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CFD modelling of non-metallic inclusions removal process in the T-type tundish

M. Warzecha [a,*], T. Merder [b], P. Warzecha [c]
[a] Department of Metals Extraction and Recirculation, Czestochowa University of Technology, Al. Armii Krajowej 19, 42-200 Częstochowa, Poland
[b] Department of Metallurgy, Silesian University of Technology, ul. Krasińskiego 8, 40-085 Katowice, Poland
[c] Institute of Thermal Machinery, Czestochowa University of Technology, Al. Armii Krajowej 21, 42-200 Częstochowa, Poland
* Corresponding e-mail address: warzecha@wip.pcz.pl

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Analysis and modelling

ABSTRACT

Purpose: The aim of performed research is to diagnose the possibilities of non-metallic inclusions removal from liquid steel flowing through the two-strand T-type tundish with its current configuration.

Design/methodology/approach: Research were performed with numerical simulations. Initial conditions for inclusions distribution were obtained earlier with experimental measurements during industrial casting conditions.

Findings: Numerical simulations let to investigate the flow field structure of liquid steel in the tundish and its impact on inclusions trajectories and separation from steel to the slag. Moreover it was found that standard boundary condition (trap) available in commercial code for disperse phase is not suitable to model complex physical phenomena occurring at the steel-slag interphase.

Research limitations/implications: Commercial use of computational codes for the analysis of work and design of industrial facilities is a relatively inexpensive tool

Practical implications: The research results presented in the paper can be used for steel production of high purity steels.

Originality/value: Presented results may contribute to significant improvements in process efficiency of investigated tundish.

Keywords: Continuous casting; Tundish; Non-metallic inclusions; Numerical modelling

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1. Introduction

The quantity, size, shape and type of inclusions has a significant influence on the properties of steel produced. Mainly on the mechanical properties. Different technological procedures in the manufacture of steel are taken for the emergence of non-metallic inclusions. The intent is to limit their number to the lowest possible levels that result from the genre and purpose of the steel. In recent years a number of different studies have been taken on the influence of the casting of steel process on the behaviour of non-metallic inclusions, regardless of their exogenous or endothermic nature [1-4].

Modern equipment for continuous casting of steel are designed to provide the best possible casting operating conditions. In practice this means that certain grade of steel is cast in the longest possible sequences, and change of steel grades are planned together with the exchange of tundish. Therefore, the tundish plays an important role in the continuous casting of steel. It performs several important functions. It provides uniform distribution of steel to the individual strands and maintains the desired casting speed. It keeps the temperature on the same level and protects it from excessive cooling. Current tendency is the full use of the tundish for the disposal of non-metallic inclusions. Improving the casting conditions, one can enhance the processes of separation and flotation of inclusions. The most common way of using it for this purpose, is to put inside the tundish one of the flow control devices (FCD) [5-7]. This increases the turbulence intensity of the liquid steel flow field, which promotes coagulation and coalescence of inclusions and in turn promotes inclusions flotation to the covering slag due to flotation. Depending on the geometry of the tundish working space there are zones of varying intensity fluctuations, which can be divided into two areas: active and stagnant (often called dead) zones as shown in Figure 1.

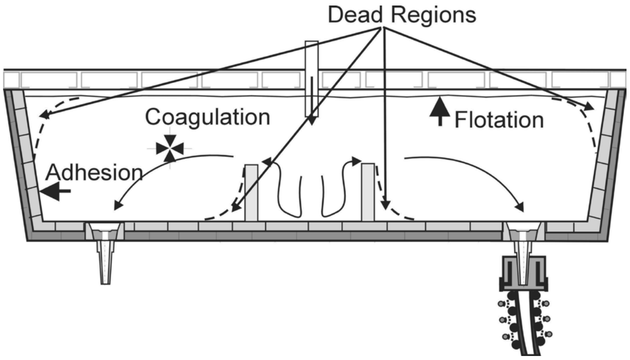

Fig. 1. Schematic of the tundish with representation of melt flow having dead volume and removes inclusion mechanism

