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ANALYSIS OF LIQUID STEEL FLOW IN A MULTI-STRAND TUNDISH USING NUMERICAL METHODS

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The article presents the results of liquid steel flow and mixing in tundish when applying turbulence inhibitor to modernize the tundish working zone. The flow of six-strand continuous casting tundish of a trough-type was investigated with numerical modeling. For turbulence modeling, the Reynolds-Averaged Navier-Stokes (RANS) equation and the Large Eddy Simulation (LES) methods have been used. Numerical simulations are carried out with the finite-volume commercial code AnsysFluent.

Key words: steel, continuous casting, tundish, numerical modeling

INTRODUCTION

The requirements and regulations regarding the purity of steel produced are constantly increasing; therefore modern tundishes start to play an important role of refining treatments by improving the quality and purity of cast steel [1]. One of the important factors affecting the purity of steel is the content of non-metallic inclusions in the steel product, including their size, quantity, distribution, chemical composition and mineralogy. As the inclusions follow the movement of liquid steel, it is therefore necessary to analyze in detail its structure, which influences the transport and separation of non-metallic inclusions [2-3].

Significant impact on the flow field has also the building of the tundish workspace [4]. Analysis of the liquid steel flow structure inside the tundish is difficult to perform, mainly due to high temperatures of the process occurring in the tundish and visual opacity of the liquid steel. These limitations impacted the fact that experimental studies are strongly supported by numerical modeling [2, 4].

The present state of the Computational Fluid Dynamics (CFD) techniques allows calculating the fluid flow in tundish with a satisfying accuracy. This is confirmed by a good agreement between flow fields predicted mathematically and measured with laser-optical method done in water models [5].

For modeling turbulent flow based on the Reynolds-Averaged Navier-Stokes equation (RANS) equation, standard [6-8] or realizable [9] k-ε models are mostly used. Numerical simulations are carried out with the finite-volume commercial code AnsysFluent, using a numerical method based on the Navier-Stokes equations. Today, it is wide used in comprehensive analysis of commercial plants. In numerical modeling, the choice of proper turbulence model is crucial, as it has a great impact on the flow structure of the fluid. In the analysis of the turbulent flow using RANS method one get the averaged values. In the case of the Large Eddy Simulation (LES) method, which was used to carry out present numerical simulations, all large turbulent scales are solved directly and only a small scales, smaller than the filter size are being modeled. From those simulations one gets also the information about the instantaneous velocity field inside the tundish.

INVESTIGATED TUNDISH DESRIPTION

The subject of this study is a CSC tundish operating at a steel plant in Poland. This is a trough-type tundish with six nozzles and nominal capacity of 22 Mg. It is used for casting ingots intended for production of small cross-section rolled products. It is symmetrical with respect to its central cross-section. The basic refractory lining is produced of andalusite tiles, and the working layer is made up of a high-magnesite gunite mix. The tundish is equipped with a turbulence inhibitor. The tundish is used for sequence casting (more than ten heats). Technological conditions of tundish operation, as used in numerical simulations, are given in Table 1. These relate to the actual casting square ingots with dimension of 160 x 160.

NUMERICAL MODEL

One of the problems encountered with the modeling of the flow through the tundish is to describe the structure of turbulence. Turbulent flows are characterized by the

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Table 1 **Parameters used in the investigated tundish**

Parameter	Value
Nominal capacity / Mg	22
Molten steel level / m	0,78
Shroud diameter / m	0,05
Number of tundish nozzles	6
Outlet diameter / m	0,017
Casting speed / m·min^{-1}	1,9

vortex structures with a wide range of spatial and time scales. The largest eddies are comparable with the characteristic length scale of the average flow. The smallest scale eddies are responsible for dissipation of kinetic energy. Using the Favre averaging [10] method for the Navier-Stokes equation, one gets the well-known continuity and momentum equations for the RANS method [11]:

$$\frac{\partial \overline{u}_i}{\partial x_i} = 0 \tag{1}$$

$$\rho \frac{\partial \overline{u}_i}{\partial t} + \rho \overline{u}_j \frac{\partial \overline{u}_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left(2\mu S_{ji} - \rho \overline{u_j' u_i'}\right) \tag{2}$$

The vectors u_i and x_i are velocity and position, t is time, p is pressure, ρ is density, μ is molecular viscosity and S_{ji} is the strain-rate tensor defined by:

$$S_{ji} = \frac{1}{2}\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right) \tag{3}$$

The last term in the equation (2) that contains the fluctuating velocities u' represents the effect of turbulence, which requires modeling. One of the most commonly used methods is the Boussinesq's hypothesis [12] that relates the Reynolds stresses to the average speed gradients.

The LES method uses a spatial filtering operation to filter out all scales smaller than the filter size. Structures that are smaller than the filter size are considered to be unknown and must be modeled. As a result of spatial filtering and the Favre averaging procedure applied to continuity and momentum equations, a system of differential Navier-Stokes equations for LES method can be obtained [11]. One of the most commonly used subgrid-scale model for the LES method is the Smagorinsky model [13].

For the purpose of solving the differential equation system, it is necessary to assume suitable initial and boundary conditions, which correspond to the conditions used in industrial process. In order to correspond in the investigated process to real casting conditions, the boundary conditions for steel flowing through the shroud was adopted having the velocity of 0,985 m/s and turbulence intensity of 5 %. The scheme of the tundish and boundary conditions used in computations are shown in Figure 1.

Figure 2 shows cross sections of the tundish through the inlet and outlet zones. Results presented further in this paper are shown for these cross-sections.

Detailed boundary and operating conditions which correspond to the conditions of the industrial process can be found in Table 2.

