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Numerical Modelling of Fluid Flow and Thermal Phenomena in the Tundish of CSC Machine

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Abstract

The mathematical and numerical simulation model of the liquid steel flow in a tundish is presented in this paper. The problem was treated as a complex and solved by the finite element method. The single-strand slab tundish is used to continuous casting slabs. The internal work space of the tundish was modified by the following flow control devices. The first device was a striker pad situated in the pouring tundish zone. The second device was a baffle with three holes and the third device was a baffle without hole. The main purpose of using these devices was to cause a quiet liquid mixing as well as give directional metal flow upwards which facilitated inclusion floatation. The interaction of flow control devices on hydrodynamic conditions was received from numerical simulation. As a result of the computations carried out, the liquid steel flow and steel temperature fields were obtained. The influence of the tundish modification on velocity fields in the liquid phase of steel was estimated, because these have an essential influence on high quality of a continuous steel cast slab.

Keywords: Solidification process, Application of information technology to the foundry industry, Continuous casting tundish, Molten metal flow

1. Introduction

Today, the dominant method of global steel production is the continuous casting, hence the need for continuous improvement of this method. The production of quality steel from a continuous casting machine is dependent on a large number of interlinked process parameters of main ladle, tundish and continuous steel casting (CSC) mould [1, 2]. Important continuous casting device is the tundish, in which a stabilized steel flow has a crucial effect on the quality and efficiency conditions of the CSC process. The tundish is not only a storage vessel which guaranty the continuous casting of steel, but it become an additional metallurgical stage where other operation are performed. These operations are for

example the control of melt temperature, composition and melt flow control to enable non-metallic inclusion separation [3, 4]. In order to remove inclusions in the tundish, it is necessary to have a good understanding of fluid flow. Flow behaviour in the tundish is governed mainly by the size and shape of the tundish and the location of flow control devices, such as dams, weirs, filters, striker pad, baffles with holes and turbulence inhibitors. The flow pattern is also affected by the steel flow rate and its temperature distribution [5 - 7].

The aim of the paper is to estimate, by numerical simulation method, the modification effect of the internal space of tundish by flow control devices on the molten metal flow and the temperature field within the tundish. The molten steel flow behaviour characterized by mathematical modelling in the bare

tundish and in the tundish equipped with the baffles were analyzed. In each case of a study, the velocity and temperature distribution were obtained. The velocity field is obtained by solving the Navier-Stokes equations, whereas the thermal field is calculated by solving of Fourier-Kirchhoff equation with the convection term. The problem was solved by the finite element method [8 - 10].

2. The mathematical model of the heat transfer during the molten metal motions

The mathematical model of a molten metal flow in the tundish has been proposed. The superheated metals and their alloys in the liquid state can be treated as Newtonian fluids [3, 4, 7, 8, 11], therefore in the paper is used the system of equations (1, 2) which describe the flow of viscous incompressible fluid. The equation describes the heat transfer in the region of a tundish is based on solving the Fourier-Kirchhoff equation with the convection term [4, 7, 8, 11, 12]. It was assumed that the solidification front is mushy [7 - 9, 11 - 13], but sometimes it is assumed that it can be sharp [10]. The assumption of such model (the mushy zone) allowed us to introduce the phase transformation enthalpy to the effective thermal capacity in the energy equation in the problem solution. The mathematical model is based on the solution of the following system of differential equations [7, 8, 11]:

$$\rho \frac{d\mathbf{v}}{dt} = -\nabla p + \mu \nabla^2 \mathbf{v} + \rho \mathbf{g} \beta (T - T_{in}) + \rho \mathbf{g} \quad (1)$$

$$\nabla \cdot \mathbf{v}(\mathbf{x}, t) = 0 \quad (2)$$

$$\nabla \cdot (\lambda \nabla T(\mathbf{x}, t)) - C_{ef} \frac{\partial T}{\partial t} - C_{ef} \nabla T \cdot \mathbf{v} = 0 \quad (3)$$