Explanation of the non-metallic inclusions disposal problem in the tundish due to their flotation to the steel surface and their assimilation by the covering slag is a difficult task. Industrial investigations have a lot of limitations in this field. Therefore studies are performed with different models (physical or/and mathematical). By building a water model of industrial device in a smaller scale, research can be performed and this allow to evaluate i.e. the degree of inclusions separation [8, 9]. Similarly, by constructing an appropriate mathematical model, numerical simulations of steel flowing through the tundish and the inclusions separation process from steel can be carried out. To develop a mathematical model that properly describe steel refining from non-metallic inclusions during the casting process it is necessary to adopt a number of parameters. They directly result from the implemented technology.

Present studies show the results of numerical modelling of the steel flow and behaviour of non-metallic inclusions in the two-strand tundish. The considered tundish works in normal conditions without any FCD. Numerical calculations were performed according to appropriate algorithms for computational fluid dynamics (CFD). To perform the calculations a commercial code AnsysFluent has been used [10]. In calculations the standard boundary conditions available in the code were used together with modified boundary condition implemented as an UDF (User Define Function) for modelling inclusion behaviour at the metal surface. Own boundary condition provides critical velocity of the fluid. This critical velocity decides if particle stays at the surface or is reflected and re-enter the fluid. The velocity of the fluid in each cell at the boundary (where particle reach the surface) is compared with the critical velocity. In case if the flow velocity is lower than the critical velocity the particle is trapped, otherwise it is reflected.

This approach allows to evaluate the standard boundary conditions used in the commercial code AnsysFluent. Evaluation of the results obtained using the standard condition (available in the code) has been done with modified condition which was verified with results for the water model [8].

2. Investigated object and research methodology

Investigated object is a two-strand tundish, type "T". The tundish works without any flow control devices. Nominal capacity of the tundish is 7.5 Mg. Steel is poured into the tundish by a shroud placed in the symmetry plane of the object. It is used for continuous casting of billets with cross-sections 100 x 100, 160 x 160, 240 x 100, Ø100, Ø150, Ø180 [11]. The geometry of investigated tundish is shown in Figure 2. Basic dimensions of the tundish are shown in Table 1.

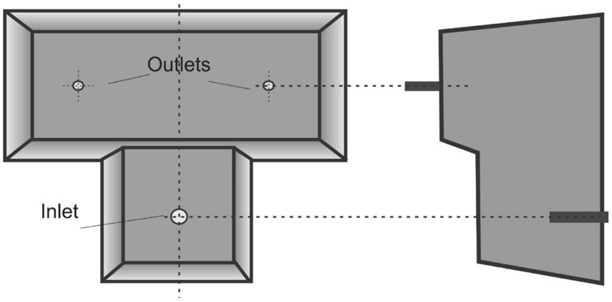

Fig. 2. Scheme diagram showing tundish geometry

Table 1.
Dimensions of the 7.5-t tundish

	Unit	Dimension
Volume of tundish at filling level H	m^3	1.07
Tundish length	m	2.30
	m	0.69
Tundish width	m	1.14
	m	0.60
Filling level (steady-state casting)	m	0.60
	m	0.44
Shroud diameter	m	0.05
Shroud position	m	0.93
SEN diameter	m	0.019
SEN position	m	0.70

To determine the boundary conditions to simulate the movement of non-metallic inclusions, the steel samples has been taken during the casting (for considered tundish) to identify the distribution of non-metallic inclusions. These studies included analysis of quantitative and partly qualitative non-metallic inclusions in low-carbon steel ingots (Ø100) casted.

The mathematical model for fluid flow and mixing of the liquid steel contain the differential equations of continuity, momentum and energy conservation equation for the turbulence and the motion of liquid steel in the tundish.

