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PHYSICAL SIMULATION OF CRITICAL BLOWING RATE OF SLAG ENTRAPMENT OF 80 TONS LADLE

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Abstract

The slag entrapment under different conditions of 80t blowing argon ladle furnace was investigated by physical simulation. The water was used to simulate liquid steel and liquid paraffin was for slag. The processing of slag entrapment under different blowing structures was analyzed and the critical velocity and critical droplets diameter of describing it was obtained. Based on the experiments, the relationship between the interface flow velocity and the critical blowing rate（CBR） was deduced. In the real process, it is suggested that the bottom blowing rate is from 40 L/min to 180L/min when the interface tension is 0.12~1.2 N/m during the soft argon blowing.

Introduction

Blowing argon of ladle is the effective way to improve the quality of steel, which has been applied widely in steel making industry. It is pivotal to control the blowing rate of argon, once it is above the critical value of slag entrapment, it will entrap slag into steel rather than cleaning the steel. Therefore, only the proper blowing rate can improve the reaction between slag and steel, uniform the composition and temperature, remove the inclusions in steel[1-3].

So far, there are many studies on the behavior of slag entrapment and factors of causing the steel exposed to the air. In order to avoid it and reduce the exposed area, the critical blowing rate(CBR) of slag entrapment is an important operating parameter[4-7]. However, there are different views about the results of CBR and few studies about the rule of critical slag entrapment[8-9]. In this study, to provide reference of blowing argon to the actual production, the CBR was obtained by physical simulation.

Experimental Method

The 80t ladle was taken as prototype for the research and the model of the ladle was constructed with a scale factor of 1:4. The N_2 was used to simulate argon and the water was simulated steel. Table 1 shows the main parameters of model and prototype of lade.

For the ladle refining system of blowing argon, the force causing the steel flowing is the buoyancy of bubbles, so under the condition of geometric similarity, the dynamic similarity can be obtained by equal modified Froude number of model and prototype. Due to $Fr_m' = Fr_p'$, the relationship of gas flowrate between the model and prototype was derived:

$$Q_m = 3.038 \times 10^{-2} Q_p \quad (1)$$

Where, Q_m and Q_p are respectively the gas flow rate of prototype and model.

The flow of steel-slag interface is mainly influenced by the interface tension, so the Weber number must be taken into consideration [10] .

According to the equal *We*, the relation of density between slag and the simulated slag is derived:

$$\rho_{ms} = \rho_w - \frac{\rho_{Ar}^2 \rho_w^4 \sigma_{s\text{-}s}^2}{\rho_{N_2}^2 \rho_s^4 \sigma_{w\text{-}ms}^2} \lambda^2 (\rho_s - \rho_{slag}) \quad (2)$$

Where, ρ_w, ρ_s, ρ_{ms} and ρ_{slag} are respectively the density of water, steel, simulated slag and slag, kg/m^3.

It is calculated that the density of simulated slag (ρ_{ms}) is 842 kg/m^3, which is very close to the density of liquid paraffin (850 kg/m^3). So the liquid paraffin dyed red by Sudan Red is chosen to simulate the slag so as to be easier observed.

In the experiment, the liquid paraffin is put into ladle slowly and keeps afloat above the water, of which the thickness meets the experimental requirement. To find out the conditions of slag entrapment, the different situations of steel-slag interface are recorded by camera under various blowing rate of nitrogen. The nitrogen injects into the bath through the air brick and the liquid in bath is uplifted with the rising bubbles, which forms the ridgy area above the steel-slag interface. The ridgy liquid flows downward by gravity causing the fluctuation of water-paraffin interface which becomes larger with the increasing of flowing rate. When the flow rate reaches a value, the drops will be formed at the interface. At this time, the value of gas flowrate is called the CBR of slag entrapment.

