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NUMERICAL ANALYSIS OF THE NON-METALLIC INCLUSIONS DISTRIBUTION AND SEPARATION IN A TWO-STRAND TUNDISH

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The tundish plays an important role in the challenging task of a "clean steel" production process. The flow of the liquid steel in tundish has a crucial influence on non-metallic inclusions distribution and separation.

The article presents computational studies of non-metallic inclusions separation in a two-strand industrial tundish during steady-state casting. Tundish capacity is 7,5 t. First, flow structure in the tundish was investigated using water model of the industrial tundish in a 1:2 scale . The experimental results, regarding RTD characteristics were used to validate numerical model. With validated model, particle distribution and separation in the two-strand tundish were investigated numerically. For modelling the separation of particles at the fluid surface, a modified boundary condition has been implemented.

Key words: continuous casting, tundish, non-metallic inclusions, numerical modelling.

INTRODUCTION

Contemporary tundish is a place of steel refining treatments to improve the quality and purity of casted steel. In the basic configuration of the tundish, controlled flow of the liquid steel should increase phenomena of growth and removal of non-metallic inclusions to the slag and their adhesion to the refractory elements.

Movement of non-metallic inclusions, or more precisely their trajectories, can be determined based on the Lagrange method [1], using the transport equation of inclusions being carried in the velocity field of steel, pre-determined, taking into account additional forces of turbulent flow.

In papers [2-5] to simulate the random effects arising from the turbulence the discrete random walk model (DRW) is used, called the stochastic model [6], in which each velocity component of non-metallic inclusion is proportional to the local turbulent energy (1).

From the literature review, one should pay attention to the appropriate choice of the boundary conditions for non-metallic inclusions. In most studies [4,5,7-9] this type of boundary conditions for the Lagrangian model is expressed by introduction of inclusions (their number and size) to the tundish together with steel through the surface corresponding to the shroud area. For the steel-slag surface it is assumed that all the inclusions are captured by the covering slag, so it is assumed that excellent absorption occurs. In contrast, for the steel-tundish lining it is assumed that non-metallic inclusions are elastically reflected, excluding adhesion or agglomeration. The inclusions in the outflow areas are flowing out with steel to the mould.

$$u_{wi} = \zeta_i \sqrt{u_i^2} = \zeta_i \sqrt{\frac{2k}{3}} \tag{1}$$

where: ζ_i – random number, normally distributed between –1 and +1 that changes at each time-step.

These conditions are quite far from reality, because the efficiency of such collisions are resolved dynamically, strongly relying on the surface interfacial phenomena.

Only spherical non-metallic inclusions modelled in the numerical calculations are considered with different sizes and densities. In the calculations, the density change interval of inclusions [10] results from the fact that aluminium inclusions form clusters of complex structure and diverse participation of Al_2O_3 in relation to the metallic phase cohesive. Following these assumptions, the results of numerical simulation solving flow equation with appropriately selected boundary conditions allows to find the path and distribution of non-metallic inclusions in molten steel in the tundish during continuous casting. It is confirmed by the results of studies [1-10], in which the movement of various non-metallic inclusions in steel flowing through different tundishes are solved.

Presented article shows the results of numerical modelling and simulation of steel casting and non-metallic inclusions behaviour in liquid steel flowing through the investigated tundish.

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TUNDISH DESCRIPTION

The object under the study is a two-strand tundish designed for the continuous casting of slabs intended for small cross-section rolled products. The object taken for investigation is a typical T-type tundish, as used in the domestic metallurgical industry. The tundish is symmetrical relative to the transverse plane. Geometry of the considered model of the tundish (in a 1:2 scale) is shown in Figure 1. In the present study, two variants of the construction work area were considered: dams and turbulence inhibitors. A detailed description of the model and the results of calculations for fluid flow and mixing of steel obtained for considered configurations are presented elsewhere [11-12].

NUMERICAL MODEL

To construct the computational grid of the investigated tundish a commercial code Gambit was used. Computational grid was built with 350000 control volumes. Numerical simulations of liquid steel flow field and distribution of non-metallic inclusions were performed using AnsysFluent commercial software. Mathematical model together with initial and boundary conditions used to calculate the flow field of liquid steel are given in details elsewhere [11-12].