The continuity equation has the following form:

$$\frac{\partial}{\partial x_j}\left(\rho u_j\right)=0 \tag{1}$$

The momentum conservation equation is expressed as follows:

$$\frac{\partial(\rho u_i)}{\partial t}+\frac{\partial\left(\rho u_i u_j\right)}{\partial x_{ij}}=-\frac{\partial P}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\mu_{eff}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\right]+\rho g_i \tag{2}$$

where effective turbulent viscosity equals:

$$\mu_{eff}=\mu+\mu_t \tag{3}$$

and where dynamic coefficient of turbulent viscosity equals:

$$\mu_t=C_\mu \rho \frac{k^2}{\varepsilon} \tag{4}$$

In order to determine the distribution of temperature fields inside the tundish, mathematical model include the general equation of energy conservation for an incompressible and inviscid fluid, in the following form:

$$\frac{\partial(\rho T)}{\partial t}+\frac{\partial\left(\rho u_j T\right)}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\frac{k_{eff}}{c_p}\frac{\partial T}{\partial x_j}\right) \tag{5}$$

The effective thermal conductivity coefficient can be written as follows:

$$k_{eff}=\lambda+k_t \tag{6}$$

and the turbulent thermal conductivity is expressed as follows:

$$k_t=\frac{c_p \mu_t}{\mathrm{Pr}_t} \tag{7}$$

The fluid flow in the tundish is considered to be turbulent. For modelling the turbulence, semi empirical, two-equations standard k-ε model has been used. This model is widely used in the analysis of many engineering problems. Equations are as follows: turbulent kinetic energy:

$$\frac{\partial(\rho k)}{\partial t}=\frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right]+G-\rho\varepsilon \tag{8}$$

dissipation rate of the turbulent kinetic energy:

$$\frac{\partial(\rho\varepsilon)}{\partial t}=\frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right]+\frac{(c_{1\varepsilon}\varepsilon G-c_{2\varepsilon}\rho\varepsilon^2)}{k} \tag{9}$$

where the generation of turbulence kinetic energy:

$$G=\mu_t\frac{\partial u_j}{\partial x_i}\left[\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\right] \tag{10}$$

Constants used in the k-ε model are shown in Table 2.

Table 2.
Constants used in the k-ε model

$c_{1\varepsilon}$	$c_{2\varepsilon}$	c_μ	σ_k	σ_ε
1.44	1.92	0.09	1.0	1.3

To ensure the uniform distribution of inclusions at the shroud cross-section, inclusions were released from the inlet surface with the same velocity as a fluid. On the base of experimental investigations concerning inclusions distribution at test samples of steel, for numerical simulations the following groups of inclusion size were selected: 2, 5, 10, 25 and 50 μm. In calculations it was assumed that inclusions are spherical with density equal to 3960 kg/m^3.

Trajectories of non-metallic inclusions were calculated based on the Lagrange method [12].

The method consists in solving the transport equation of inclusions within a predetermined flow field of liquid steel, taking into account additional effects resulting from the turbulent flow. The effect of the chaotic behaviour of non-metallic inclusions in the melt motion model is described by Discrete Random Walk model – DRW [12,13], called stochastic model, where the local velocity component of non-metallic inclusions is proportional to the local efficient turbulent energy:

$$u'_{pi}=\zeta_i\sqrt{\frac{2k}{3}} \tag{11}$$

where: u'$_{pi}$ – local velocity component of non-metallic inclusion, ζi – random number, normally distributed between –1 and +1 that changes at each time-step, k – turbulence kinetic energy.

The calculation assumes that the non-metallic inclusions flow into the tundish with a constant initial velocity equal to the velocity of the steel. It is also assumed that the surface of the tundish side walls and bottom is rough. The metal surface boundary condition is described in two different ways:

- non-metallic inclusions are captured by the slag, which corresponds to the condition of ideal absorption of inclusions by covering slag (standard condition of computational code) [14],

- non-metallic inclusions are captured by the slag or are reflected and flows further with liquid steel (modified condition, own UDF).

From other surfaces of the tundish (bottom and side walls) inclusions are reflected. Inclusions can leave the tundish through the outlets.

