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Numerical Analysis of Slag Carry-Over during Molten Steel Draining

Daniel Flores-Sanchez, Miguel A. Barron

Departmento De Materiales, Universidad Autonoma Metropolitana, Mexico City, Mexico
Email: bmma@correo.azc.uam.mx

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Abstract

Slag carry-over during the draining of molten steel from a teeming ladle is numerically studied here. Two-phase isothermal transient 3D Computational Fluid Dynamics simulations were employed to simulate the draining process. Two nozzle diameters, two nozzle positions and three slag heights were considered. From mass balances, the slag carry-over in terms of mass flow rate was obtained for each of the above variables. Besides, the draining times of the teeming ladle were estimated from theoretical considerations and CDF simulations, and compared.

Keywords

CFD Simulations, Draining Time, Multiphase Flow, Slag Carry-Over, Teeming Ladle

1. Introduction

Slag carry-over during draining of molten steel from teeming ladles is an important industrial issue given it affects the quality of the solid steel. Main problems of slag carry-over are [1]: 1) hindering of addition of alloys and conditioners; 2) high levels of FeO and MnO, which result in high oxygen content of steel; 3) increased processing time and treatment costs; 4) high inclusion formation, which causes steel cleanliness problems and increased risk of nozzle clogging during casting; 5) phosphorous reversion in the ladle; 6) poor removal of sulfur in the ladle; and 7) increased ladle refractory wear.

Tapping of molten steel without slag carry-over is a difficult task due to the formation of a draining vortex [2]. In [3] the mechanism of slag carry-over during drainage of metallurgical vessel is studied using a physical model. Vortex and drain sink formation are found to be the main mechanism of carry-over of slag to the underlying vessel. The mechanisms of vortex formation are studied in [4] using water modeling and computer simulations. The authors report that the critical bath height for vortex development increases with steel throughputs and nozzle opening.

In this work, the slag carry-over during molten steel draining from a teeming ladle (see **Figure 1**) is numerically studied using 3D transient isothermal Computational Fluid Dynamics (CFD) simulations. A circular nozzle is located at two positions of the bottom of the ladle: centered and off-centered (0.5 m from low border). Two diameters of the nozzles, and three heights of the slag layer are considered. The slag carry-over in terms of mass flow rate of slag is quantified through mass balances as function of nozzle diameter, nozzle position and slag height.

2. Mathematical Model

The flow of an isothermal incompressible Newtonian fluid and the mass conservation are represented by the Navier-Stokes equations and the continuity equation,

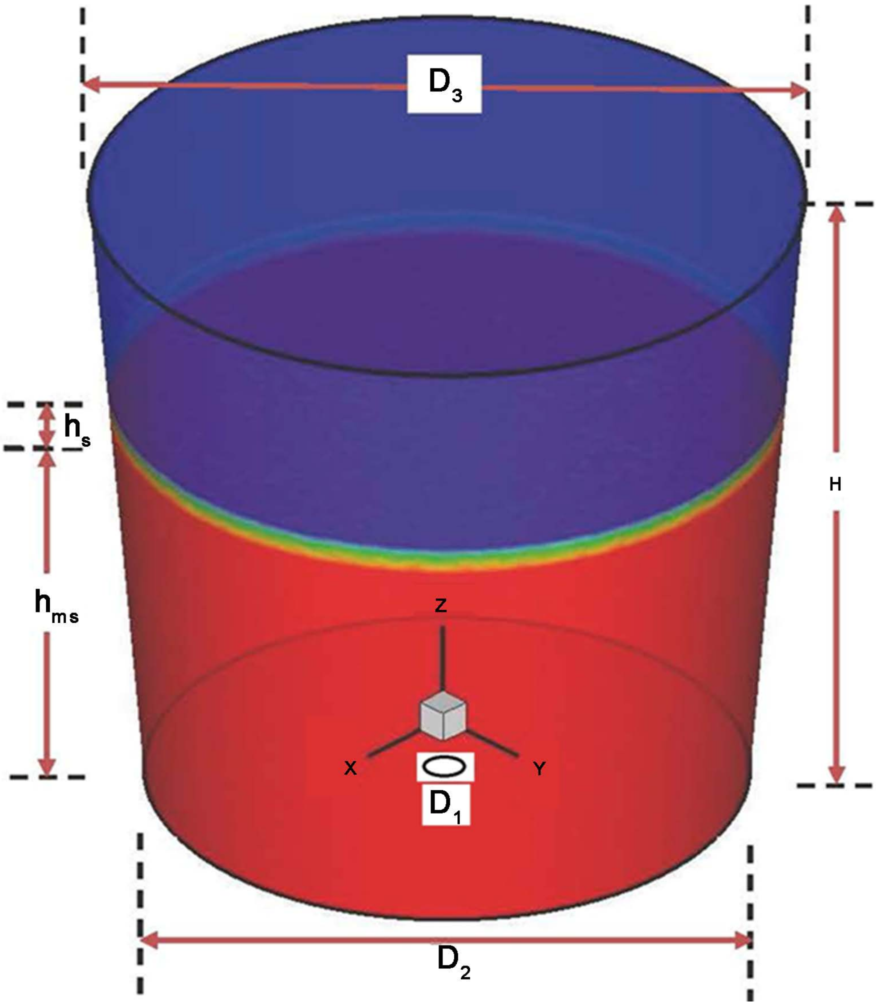

Figure 1. The teeming ladle. In this figure h_{ms} is the height of molten steel and h_s is the height of slag.