Table I Main parameters of prototype and model

Parameter	Upper diameter (mm)	Bottom diameter (mm)	Bath height (mm)	Gas density (m^3/h)	Liquid density (m^3/h)	Surface tension (N/m)
Prototype	2650	2300	2600	1.79	7000	1.22
Model	662.5	575	650	1.25	1000	0.042

Results and Discussions

The qualitative description of slag entrapment

Fig.1 shows the variation of simulated slag entrapment with the incensement of blowing rate when the gas injects through single air brick. The mild fluctuation occurs at paraffin-water interface when the blowing rate is small, and the gas discharges through the liquid paraffin (as shown in fig.1a); when the blowing rate become larger, as shown in fig.1b, there is emerging a ridgy area at the paraffin-water interface and there is no paraffin drops breakup; while the blowing rate is increasing as shown in fig.1c and fig.1d, the distinct fluctuation appears at interface and the liquid paraffin layer was blown a round area where the water exposed to air. There are few numbers of scattered paraffin drops is involved in water but quickly ascents back to paraffin layer; as the blowing rate is increasing continuously, as shown in fig.1e and fig.1f, there are more paraffin drops scattering deeply in the water and they are difficult to rise back to the interface. The above phenomenon is consist with the description of slag entrapment in Chen's study [11].

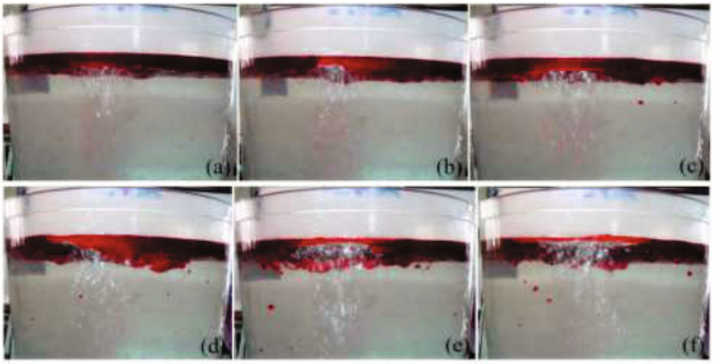

Fig. 1 Pictures of liquid paraffin-water interface at different gas flowrates with a single air brick

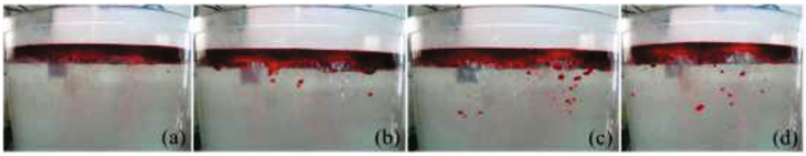

Fig. 2 Pictures of liquid paraffin-water interface at different gas flowrates with double air bricks

In fig.2, it gives the variation of simulated slag entrapment under different bottom blowing rate through two air bricks. With the increase of blowing rate, the phenomenon is similar with that blowing with single air brick. The blowing rate in fig.2a, fig.2b, fig.2c and fig.2d is respectively matching that in fig.1c, fig.1d, fig.1e and fig.1f. Compared with fig.1, under the same bottom blowing rate, the fluctuation in fig.2 is smaller than that in fig.1; the diameter of scattered drops in fig.2 is larger than that in fig.1 but the depth that the drops reach in fig.2 is smaller. That is the scattered drops with blowing through two bricks are liable to come back to the paraffin-water interface. And the blowing rate causing the paraffin drops through two air bricks is greater than that through single air brick.

Slag drops entrapment of bottom blowing

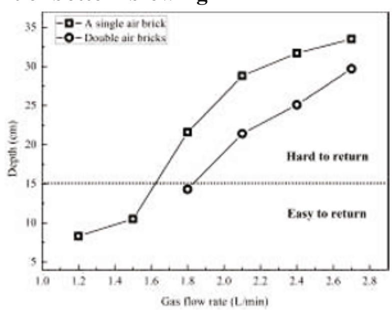

Fig. 3 Effect of gas flow rate on the depth of droplets into the water

Fig.3 shows the depth of slag drops in bath influenced by bottom blowing rate of argon. When gas flow rate is below 1.8L/min, the depth of slag drops entrapped into bath varies slightly with rising of gas rate. It is becuase the inertial force of drops is smaller than the buoyancy due to low speed of it. And Zheng's study[12] shows that the liquid drops can be float up to interface by its own buoyancy when the immersion depth is below 15cm.And it quickly increases to 22cm at the gas flow rate of 1.8L/min,with ascent of bottom blowing rate the speed of liquid is become larger, the circulation velocity of liquid aroud gas column enlarges and the drops velocity to bottom is also increasing. The inertial force of drops is larger than the buoyancy, so the drops is hard to come back to the paraffin-water interface. Therefore, the gas flow rate should be less than 1.8L/min in oder to littel drops involved in water.