where: T - the temperature [K], $\rho = \rho(T)$ - the density [kg/m^3], λ - the thermal conductivity coefficient [$\text{W}/(\text{mK})$], $\mathbf{v}(u, v)$ - the velocity vector of a molten metal flow [m/s], $\mu(T)$ - the dynamical viscosity coefficient [Ns/m^2], $\mathbf{x}(x, y)$ - the coordinates of the vector of a considered node's position [m], p - the pressure [N/m^2], C_{ef} ($C_{ef} = \rho_{LS} c_{LS} + (\rho_S L)/(T_L - T_S)$) [7, 8, 12] - the effective heat capacity of the mushy zone [$\text{J}/(\text{m}^3\text{K})$], L - the latent heat of solidification [J/kg], c_{LS} - the specific heat of the mushy zone [$\text{J}/(\text{kgK})$], $\rho_S, \rho_L, \rho_{LS}$ - the density of solid phase, liquid phase, and mushy zone, respectively [kg/m^3], \mathbf{g} - the vector of the gravity acceleration [m/s^2], t - time [s], β - the volumetric thermal expansion coefficient [$1/\text{K}$], T_{in} - the initial temperature (tundish inlet) [K].

The equations above (1 - 3) create a closed, coupled system of equations describing the molten metal flow. The momentum equations (1), continuity equation (2) and equation of heat conductivity (3) are completed by the appropriate initial conditions and the classical boundary conditions [7 - 14]. For the energy equation is: the pouring temperature and the boundary condition of type III. For the momentum equations are: - the pouring velocity and the velocity components normal and

tangential to the walls are set at zero [7]. The above problem was solved by the finite element method in the weighted residuals formulation [7 - 11].

3. Example of numerical simulations

The calculations were performed for the tundish with a cross-section 3.3×1.44 and the length 4.7 m. The overheated steel with temperature $T_{in} = 1906$ K was poured with velocity $v_{in} = 0.45$ m/s into the tundish with the initial temperature $T_t = 1300$ K. The thermophysical properties of the cast steel and tundish were taken from works [1, 3, 8, 14, 15]. The characteristic temperatures of the molten steel were equal to: $T_L = 1810$, $T_S = 1760$ K and ambient temperature $T_a = 305$ K. The heat-transfer coefficient (α) between the tundish and ambient was equal $\alpha_r = 30$ $\text{W}/(\text{m}^2\text{K})$ and between the slag and ambient $\alpha_s = 3$ $\text{W}/(\text{m}^2\text{K})$ [1, 14, 16]. The thermal and fluid flow phenomena proceeding in the considered system were analyzed. Examples of calculation results are shown in the form of the temperature and velocity fields (Fig. 1, 2). The internal working space of the tundish has been modified by the location of added flow control devices, such as the striker pad (Fig. 1), baffle with three holes (Fig. 2a) and baffle without hole (Fig. 2b). An influence of the interaction of this flow control devices on the velocity fields in the liquid phase of steel were estimated. The main objective of the velocity field change was to enable non metallic inclusion separation and give directional metal flow upwards which facilitated inclusion floatation.

4. Conclusions

This paper presents the coupled model of solidification for the transient evaluation of fluid flow and heat transfer in the tundish during continuous casting processes. The problem was treated as a complex and solved by the finite element method. Numerical simulation results are shown in the form of the temperature and velocity fields (Fig. 1, 2). It was noted, that the velocity field of a liquid phase has a significant influence on the temperature field. A small intensity of the molten metal motion near the slag layer causes the formation of dead zones and the local temperature drop in the outflow tundish zone (Fig. 1). Next, two modification variants of the internal work space of the tundish were performed (Fig. 2). In the second variant, the minimum dead volume is visible because the baffle gives a directional metal flow upwards allowing the inclusions to float toward the slag layer (Fig. 2a). In the third variant, the excessive flow directed across the top surface can produce vortex flow and lead to reoxidation and slag entrainment (Fig. 2b). This variant turned out to be worse, to enable non metallic inclusion separation than the second variant. Generally summarize, the flow field inside the tundish is frequently unsteady and is an important mechanism for inclusion elimination from liquid steel allowing the inclusions to float toward the slag layer. It has an essential influence on obtain high-quality of the continuous steel cast slab. It is very important for the practice casting.