The mass conservation equation (equation of continuity) has the following form:

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_j}(\rho u_j)=0 \tag{2}$$

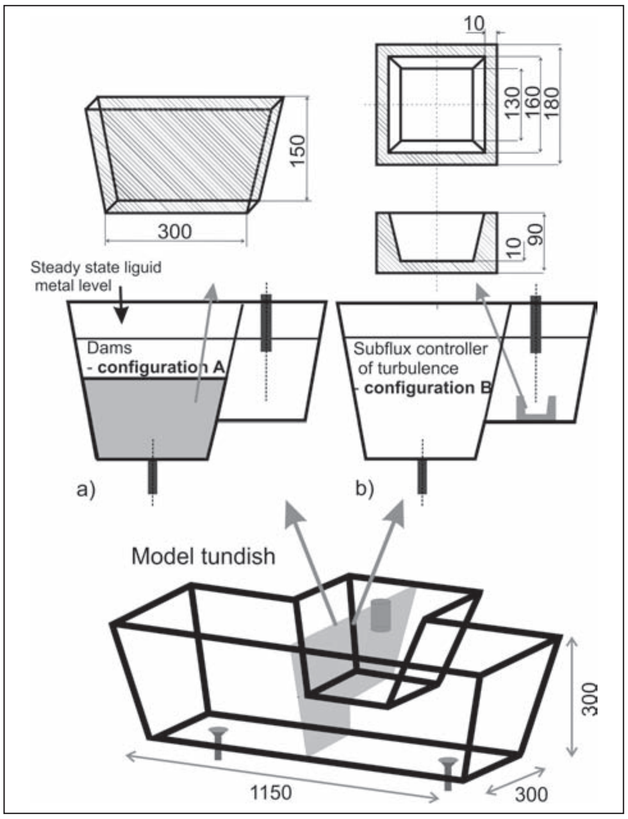

Figure 1 Different tundish configurations studied in present work / mm

The momentum conservation equation is defined as follows:

$$\frac{\partial(\rho u_i)}{\partial t}+\frac{\partial(\rho u_i u_j)}{\partial x_{ij}}=$$

$$-\frac{\partial P}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\mu_{eff}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\right]+\rho g_i \tag{3}$$

To determine the distribution of temperature fields within the tundish, it is necessary to use the energy conservation equation in the form as below:

$$\frac{\partial(\rho T)}{\partial t}+\frac{\partial(\rho u_j T)}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\frac{k_{eff}}{c_p}\frac{\partial T}{\partial x_j}\right) \tag{4}$$

The equations are represented in the Cartesian coordinate system and index notation.

To describe the turbulent flow field of steel, k-ε model [13] was used.

At the shroud impact velocity of steel casting corresponding to the speed of 1,0 m·min^{-1} and the turbulence intensity of 5% were set. The outflow rate from the tundish is calculated from the mass balance. The operating and boundary conditions of the mathematical model are based on the actual industrial data. They relate to the round ingot casting with dimensions of ϕ100 mm.

The SIMPLEC algorithm was used in numerical simulations. During iteration, the convergence was assumed to reach a point where all the normalized residuals were smaller than 10^{-6}.

Trajectories of non-metallic inclusions were calculated based on the Lagrange method [6]. The method consists in solving the transport equation of non-metallic inclusions within a predetermined flow vector velocity field of steel, taking into account additional effects resulting from turbulent flow. In order to calculate non-metallic inclusions in the tundish it is necessary to supplement the system of equations for a differential equation describing the motion of particles in the liquid phase:

$$\frac{d u_{inc.}}{d t}=\frac{3\mu_{st.}C_D Re_p}{4\rho_{inc.}d_{inc.}^2}(u_{st.}-u_{inc.})+\frac{g(\rho_{inc.}-\rho_{st.})}{\rho_{inc.}}+$$

$$+\frac{1}{2}\frac{\rho_{st.}}{\rho_{inc.}}\frac{d}{dt}(u_{st.}-u_{inc.})+\frac{\rho_{st.}}{\rho_{inc.}}\frac{d u_{st.}}{d t} \tag{5}$$

where: $u_{inc.}$, $u_{st.}$ – inclusion or liquid steel velocity, $\rho_{inc.}$, $\rho_{st.}$ – inclusion or liquid steel density, $d_{inc.}$ – inclusion diameter, C_D – drag coefficient, Re_p – particle Reynolds number, g – gravitational constant, $\mu_{st.}$ – molecular viscosity of the liquid steel.

Boundary conditions used in the numerical model are shown in Figure 2.

For such a model a modified boundary condition for non-metallic inclusions has been used, implemented at the liquid metal surface through the Users Defined Function (UDF) in ANSYS Fluent code.