Figure 3 presents the description of the boundary conditions set for disperse phase (non-metallic inclusions), typically used in the calculations and for modified boundary condition implemented in the code via an UDF.

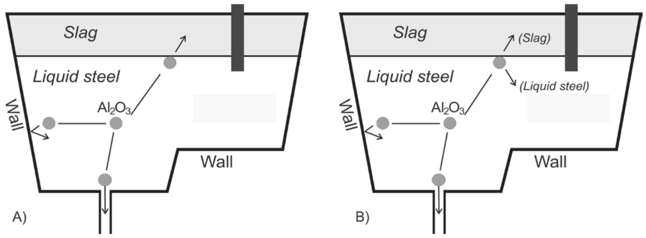

Fig. 3. Boundary conditions set for disperse phase a) standard boundary condition, b) modified boundary condition (UDF)

3. Results and discussion

As a result of numerical calculations, spatial distribution of velocity vectors and turbulence energy fields of liquid steel flowing through the tundish were obtained. The detailed results of these calculations are given elsewhere [11]. Based on these results, residence time distribution (RTD) characteristics and trajectories of non-metallic inclusions in the tundish were evaluated. This, in turn, allowed to estimate the capability of investigated tundish for removal of non-metallic inclusions due to flotation to the slag phase and to determine the spatial distribution of inclusions in the steel and the other flowing through the individual strands.

Figures 4 and 5 show the velocity vectors of liquid steel and the distribution of turbulent kinetic energy in the vertical plane passing through the tundish outlets.

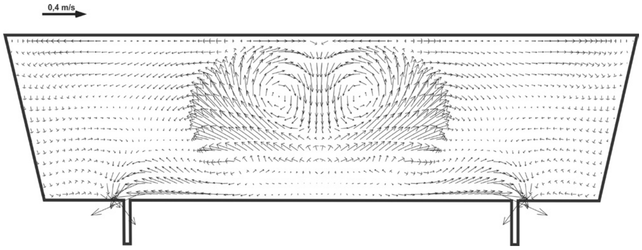

Fig. 4. Velocity field of liquid steel ($m\cdot s^{-1}$) at the selected levels

The obtained velocity and turbulence fields of liquid steel in the tundish provide important knowledge about the conditions of casting, but these characteristics do not explain directly, or the state of the tundish is suitable for mixing processes and removal of non-metallic inclusions.

Fig. 5. Distribution of turbulent kinetic energy [m^2/s^2] of steel in the tundish

The evaluation of inclusion removal efficiency in the investigated tundish is based on the balance of amount of non-metallic inclusions. Assuming that the inclusions are poured into a tundish with liquid steel in an amount corresponding to 100% (random sample of 5000 units), theirs trajectories are calculated with time. Some of these inclusions flow out to the slag, the rest comes out from tundish with steel flowing out through the individual nozzles.

Additional particles which are the product of re-oxidation, erosion from the refractory material or re-entrainment from the slag in the real process are not considered here. The separation rate of the particles from the tundish due to flotation is calculated with the formula:

$$\beta = \frac{N_{in} - N_{out}}{N_{in}} \times 100\% \qquad (12)$$

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.

Numerical simulations have been performed to calculate the number of inclusions which separate at the metal surface and which flow out from the tundish with liquid steel. Predicted numerically separation rates obtained with standard (trap) and modified (UDF) boundary conditions are shown in Figure 6. Using standard boundary condition, ideal inclusions absorption by a slag is assumed.

