon bubbles escape from liquid surface in the ladle. In liquid steel free surface, the gas leaves from the ladle at the speed of its velocity of reaching the surface of the ladle, and the two phases are given a zero shear stress condition. Set the blowing entrance at the bottom of ladle as speed entry. Set the steel liquid surface as symmetric boundary. The ladle wall and ladle bottom surface are considered as the stationary wall. The main parameters of prototype are shown in Table 1, and the material properties are shown in Table 2.

Table 1 Main parameters of prototype

Ladle top diameter/mm	3 154
Ladle bottom diameter/mm	2 781
Depth of molten pool/mm	3 850
Gas flow rate/(L·min^{-1})	0–700

2 Results and Analysis

The original data of 150 t ladle is used in the simulation. The single-hole gas injection is adopted, and the vent is set at the point of 1/2 R of the bottom (is the bottom radius of ladle). An immersed cylinder with the diameter of 788.5 mm and height of 850 mm is inserted

Table 2 Properties of materials

Material	Steel	Argon
Density/(kg·m^{-3})	7 000	1.622 8
c_P/(J·kg^{-1}·K^{-1})	750	520.64
Thermal conductivity/(W·m^{-1}·K^{-1})	41	0.015 8
Viscosity/(Pa·s)	0.006	2.125×10^{-5}
Molecular mass/(kg·mol^{-1})	55.847	39.948
Reference temperature/K	1 600	25

from liquid steel surface, which is coaxial with the bottom blowing holes. The phenomenon of slag entrapment on the surface of liquid steel is discussed under the conditions of different bottom blowing gas rates with and without immersed cylinder.

2.1 Molten steel flow field in ladle

Fig. 2 shows the velocity vector field of ladle without immersed cylinder. In the bottom blown ladle without immersed cylinder, two recycle streams are formed. One of streams is big, and the other one is small. In the longitudinal area, the recirculation based on the two-phase region of gas-liquid is formed among the steel surface, the ladle wall and the bottom of the ladle. In the lateral region, symmetrical recycle stream, whose axis is the diameter of jet nozzle, is formed. When the gas and liquid arrive at the surface of the liquid, gas and liquid will separate. Then, the gas goes into the atmosphere, meanwhile the liquid forms a layer of horizontal flow with the help of inertial force. The speed of horizontal flow will reduce, and then flow down near the ladle wall with the effect of continuously rising steel flow. Recycle stream is formed in the ladle because the steel liquid is driven by the force in the two-phase region. The speed of the liquid steel in the horizontal direction will become larger when enlarging the rate of bottom blowing gas flow. There is a big weak zone in the center of the circulation and the

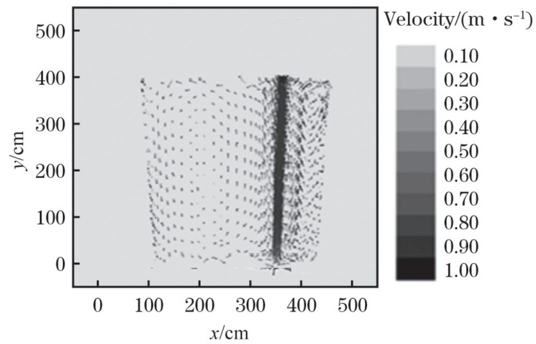

Fig. 2 Velocity vector field in the ladle without immersed cylinder