It is the similar results that the immersion depth of slag drops influenced by bottom blowing rate both through two air bricks and single one. But under the same blowing rate, the immersion depth of slag drops is smaller with blowing through two air bricks, which is consistent with the situation in fig.1 and fig.2. It is because that the injection area of two air bricks is larger than that of single air brick, the injection speed through two air bricks is lower, so the circulation speed of liquid is lower and the slag drops of inertia force under two air bricks is smaller, causing the smaller immersion depth.

There are three forces exerted on a paraffin drop in the process of the paraffin drop fall from the parafiin layer[11], respectively inertia forece F_i coming from fluid flow, interfacial tension F_s and the buoyancy F_b due to density difference. Assumed that the angle between the entrapment direction of paraffin drops and vertical direction is α, when $F_i \geq F_b/\cos\alpha + F_s$ the paraffin drops fall from paraffin layer and surbmerges in the bath; when $F_i = F_b/\cos\alpha + F_s$, the paraffin drops is in the critical state of slag entrapment. Therefore, when α=0° , it is easiest to appear slag entrapment because of the minimum intertia force needed under this condition; when α=90° the directions of inertia force and interfical tension exerted on drops is horizontal and opposite, so the paraffin drop can float up to the interface by buoyancy rather than entrapment.

According to the condition of slag entrapment, literature [11] gives ciritical velocity of slag entrapment and critical diameter of slag drops respectively shown in Formula (3) and (4):

$$u_{cr} = 2\sqrt{\frac{\sqrt{6\sigma g(\rho_s - \rho_{slag})\tan\alpha}}{\rho_{slag}}} \tag{3}$$

$$d_{cr} = \sqrt{\frac{3\sigma}{g(\rho_s - \rho_{slag})\tan\alpha}} \tag{4}$$

It is assumed that the paraffin drop generates at the intersection of gas column and paraffin-water interface and the direction of slag entrapment is along the tangent of interface, so the α can be obtained by width of gas column under different blowing rate. Table Ⅱ calculates the critical velocity and critical diameter of slag entrapment according to formula (3) and (4).

Table Ⅱ The value of critical velocity and critical diameter of droplets

The width of air column (m)	α (°)	Critical velocity (m/s)	Critical diameter of droplets (mm)
A single air brick	81.2	0.482	2.48
	80.5	0.473	2.57
	78.0	0.446	2.91
	77.4	0.441	2.98
	76.0	0.428	3.15
	74.8	0.419	3.28

Double air bricks	78.7	0.455	2.79
	78.3	0.449	2.86
	78.1	0.446	2.89
	77.6	0.441	2.96
Actual measurement	47	0.307	6.10
	30	0.264	8.30

From table 2, in this study, it is difficult to appear slag entrapment when the α is near 90°; but the probability of it is increasing with decreasing of α and the low critical velocity cause to large critical diameter of paraffin drops. So as to avoid slag entrapment, the interface rate must be smaller than that in Table 2. However, in practical production, the interface rate only can be controlled by bottom blowing rate. So it is important to find out the relationship between argon blowing rate and interface rate, which can give full play to clean steel by blowing argon.

The relationship between critical velocity and critical blowing rate

The kinetic energy of paraffin drops separating from slag is from the kinetic of blowing gas by water (steel) transmitting. It is supposed that u_w is water velocity and u_s is velocity of paraffin layer. Due to little diameter of paraffin drops formed at interface, it is considered that the velocity of interface is equal to the velocity of paraffin layer. According to equivalent shear force of paraffin and water, Oersted [13] deduced the formula of dimensionless number $U=u_i/u_w$:

$$U = 0.1367\left(\frac{\rho_w}{\rho_{ms}}\right)^{2/3} \cdot \left(\frac{u_w l}{v_{ms}}\right)^{1/3} \cdot \left(\frac{u_w l}{v_w}\right)^{-2/15} \cdot [(1-U)(0.1108-0.0693U)]^{2/15} \quad (5)$$