respectively [5]. Turbulence in the mold is simulated by means of the classical two equations K-ε model [6]. The multiphase nature of the ladle flow is simulated by means of the Volume of Fluid (VOF) model [7], which considers that all the present phases share the same flow field. The mass conservation principle forces that the whole of the phase volume fractions sums the unity.

A mass balance in the teeming ladle yields the following expression, which tracks the time evolution of the molten steel height:

$$\sqrt{h_{ms}}(t) = \sqrt{h_{ms0}} - \left(\frac{1}{2}\left(\frac{D_1}{D_2}\right)^2 C_D\sqrt{2g}\right)t \qquad (1)$$

where h_{ms0} is the initial height of molten steel, C_D is the nozzle discharge coefficient, g is gravity, and t is time.

On the other hand, the teeming ladle becomes empty when the molten steel height and the slag height become null. In this case, the draining time from Equation (1) is given by:

$$t_d = \frac{2\sqrt{h_{ms0} + h_s}}{\left(\frac{D_1}{D_2}\right)^2 C_D\sqrt{2g}} \qquad (2)$$

3. Numerical Simulations

A cylindrical teeming ladle in which $D_2 = D_3$ (see **Figure 1**) is considered in the computer simulations. The mesh consists in 250,000 tetrahedral cells. The ladle model is solved using commercial CFD software. **Table 1** shows the main parameters of the ladle.

4. Results and Comments

Figure 2 and **Figure 3** show the slag carry-over corresponding to the 0.05 m diameter nozzle, in centered and off-centered position, respectively, as function of the slag height. The molten metal height is kept constant at 0.75 m. These Figures show that for both nozzle positions, slag carry-over starts at 1230, 1270

Table 1. Main parameters of the teeming ladle.

NAME	SYMBOL	VALUE
Ladle diameter	D_2	3.0 m
Nozzle diameter	D_1	0.05, 0.1 m
Nozzle discharge coefficient	C_D	1.0 (dimensionless)
Initial molten steel height	h_{ms0}	0.75 m
Slag height	h_s	0.1, 0.15, 0.2 m
Molten steel density	ρ_{ms}	7100 kg·m^{-3}
Slag density	ρ_s	2500 kg·m^{-3}

and 1295 s of elapsed time for slag heights of 0.2, 0.15 and 0.10 m, respectively. Besides, for the centered position of the nozzle (Figure 2), the average carry-over for 0.15 and 0.20 slag heights is 4.5 kg/s, whereas for 0.1 m of slag height the average carry-over is 4.2 kg/s. Figure 3 shows that for the 0.05 m diameter off-centered nozzle the average slag carry-over for 0.1 and 0.5 m of slag height is around 4.2 kg/s.

On the other hand, Figure 4 and Figure 5 show the slag carry-over corresponding to the 0.1 m diameter nozzle, in centered and off-centered position, respectively, as function of the slag height. As in Figure 2 and Figure 3, the molten metal height is maintained constant at 0.75 m. Figure 4 shows that for the centered nozzle position and 0.1 m of nozzle diameter, slag carry-over starts at 307, 312 and 327 s of elapsed time for slag heights of 0.2, 0.15 and 0.10 m, respectively. For the off-centered position and 0.1 m nozzle diameter, Figure 5 shows that slag carry-over starts at around 302, 310 and 318 s of elapsed time for slag heights of 0.2, 0.15 and 0.10 m, respectively. That is, for 0.1 m of nozzle diameter, slag carry-over starts first for the off-centered nozzle position.

Related to the mass flow rate of slag from the ladle for the 0.1 m diameter centered nozzle, Figure 4 shows and average of 17.5 and 17.0 kg/s for slag heights

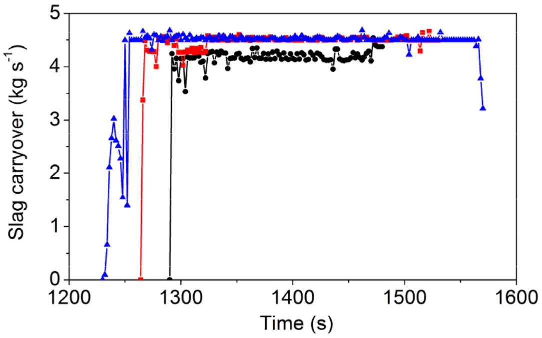

Figure 2. Time evolution of the slag carry-over for three different slag heights: 0.1 m (black), 0.15 m (red), 0.2 m (blue). Nozzle diameter, 0.05 m. Position of the nozzle: centered.

