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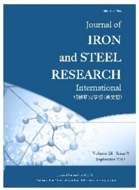

Multiphase modeling of fluid dynamic in ladle steel operations under non-isothermal conditions

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ABSTRACT

A numerical simulation was performed to study the flow pattern, mixing time and open-eye slag produced by argon gas injection in an industrial scale steel ladle under non-isothermal conditions. The liquid steel remains 5 min before the injection, and thermal stratification and convective flows were analyzed. Three different sequences in stages employing various argon-gas flow rates were simulated. In the first case, a sequence with the highest flow rates of argon was applied, while in the second and the third sequences, the intermediate and the lowest flow rates of argon gas were used, respectively. For determining the chemistry homogenization, the mixing time was computed and analyzed in all three cases. It was found that the cold steel is located near the walls while the steel with a high temperature is accumulated in the center of the ladle above the argon-gas tuyere. The higher and lower flows promote a faster chemistry homogenization owing to the secondary recirculations that are developed closer to the walls. The results from steel temperature drop show a good concordance with plant trial measurements.

1. Introduction

Heat loss from steel to the refractory walls during the holding time before the teeming promotes the thermal stratification in the ladle and this may strongly influence the ladle stream temperature. It is desirable that the change of the ladle stream temperature with time should not be great in order to obtain small variations of the tundish temperature. Many studies[1-11] have focused on quantitative heat loss in metallurgical ladles during the stirring and holding time using mathematical models. The results obtained have been used as boundary conditions to estimate the temperature drop in the metal bath. In the secondary steelmaking ladle, besides chemical reactions, some physical and physical-chemical processes are of importance, i. e., homogenization of composition and temperature, separation of nonmetallic particles from steel melt, loss and gain of heat content of the melt, and dissolution of alloying elements[12]. Therefore, to enhance the rate of the reactions in the ladle, the ladle can be equipped with gas injection at the bottom. When ascending bubbles drag liquid with them, an inverted cone, called plume, forms from a gas/liquid mixture. This plume causes a recirculating flow where the liquid ascends by the gas and then descends along the vessel walls. Early studies[13-25] of mathematical and physical simulation to understand the phenomena of fluid flow into refining ladle were conducted in two-phase 2-D models. There are mathematical models in 3-D that includes three phases: steel, slag and gas; these models compute the temperature drop, mixing time, flow patterns and slag eye aperture[26-32]. Pan et al. [26] employed numerical simulation to investigate parameters that may have significant influences on heat loss rate, thermal stratification and teeming stream temperature in steel ladle. They found that an increase in the hot face temperature in the range of 200 ℃ would generally result in a nearly 3 ℃ higher teeming stream temperature, and also a thicker slag layer led to a smaller drop rate of the teeming stream temperature, and vice versa. Lastly, the holding time has a great influence

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on the initial level of the teeming stream temperature, but with a small effect on the drop rate of this temperature. Putan et al.[28] combined a 1-D model to calculate the heat loss through refractory with a 3-D model to study the fluid flow during holding time and casting period. They reported that after 10 min, the difference of temperature is 9 ℃ and the movement of the fluid alloy, owing to its flowing out of the cast, leads to a mixing process allowing diminishing of the existent stratification. Maldonado-Parra et al.[30] developed a mathematical model to investigate the influence of the number of porous plugs and its radial position on both thermal and chemical mixing phenomena, considering the localized source of heating from three electrodes in an industrial ladle. They reported that thermal mixing is improved with one porous plug in the center of the ladle because gas plumes act as thermal barriers when two and three porous plugs are included. Also, the chemical mixing is improved with one porous plug located at a radial position of 0.67. Tripathi et al.[32] developed a mathematical model in an industrial ladle to study the completed cycle, i.e. from preheating to teeming and subsequent tapping. They observed a linear fall in temperature with the time from tapping start to end of holding period. The result for varying slag thickness shows a minor reduction in the temperature drop of molten steel as the slag thickness is increased from 40 to 80 mm. Also, the effect on temperature drop of molten steel was found to be insignificant.