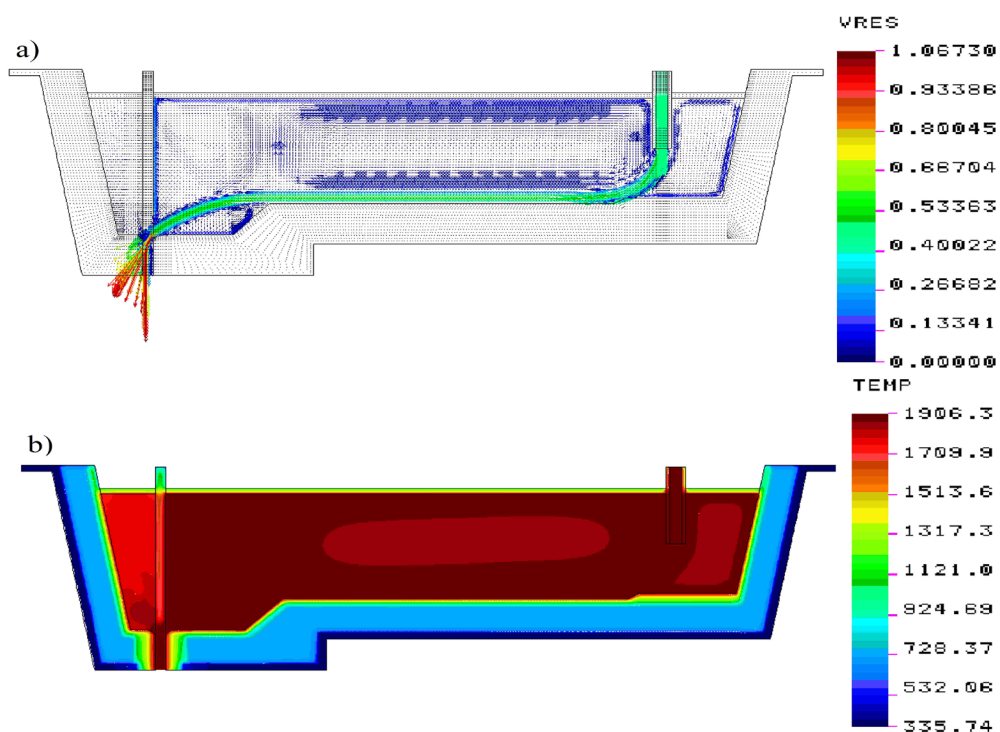


Fig. 1. Velocity vectors (a) and temperature field (b) after time 720 s, I variant

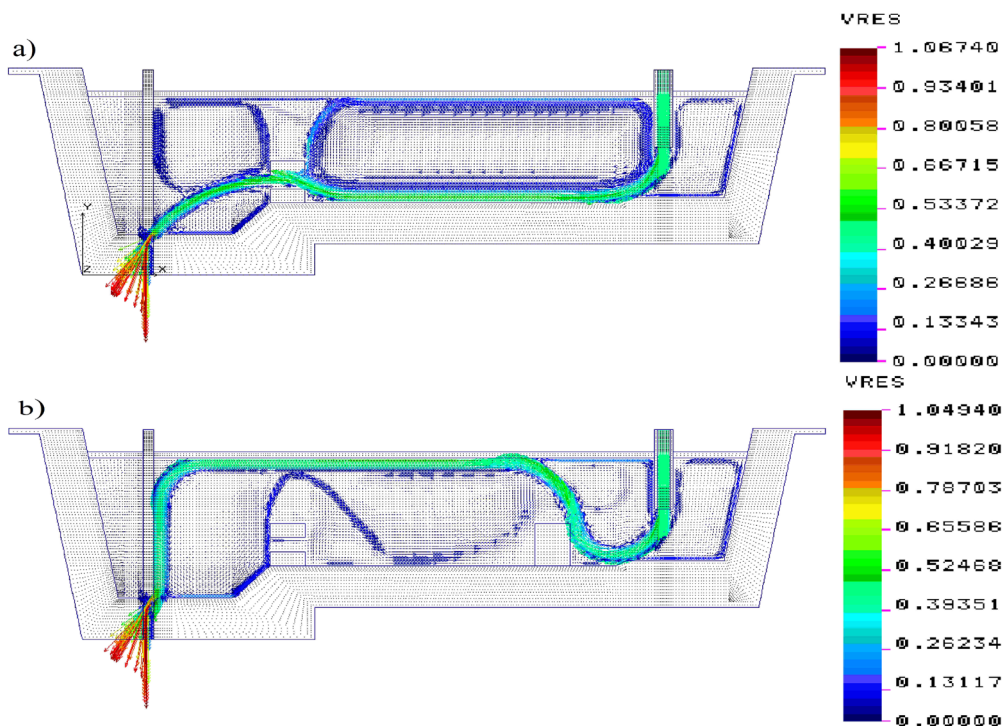


Fig. 2. Velocity vectors after time 720 s: a) II variant, b) III variant

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