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Molten Steel Flow in a Slab Continuous-casting Tundish

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Abstract: Fields of fluid flow and temperature, and residence time distribution (RTD) curves were investigated by mathematical simulation in a one-strand tundish for continuous casting. It was known from the investigation that a big "spring uprush" formed on surface around the long shroud when molten steel flowed into a turbulence inhibitor (TI) with extending lips and rushed up reversely out of the TI, while four small "spring uprushes" existed on surface when a TI without extending lips because the liquid steel flowed mainly out of the 4 corners of the TI. The flow of liquid steel in the former tundish configuration was not reasonable and the height of an area where temperature was less than 1819 K was about half of liquid surface height on the right side of the stopper, which meant that big dead zone existed in the former tundish configuration. In the optimal one, the height of such area was only seventh of the liquid surface height. The RTD curves obtained from the mathematical simulation basically agreed with those from the physical modeling and the flow characteristics obtained from these two methods agreed with each other.

Key words: slab continuous-casting; one-strand tundish; flow control device; molten steel flow; mathematical simulation

Tundishes are necessary storing and distributive vessels between ladles and molds in continuous casting process. The effects of tundishes are to reduce liquid steel pressure, make it steadily flow for reduction in impaction and agitation of flow to molten steel in molds, store and distribute liquid steel according to process requirement, guarantee smooth casting start, stop and ladle change, and implement even, continuous and steady providing of molten steel for continuous casters[1, 2]. As a continuous metallurgical reactor, tundish also has some additional metallurgical functions besides the above basic effects, for example, liquid steel refining and cleaning[3-6]. Flow of liquid steel in tundishes can be improved by using suitable flow control devices to form optimum tundish configurations, which can increase residence time of molten steel in tundishes, enhance floatation-up of non-metal inclusions, improve steel cleanness, reduce steel flow impaction to tundish refractory, and prevent slag entrapment, etc[6-12].

Optimum tundish configurations should be of large minimum residence time, peak concentration time and average residence time, great plug flow volume, small dead zone volume, and reasonable mixing flow volume. The velocity and temperature fields and residence time distribution (RTD) curves for the former and optimum configurations in a one-strand slab continuous-casting tundish were investigated by mathematical simulation and compared to the results obtained in the physical modeling[13] for verification of the mathematical results in this study.

1 Mathematical Model for Liquid Steel Flow in Tundish

The Calculation domain of the tundish studied and its former configuration is presented in Fig. 1. The steel flow in tundishes is a complete turbulent flow. The molten steel was treated as a homogeneous phase and its flow in the tundish as a steady incompressible viscous flow with ignoring the influence of the liquid surface fluctuation and slag layer. The density of liquid steel was considered to be constant. The fluid flow in tundishes is governed by basic conservation laws including mass, momentum, energy and component conservations. Therefore, it can be described with continuity, momentum, energy and component transfer equations.

1.1 Governing equations

The governing equations for the steady turbulent incompressible viscous flow of molten steel in tundishes can be expressed as:

Continuity
$$\frac{\partial}{\partial x_i}(\rho u_i)=0 \tag{1}$$

Momentum
$$\frac{\partial}{\partial x_j}(\rho u_i u_j)=-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\mu_{\text{eff}}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\right]+\rho g_i \tag{2}$$

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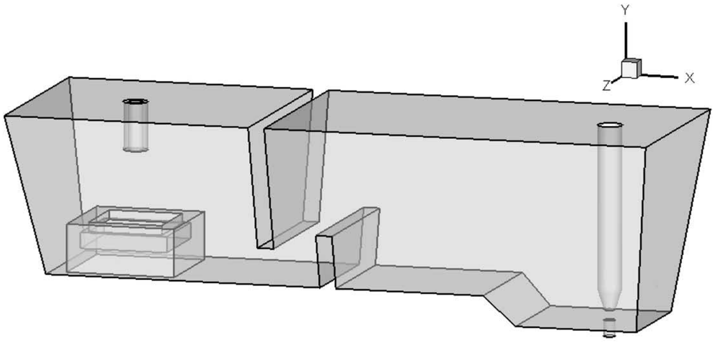

Fig. 1 Calculation domain of tundish and the former tundish configuration

where, u_i and u_j are time-mean velocity, x_i and x_j represent the three coordinate directions, ρ is the density of melt, p the pressure, g the gravitation acceleration, and μ_{eff} the effective viscosity.