The purpose of the present work was to study the thermal and chemical homogenization using argon injection sequences as it is used in the industry. Four-phase (air, slag, steel and argon-gas) 3-D numerical simulation was performed in a metallurgical ladle with three different sequences varying the flow rate, and the temperature drop in the liquid steel agrees well with industrial measurements for the different sequences employed. The study involved the holding time thermal stratification and the heat losses on the side walls and bottom, from the ladle. The fluid pattern, the mixing time and the thermal stratification with gas injection by two tuyeres were analyzed.

2. Mathematical Model

In the present work, the following assumptions are considered for the four-phase model (air, steel, slag, argon-gas):

(1) The geometry was developed in a three-dimensional Cartesian coordinate system.

(2) The fluid inside the ladle is Newtonian fluid.

(3) The flow is fully turbulent.

(4) The state is non-isothermal.

(5) No slip occurs on all surfaces.

(6) The gravitational force acts only on negative y-axis.

(7) The interfacial tensions between the fluids were considered.

(8) Gas was injected through tuyeres instead of porous plug.

2.1. Governing equations

To solve the fluid dynamics of the system, a set of Navier-Stokes equations were used.

(1) Continuity equation

$$\frac{\partial \rho}{\partial t}+\rho(\nabla u)=0 \tag{1}$$

(2) Momentum equation

$$\rho\frac{\partial u}{\partial t}+\rho[u\cdot\nabla]u=-\nabla P+\mu_{\mathrm{eff}}\nabla^2 u+\rho g \tag{2}$$

where, ρ is the fluid density; u represents the velocity; t is the time; P and g represent the pressure and the gravity acceleration, respectively; and μ_{eff} is the effective turbulent viscosity.

(3) Turbulent equations

The standard two-equation k-ε model is used to model turbulence, which solves two equations for the transport of turbulent kinetic energy, k, and its dissipation rate, ε, to obtain the effective viscosity field; therefore, μ_{eff} is the sum of the molecular viscosity μ and turbulent viscosity μ_{t}:

$$\mu_{\mathrm{eff}}=\mu+\mu_{\mathrm{t}}=\mu+\rho C_{\mu}\frac{k^2}{\varepsilon} \tag{3}$$

where $C_{\mu}=0.09$. Finally, Eq. (3) is employed to solve the turbulence model.

Turbulent kinetic energy

$$\rho\frac{\partial k}{\partial t}+\rho\frac{\partial k u_i}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_{\mathrm{t}}}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k-\rho\varepsilon \tag{4}$$

where, G_k is the generation of turbulence kinetic energy owing to the mean velocity gradients,

$$G_k=\mu_{\mathrm{t}}\frac{\partial u_j}{\partial x_i}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right) \tag{5}$$

Kinetic dissipation rate

$$\rho\frac{\partial \varepsilon}{\partial t}+\rho\frac{\partial \varepsilon u_i}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_{\mathrm{t}}}{\sigma_{\varepsilon}}\right)\frac{\partial \varepsilon}{\partial x_j}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}G_k-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{6}$$

where, x_i and x_j are the Cartesian components of the velocity; $C_{1\varepsilon}$, $C_{2\varepsilon}$, σ_k, and σ_{ε} are the empirical constants, whose values are 1.38, 1.92, 1.00 and 1.30[29], respectively.

(4) Volume of fluid (VOF) model

The VOF formulation relies on the fact that two or more fluids or phases are not interpenetrating. For each additional phase added to the model, a new variable is introduced (the volume fraction in the computational cell). A continuity equation has to be solved for the volume fraction of one or more of the phases,

$$\partial \alpha_q/\partial t+u\cdot\nabla\alpha_q=S\alpha_q/\rho_q \tag{7}$$