Where, u_w and u_i is respectively the interface velocity of water and interface, m/s; v_{ms} and v_w is the kinematic viscosity of paraffin and water, respectively 1.0×10^{-6} m^2/s and 34.5×10^{-6} m^2/s; l is the length of paraffin-slag interface exerting shear force on, $l=H_{ms}/\cos\alpha$, m; H_{ms} is the thickness of simulated slag, namely thickness of paraffin layer, in this study, the thickness is 0.03m.

Below the interface, the velocity of water u_w is equal to the liquid velocity u_b in gas column, above the interface it is accelerating by the gravity [15].

$$u_w = \sqrt{u_b^2 + gH_{ms}} \quad (6)$$

$$u_b = 1.17\left(\frac{Q_g H_w}{A_b}\right)^{0.346} \quad (7)$$

Where, u_b is water velocity in the gas column, m/s; Q_g is bottom blowing rate, m^3/h; H_w is the depth of bath, m; A_b is the gas-liquid area of cross-section, m^2.

The interface rate of paraffin drops is calculated according to formula (5)~(7). In the calculation, the fluctuation of interface, namely the thickness of paraffin layer, affected by fluctuation is taken into consideration. The thickness paraffin layer is, the easier to form paraffin drops at the thickest paraffin layer. In this study, the thickness of simulated slag layer is 0.03m and its maximum thickness is 0.06m during the bottom blowing. Compared the critical interface rate obtained by theoretical calculation in table 2 with that deduced by experimental flowrate, it shows that they matches each other in fig.4. It also concluded that the critical blowing rate instead of critical interface rate can be used to estimate the slag entrapment, and there is a relationship between them.

Combined with conditions of this study, the dimensionless number (U=0.55) is calculated from formula (5)~(7), accordingly, $u_i=0.55u_w$.

$$Q_g^{0.692} = \left(2.41u_i^2 - 0.73gH_{ms}\right) \cdot \left(A_b / H_w\right)^{0.692} \quad (8)$$

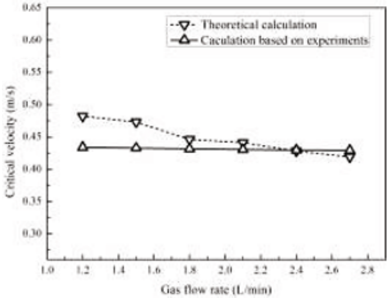

Fig. 4 Morphology of typical inclusions at the beginning of LF

Under the maximum interface rate of this study, the critical bottom blowing rate are respectively 1.49 L/min and 1.70 L/min through single air brick and two air bricks. A more narrow range of critical gas blowing rate is obtained by the above conclusion.

Critical flowing rate in practical

For the slag-steel system of ladle, the Weber number is the definite number describing the state of the system [16]. According to similar principle, the interface rate of steel is derived:

$$We_{\text{liquid paraffin/water}} = We_{\text{slag/steel}} = \frac{U_s^2 \cdot \rho_s}{[\sigma_{\text{s-s}} \cdot g(\rho_s - \rho_{\text{slag}})]^{1/2}} = 22.6 \quad (9)$$

$$U_s = \sqrt{\frac{22.6 \cdot [\sigma_{\text{s-s}} \cdot g(\rho_s - \rho_{\text{slag}})]^{1/2}}{\rho_s}} \quad (10)$$

In literature [17], the slag-steel interface tension of steady state is 1.2N/m and it varies from 0.12N/m to 1.2 N/m when in interface reaction and in unstable state. The flow velocity of steel at the interface is 0.458~0.814m/s by formula (10). Take the results into formula (8), the blowing rate in practical production is 40~180L/min when the interface is unsteady.

Due to the unfinished reconstructing of ladle, the industry test is to be carried out in the coming.