The turbulent viscosity is calculated through its relationship with the turbulent kinetic energy and its dissipation rate. The turbulent kinetic energy, k and its dissipation rate, ε can be expressed with the following equations:

Turbulent kinetic energy

$$\frac{\partial(\rho k u_i)}{\partial x_i}=\frac{\partial}{\partial x_i}\left(\frac{\mu_t}{\sigma_k}\frac{\partial k}{\partial x_i}\right)+\mu_t\frac{\partial u_j}{\partial x_i}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)-\rho\varepsilon \quad (3)$$

Dissipation rate of turbulent kinetic energy

$$\begin{aligned}&\frac{\partial(\rho\varepsilon u_i)}{\partial x_i}=\frac{\partial}{\partial x_i}\left(\frac{\mu_t}{\sigma_\varepsilon}\frac{\partial\varepsilon}{\partial x_i}\right)+\\&C_1\mu_t\frac{\varepsilon}{k}\frac{\partial u_j}{\partial x_i}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)-C_2\frac{\rho\varepsilon}{k}\varepsilon\end{aligned} \quad (4)$$

C_1, C_2, C_μ, σ_k and σ_ε are the empirical constants of the k-ε model and were assigned to their standard values from Launder and Spalding[14]: 1.44, 1.92, 0.09, 1.0 and 1.30, respectively. μ_{eff} can be calculated with Eq. (5):

$$\mu_{\text{eff}}=\mu_1+\mu_t=\mu_1+\rho C_\mu k^2/\varepsilon \quad (5)$$

The heat transfer in the tundish is governed by energy equation as follows:

$$\frac{\partial(\rho C_{\text{P}}u_iT)}{\partial x_i}=\frac{\partial}{\partial x_i}\left(\lambda_{\text{eff}}\frac{\partial T}{\partial x_i}\right) \quad (6)$$

where the effective thermal conductivity, λ_{eff}, is the sum of two components:

$$\lambda_{\text{eff}}=\lambda+\frac{C_{\text{p}}\mu_{\text{t}}}{Pr_{\text{t}}} \quad (7)$$

where, Pr_{t} is the turbulent Prandtl number, λ is thermal conductivity, C_{p} is heat capacity and T is temperature.

To calculate the residence time distribution curves of the molten steel in the tundish with different configurations, a pulse of tracer was introduced into the melt through the inlet and allowed to flow with the melt. The transport of the tracer and the variation in tracer concentration is governed by the mass transport equation as follows:

$$\frac{\partial c}{\partial t}+\frac{\partial(u_ic)}{\partial x_i}=\frac{\partial}{\partial x_i}\left(D_{\text{eff}}\frac{\partial c}{\partial x_i}\right) \quad (8)$$

where c represents the concentration of the tracer, t is the time and D_{eff} is the effective mass diffusion coefficient and is the sum of the molecular and turbulent diffusivity as follows:

$$D_{\text{eff}}=(D+D_{\text{T}}) \quad (9)$$

Under the condition where turbulent Schmidt number is equal to 1, one has:

$$\frac{\rho D_{\text{eff}}}{\mu_{\text{eff}}}\approx 1 \quad (10)$$

1.2 Boundary conditions

(1) Velocity field

Non-slipping conditions were applied as boundary conditions to all solid walls. Frictionless conditions were used to the free surface of liquid steel. The logarithmic law was employed to all nodes closest to any solid walls. The vertical velocity profiles of the liquid steel at the inlet as well as at the outlet of the tundish were assumed to be uniform through the cross sections and the other two velocity components were assumed to be zero. The values of k and ε at the inlet were calculated from the inlet average velocity through the well known equations. A constant mass flow rate of steel from the ladle to the tundish was 2.98 t/min for the mathematical simulation.

(2) Temperature field

For the boundary conditions of temperature field,