It was assumed that non-metallic inclusions are spherical and released from the inlet surface with the

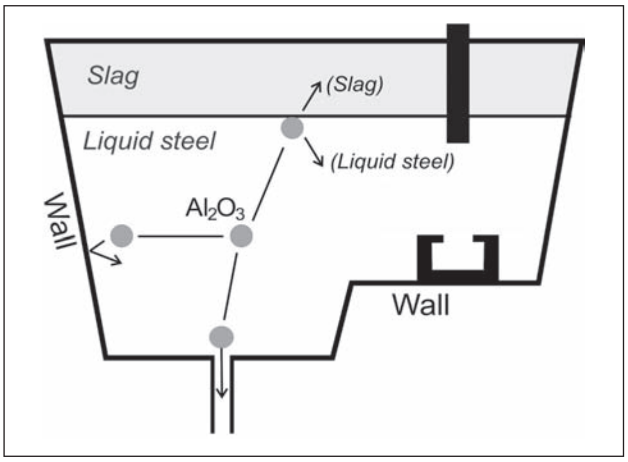

Figure 2 Boundary conditions for fluid and inclusions adapted in numerical calculations

same velocity as a fluid and their trajectories are calculated with discrete random walk model.

Two options where considered: first, with different densities of inclusions (3 960 and 5 000 kg·m^{-3}) and the second for selected sizes of inclusions: 2, 5, 10, 20, 25, 50 μm. The adopted density range of inclusions follows from the fact, that the aluminium inclusions form clusters of highly structured and diverse participation of Al_2O_3 for a cohesive phase which is steel.

RESULTS

As a result of numerical simulations, the spatial velocity field and the turbulence intensity of liquid steel are shown.

Based on these results, the trajectories of non-metallic inclusions were developed in the interior of the vessel. This allowed to estimate the range of different options for removal of non-metallic inclusions to the slag phase due to flotation and determine the spatial distribution of inclusions in the tundish and flowing with the steel through the tundish outlets.

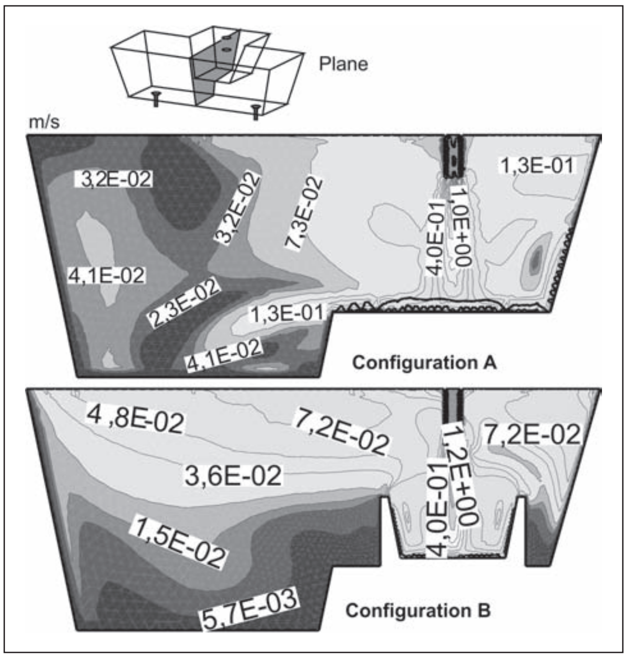

Figure 3 The velocity field of liquid steel for the studied cases

Figure 3 shows the velocity field of liquid steel for the selected plane.

The distributions of steel velocity and turbulent kinetic energy in the tundish working space (see Figures 3 and 4), provide a source of good knowledge about the steel casting conditions. However, these characteristics do not explain directly whether the identified condition of steel flows in the tundish is appropriate for non-metallic inclusions removal. For such a judgment additional numerical simulations are needed. These are simulations using Discrete Phase Model (DPM). On pre-calculated flow and turbulence fields, the transport of disperse phase is treated. The separation rate of the particles from the tundish due to flotation is calculated with the formula:

$$\beta = \frac{N_{in} - N_{out}}{N_{in}} \times 100/\ \% \qquad (6)$$

where N_{in} is the number of particles at the inlet of the tundish and N_{out} is the number of particles at the outlet of the tundish.