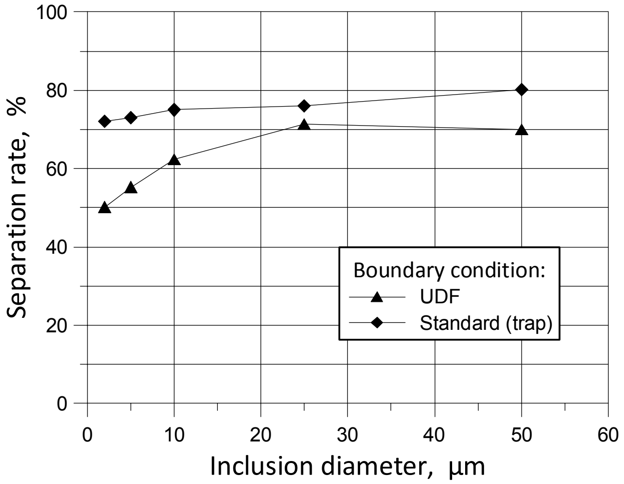

Fig. 6. Inclusions separation rate in the investigated tundish

Form Figure 6 it can be seen, that separation rate obtained with standard boundary condition is higher for all inclusion diameters. These results do not correspond to the values of inclusion numbers found in the billets during experimental determinations. It is expected that the separation of the inclusions with diameters between 2-10 μm is much lover then predicted numerically since they are found mostly in the billet.

Rationales coming from industrial and laboratory investigations, indicating that separation rate of such inclusions (diameter less than 30 μm), is very low, have been the reason for searching improved boundary condition describing the inclusion separation at the steel-slag interface. The velocity of fluid in the vicinity of a steel-slag border is considered. According to Engh [14] the critical velocity of fluid, above which the particle can be re-entrained to fluid, can be derived from a force balance. The shear force is calculated considering the drag force:

$$\tau_0 \pi r_{inc.}^2 = \rho_{st.} u_b^2 \varphi \pi r_{inc.}^2 \tag{13}$$

where: τ_0 is shear stress, $r_{inc.}$ is inclusion radius, u_b is the velocity outside the boundary layer, φ is an empirical friction factor, for a plane surface it is equal to:

$$\varphi = 0.03 (\mathrm{Re}_x)^{-1/5} \tag{14}$$

with

$$\mathrm{Re}_x = u_b x / \nu_{st.} \tag{15}$$

where: x is the distance from the leading edge of the plane and $\nu_{st.}$ is kinematic viscosity of liquid steel. With the approximation that the shear force and the gravity force are equal and opposite, the critical velocity can be described as:

$$u_b = \left[\frac{4 g (\rho_{st.} - \rho_{inc.}) r_{inc.} x^{1/5}}{3 \rho_{st.} \cdot 0.03 \nu_{st.}^{1/5}} \right]^{5/9} \tag{16}$$

The velocity u_b has been included in the boundary condition at the surface via an UDF (User Defined Function). Velocity of the fluid in cell at the border where particle reach the surface is compared with the critical velocity. In case if the fluid velocity is lower than the critical velocity the particle is trapped, which means that the inclusion is absorbed by covering slag, otherwise particle come back to the computational domain which means that inclusion flows farther with the fluid (the results are shown also in Figure 6). It can be seen that separation rate for all inclusions diameters are less than predicted with standard boundary condition. It means that not all inclusions that reach the steel-slag interface come to the slag. The differences are higher especially for the smallest inclusions size (2 and 5 μm).

4. Conclusions

Numerical calculations allowed to determine the non-metallic inclusions trajectories in molten steel flowing through the tundish during the continuous casting process. On the basis of obtained results it can be concluded that:

- numerical simulations allow, with a good approximation, to determine the transport path of non-metallic inclusions in the tundish which is impossible (using contemporary measuring technology) to achieve on the real, industrial object,
- it has to be noticed that using the standard boundary conditions (available in the commercial codes), one should pay attention that the results may introduce some errors (the difference between the standard model and UDF),
- refining capacity (adverse conditions occurring in the tundish) of the industrial tundish can be improved by application of an additional flow control devices in the tundish working space.

Concluding, more work need to be done to include additional forces to the modified boundary condition set for inclusions at melt surface. However the results obtained with the UDF function shows better agreement with experimental investigations performed with water models and at industrial conditions, which show that inclusions in a range up to 10-20 μm are almost not separated in the tundish and flowing out to the mould.

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