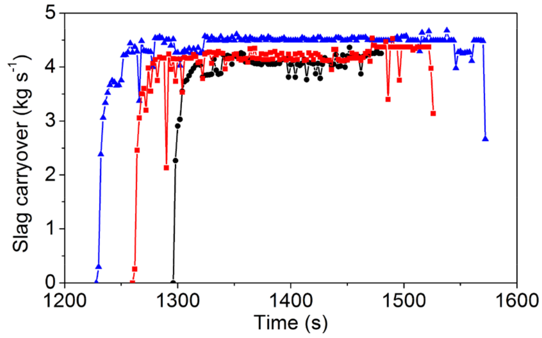

Figure 3. Time evolution of the slag carry-over for three different slag heights: 0.1 m (black), 0.15 m (red), 0.2 m (blue). Nozzle diameter, 0.05 m. Position of the nozzle: off-centered.

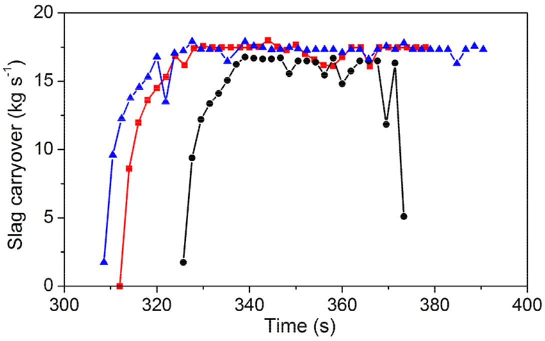

Figure 4. Time evolution of the slag carry-over for three different slag heights: 0.1 m (black), 0.15 m (red), 0.2 m (blue). Nozzle diameter, 0.1 m. Position of the nozzle: centered.

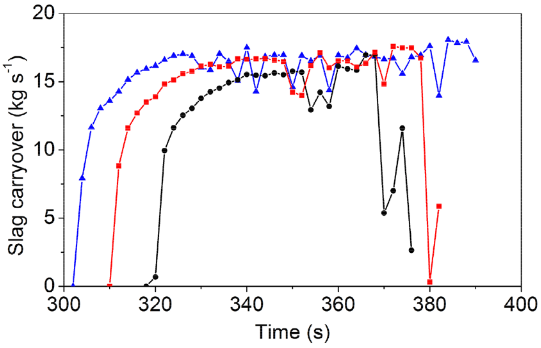

Figure 5. Time evolution of the slag carry-over for three different slag heights: 0.1 m (black), 0.15 m (red), 0.2 m (blue). Nozzle diameter, 0.1 m. Position of the nozzle: off-centered.

Table 2. Draining time for a 0.05 m diameter nozzle.

Slag layer thickness (m)	Draining time (s), Equation (2)	Draining time (s) for centered position, CFD simulations	Draining time (s) for off-centered position, CFD simulations
0.10	1498.6	1470.0	1480.0
0.15	1542.1	1520.0	1526.0
0.20	1584.3	1570.0	1570.0

Table 3. Draining time for a 0.10 m diameter nozzle.

Slag layer thickness (m)	Draining time (s), Equation (2)	Draining time (s) for centered position, CFD simulations	Draining time (s) for off-centered position, CFD simulations
0.10	374.7	372.0	376.0
0.15	385.5	378.0	382.0
0.20	396.1	390.0	390.0

of 0.15 - 0.20 and 0.1 m, respectively. For the 0.1 m diameter off-centered nozzle, Figure 5 shows and average of 17 and 17.0 kg/s for slag heights of 0.15 - 0.20 and

0.1 m, respectively.

Finally, the draining times were determined from Equation (2) and from CFD computer simulations, considering a molten steel height of 0.75 m and a nozzle discharge coefficient of 1.0. These draining times are shown in Table 2 and Table 3. It can be observed that the draining times calculated from Equation (2) are slightly larger than those estimated through CFD simulations. This is due to the fact that in CFD simulations some slag is retained in the ladle, whereas Equation (2) considers that the molten steel and the slag are fully drained. Besides, in accordance to CFD simulations, draining time are slightly larger for the off-centered position than that of the centered position.

5. Conclusions

The slag carry-over from a teeming ladle was numerically studied. Two nozzle diameters, two nozzle positions and three slag heights were considered in the 3D transient isothermal CFD computer simulations. The following conclusions arise:

1) Slag carry-over in terms of mass flow rate is significantly increased as the nozzle diameter is increased.

2) Starting time of slag carry-over increases as the slag height decreases.

3) Mass flow rate of slag is slightly larger for the nozzle centered position than that corresponding to the off-centered position.

4) Draining time depends inversely on the nozzle diameter. As the nozzle diameter is increased, the draining time is decreased.

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