Conclusion

(1) The slag entrapment in steel refining is influenced by the bottom argon blowing rate definitively; when the blowing rate increased to 1.8L/min the depth of paraffin falling into the bath largely increases. To avoid slag entrapment, the blowing rate should be controlled below 1.8L/min. It is more suggestion that the bottom blowing rate should be below respectively 1.49 L/min and 1.70L/min through single air brick and two air bricks.

(2) The critical blowing rate instead of critical interface rate can be used to estimate the slag entrapment when the thickness of paraffin changes due to fluctuation of interface. The relationship between them is shown as: $Q_g^{0.692}=(2.41u_i^2 - 0.73gH_{ms})(A_b / H_w)^{0.692}$.

(3) The critical blowing rate in practical is influenced by temperature and instability of interface reaction and it is suggestion that the blowing rate of argon is controlled from 40 L/min to 180 L/min during soft blowing.

REFERENCES

1. Xiao Z Q, Liu C L, Hu L X, et al. "Behavior and Source of Ladle Inclusions in Steel Treated by Power Injection", *Iron and Steel*, 1988, 23(2):23-29.

2. Gupta D, Lahiri A K. "A water model study of the flow asymmetry inside a continuous casting mold", *Metall. Mater. Trans. B*, 1996, 27(5): 757-762.

3. Zheng S G, Zhu M Y. "Water model study on removing inclusions in a ladle with argon injected through nozzle and porous plug", *Acta Metallurgica Sinica*, 2006, 42(11): 1143-1148.

4. Jonsson L, Joensson P. "Modelling of fluid flow conditions around the slag/metal interface in a gas-stirred ladle". *ISIJ Int.*, 1996, 36(9): 1127-1134.

5. Han J W, Heo S H. "Transient fluid flow phenomena in a gas stirred liquid bath with top oil layer-approach numerical simulation and water mold experiment". *ISIJ Int.*, 200l, 4l(10): 1165-1172.

6. Krishnapisharody K, Irons G A. "Modeling of slag eye formation over a metal bath due to gas bubbling". Metall. Mater. Trans. B, 2006, 37(5): 763-772.

7. Li B K, Gu M Y, Qi F S, et al. "Modeling of three-phase(gas/molten steel/slag) flows and slag layer behavior in an argon ags stirred ladle". *Acta Metallurgica Sinica*, 2008, 44(10): 1198−1202.

8. Mamabu I, Yutaka S, Ryusuke O, et a1. "Evaluation of critical gas flow rate for the entrapment of slag using a water model". *ISIJ Int.*, 1994, 34(2): 164-170.

9. Kim S H , Fruehan R J , Guthrie R I L. "Physical model studies of slag/metal reactions in gas sti rred ladles-determination of critical gas flow rate". *Iron & Steel Maker*, 1993 , 20(11): 71.

10. Zhu M Y, Xiao Z Q. "Mathmatical and physical simulation in steel refining". Beijing, Metallurgical Industry Press, 1998.

11. Cheng G G, Zhang J, Yi X J. "Study on mechansim of slag entrapment in bottom Ar-blowing for ladle". *Steelmaking*, 1993, (6): 23-25.

12. Zheng W, Tu H, Li G Q, et al." Modeling of slag entrapment and molten steel expsed to atmosphere in refining of 250 t ladle weith bottim-blown argon". *The Chinese Journal of Process Engineering*, 2014, 14(3): 361-367.

13. Franz Oeters, Metallurgy of Steelmaking ,Berlin, Verlag Stahleisen mbH, 1989.

14. Masamichi S, Kazumi M. "Fluid flow and mixing characteristics in a gas-sti rred molten metal bath". *Transact ions ISIJ*, 1983, 23: 169-175 .

15. Gan L, He P. "Study on the characteristics of critical gas flowrate for the entrapment of slag in gas-stirred ladles," *Steelmaking,* 2009, 25 (1): 17-21.

16. Xiao Z Q, Peng Y C. "Mathematical modelling of entrapment phenomena at slag/metal interface in gas stirred ladle," *IRON AND STEEL,* 1989, 24 (10): 41-46.

17. Szekely J, *Fluid flow phenomena in metals processing* (Academic Press, 1979).

18. Qu Y, *Theroy of Steelmaking* (Beijing, BJ: Metallurgical Industry Press, 1980).