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Numerical Simulation of Coupled Molten Steel Flow and Temperature Fields in Compact Strip Production Casting

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Abstract: Based on the casting manufacture practice of steel slabs by CSP technology, the flow and the temperature fields of the funnel mould and the secondary cooling segment were simulated using the commercial code, CFX4. Compared with other physical investigations, the correlative data of the present simulation results are in good agreement with them. Therefore, a more comprehensive survey for metallurgy characteristic of the flow and the temperature fields in CSP continuous casting process can be achieved.

Key words: compact strip production; numerical simulation; flow field; temperature distribution

Flow of molten metal in the mould region during the continuous casting (CC) process of steel is of considerable interest because it influences many important phenomena, which have far-reaching consequences on strand quality[1]. The flow transport characteristics in the mould during the conventional CC process can be studied in large quantities using mathematical models, physical water models, and plant measurements. Compact strip production (CSP) technology, which probably is to be further improved, replaces the conventional casting process at the beginning of the 21st century because of its high profitability. However, compared with the conventional CC process, CSP technology has been developed over the recent years and the transport characteristics in CSP casting process are rarely documented in the correlative investigations.

1 Mathematical Modeling Description

1.1 Assumptions of modeling

To understand the turbulent flow pattern in the CSP casting process, numerical modeling of 3D coupled turbulent flow, heat transfer, and solidification in the CSP continuous slab caster is described. The following assumptions are made in the formulation of the mathematical model:

(1) With respect to the fixed laboratory frame of reference, the casting process is in steady state and can be represented by the steady, three-dimensional turbulent Naive-Stokes and energy transport equations.

(2) Molten steel is taken as an incompressible Newtonian fluid.

(3) The top surface is also covered with a protective slag layer, which keeps the surface thermally insulated from the surroundings.

(4) Heat release caused by solid-solid transformation (viz. δ-γ etc.) is negligible. Only the evolution of latent heat caused by solid-liquid phase change is taken into account.

1.2 Description of solidification model

When high flow rates are involved, the numerical model should account for turbulence. Although there is a layer of solidified shell in the mould in the real continuous casting practices, previous numerical simulation studies of the flow field in mould of plate and billet continuous casting never took the layer into consideration[2,3]. The reason is that the thickness of solidified shell in the mould outlet is only 1%−10%

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of that of the mould thickness. In addition, it is difficult to mesh grids because of the complex shape of solidified shell. Whereas, under the condition of CSP technology, the thickness of the shell is about half of the mould outlet[4]; thus, the effects of heat transfer and solidification should be taken into account when the flow field is calculated.

The solidification model uses a fixed-grid approach with source terms representing the transient and the convective evolution of the latent heat. The local temperatures of the solid and the liquid phases of the solidifying material are assumed to be in equilibrium and the model therefore works in a single-phase framework. Phase transition occurs in a finite temperature range between the solidus and liquidus temperatures and is well suited to the simulation of solidification. Between these two temperatures, a mushy region of the solid and the liquid exists.

Following Bennon W D et al[5,6], the transport equations for momentum and enthalpy are obtained by summing the solid- and the liquid-phase transport equations. If it is assumed that the solid phase density ρ_s and the liquid phase density ρ_l are equal, the continuity equation is then given as:

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

where ρ is density; t is time; and the mixing velocity, U is expressed in terms of solid and liquid volume fractions, f_s and f_l.

$$U=f_l U_l+f_s U_s \tag{2}$$

where U_l, U_s are velocity of solid and liquid, respectively.

Similarly, the momentum equation is derived as follows:

$$\frac{\partial}{\partial t}\rho U+\nabla \cdot (\rho U \otimes U)=-\nabla p+\nabla \cdot (\mu_l \nabla U)-\frac{\mu_l}{K}(U-U_s) \tag{3}$$

where μ_l is laminar flow viscosity; and K is permeability.

The final term of the momentum equation represents the resistance to flow of liquid through the mushy region. It is in the form of a Darcy-like resistance source, and in the limit as the f_l tends to be zero, it forces the velocity to that of the solid, as specified using the casting speed.

The permeability, K, is related to f_l via the Kozeny-Carman equation:

$$K=K_0\left[\frac{f_l^3}{(1-f_l)^2}\right] \tag{4}$$

The Darcy constant, K_0, is dependent on the morphology of the particular solidifying material involved.

The enthalpy equation for the solidifying material is obtained as follows:

$$\frac{\partial}{\partial t}\rho H+\nabla \cdot \rho U H-\nabla \cdot \lambda \nabla T=-\rho_l\left[\frac{\partial f_l}{\partial t} \cdot \nabla f_l\right] \tag{5}$$

The term on the right hand side of the enthalpy equation represents the transient and convective evolution of the latent heat. The mixing enthalpy, H, is the weighted enthalpy of the solid and the liquid.

$$H=f_l H_l+f_s H_s \tag{6}$$

The f_l is deduced from the temperature and is assumed to linearly vary between the solidus temperature, T_s, and the liquidus temperature, T_l.

$$f_l=\left[\frac{T-T_s}{T_l-T_s}\right] \tag{7}$$

Damping terms are added to the k and ε equations such that the turbulence tends to be zero as the material becomes fully solid, as described by Reza Aboutalebi et al[7]:

$$S_k=\frac{-A(1-f_l^2)}{f_l^3}k \tag{8}$$

$$S_\varepsilon=\frac{-A(1-f_l^2)}{f_l^3}\varepsilon \tag{9}$$

where the damping constant, A, is selected as 1.0×10^6.

2 Modeling Object

2.1 Geometrical surface of funnel shape mould fit formula

The schematic of model domain is shown in Fig. 1. The cross-sectional dimension of the mould outlet is 1 250 mm×60 mm, and the submerged entrance nozzle (SEN) is a 2-port design with two big exit ports large-angled downward from the horizontal level.

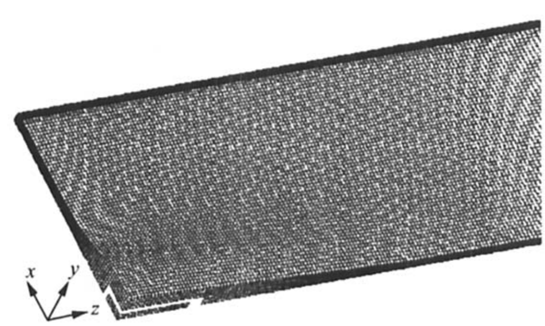

Fig. 1 Schematic of a quarter section of funnel-shaped mould