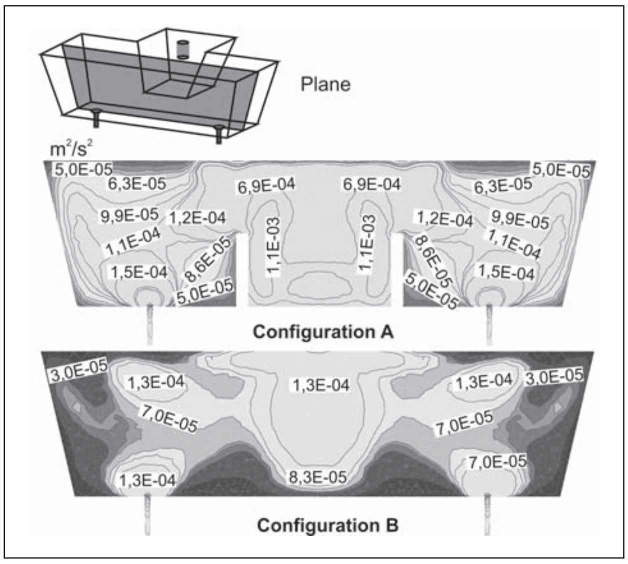

Figure 4 Isolines of turbulent kinetic energy of steel for the studied cases

Numerical simulations have been performed to calculate the inclusion separation rates for both working tundish configurations. For modelling the separation of particles at the fluid surface, a modified boundary condition has been implemented, which can be found elsewhere [14]. Predicted numerically separation rates are shown in Figure 5.

From the results presented in Figure 5 it can be seen that inclusions density change the separation rates for all investigated inclusion diameters.

The results presenting inclusions flowing out through the tundish outlet for both investigated configurations are shown in Figure 6. It can be seen that by installing dams, the separation rate of inclusions in a range be-

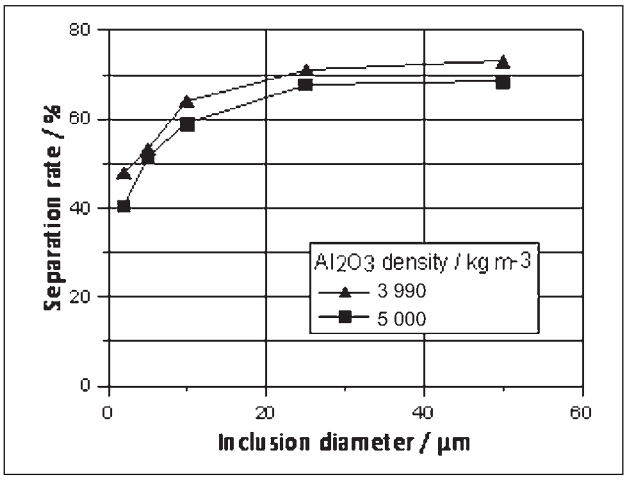

Figure 5 Separation rate for the studied cases

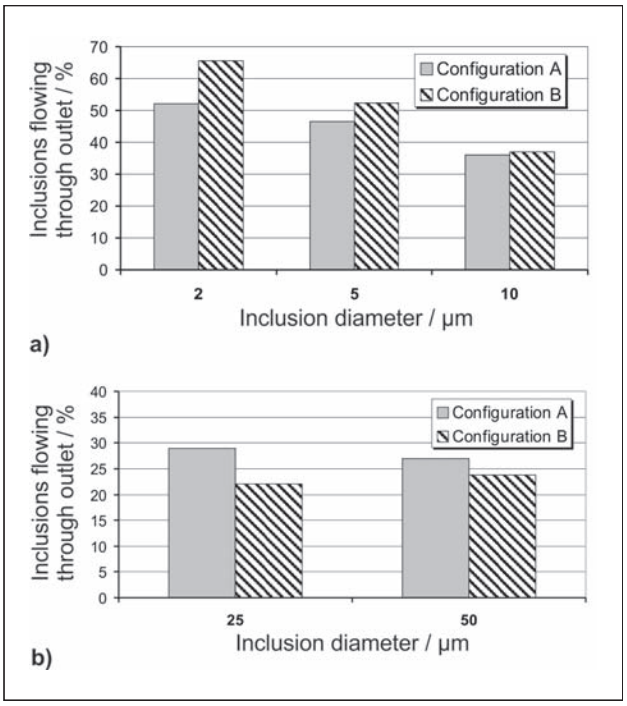

Figure 6 Inclusions flowing with liquid steel through the outlet

tween 2 and 10 µm can be improved, since less inclusions flows with steel to the mould. For inclusions with diameter of 25 and 50 µm, better separation rate was obtained with turbulence inhibitor.

CONCLUSIONS

Performing research related to optimization of industrial facilities enable connecting theoretical and practical information on a continuous casting process for the permanent improvement of this process and to obtain ingots of higher and higher purity.

Presented results concern the evaluation of the changes in non-metallic inclusion separation due to modifications of the tundish working space and inclusions density.

Observations collected during the investigations can be summarized as follows:

- Changes of non-metallic inclusions density has influence on their separation rate due to flotation.
- The results of numerical simulation show that dams installed in tundish working space decreased number of small inclusions which flow out with steel to the mould.

Performing numerical simulations using the mathematical model should be an important element in the design and optimization process of the final steel refining process in the tundish.

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Note: The responsible translator for English language is P. Nowak