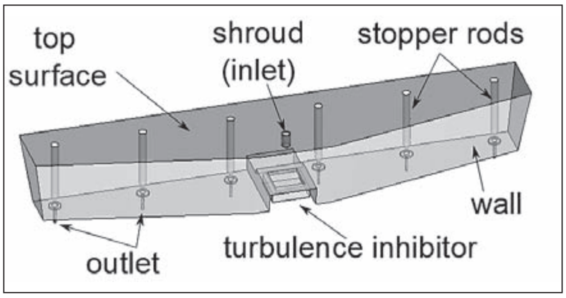

Figure 1 Scheme of the tundish with boundary conditions adapted in numerical calculations

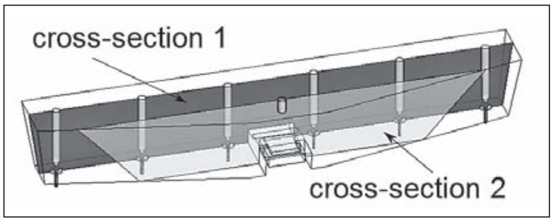

Figure 2 Location of the cross-sections of the tundish to visualize the results

Table 2 **Technology-specific operating conditions of tundishes used in simulations**

Parameter	Value
Inlet velocity / m·s^{-1}	0,985
Inlet turbulence intensity / %	5
Inlet temperature / K	1 781
Density of molten steel / kg m^{-3}	7 010
Viscosity of molten steel / kg m^{-1} s^{-1}	7,0·10^{-3}
Specific heat / J kg^{-1} K^{-1}	821
Thermal conductivity / W m^{-1}×K^{-1}	30,5

The computational domain discretization has been developed by applying the computational mesh consisting of over 0,6 million control volumes for the RANS test case and 2,3 million for the LES test case. First computations were carried out under steady state (stable production) casting conditions. For the computation of the liquid steel flow through the tundish, the boundary condition of "no-slip" type was adapted for all walls, using the so called "wall function" [11]. During computations, the steel free surface was assumed as a flat surface – a wall with zero shear stresses.

RESULTS

The objective of the performed studies was to analyze the flow field structure inside the six-strand tundish with the use of RANS and LES methods. Figures 3 and 4 show contour plots of the velocity and temperature field.

The numerical results are shown in two cross-sections through the inlet and outlet zones of the investigated tundish. In both methods, by comparing the velocity distribution of liquid steel inside the tundish, significant differences can be observed. In the case of the LES method, the turbulent natural convection flow with distinct vortex structures is present, while in the RANS method the smooth flow field is seen.

Similar differences are obtained for the temperature field distribution. Although the temperature range is sim-

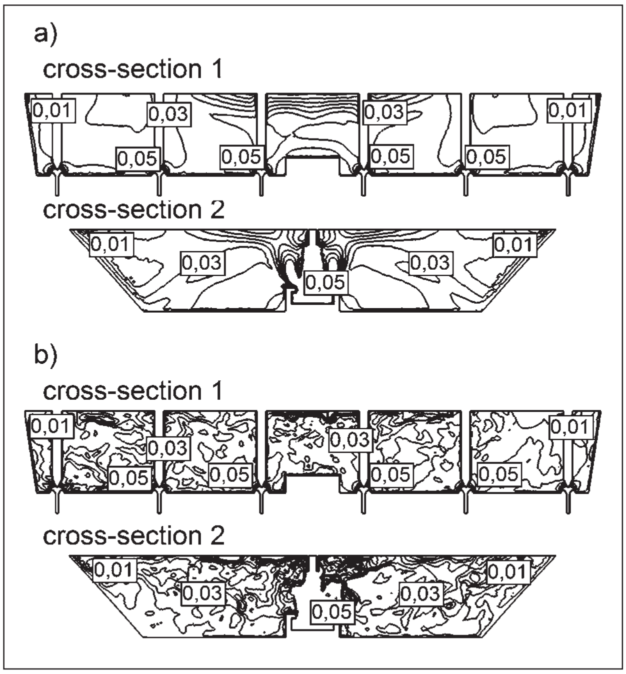

Figure 3 Instantaneous velocity field distribution, given in m/s, in cross-sections 1 and 2 using a) the RANS and b) the LES methods

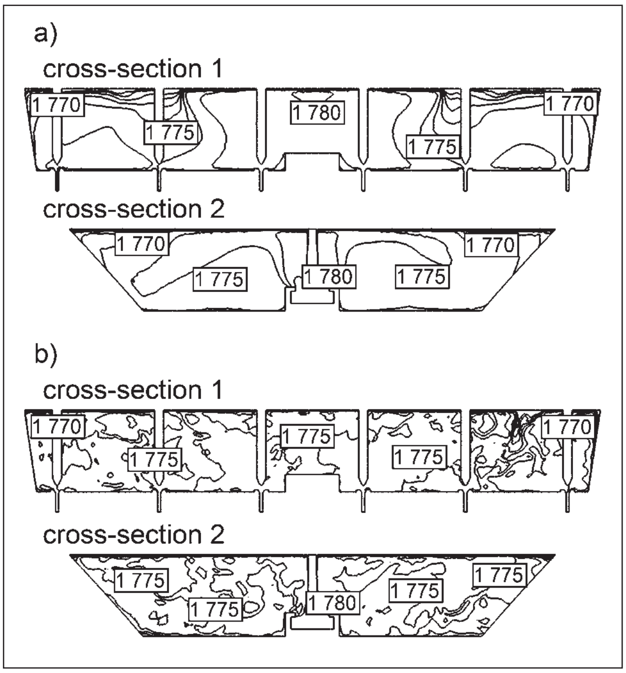

Figure 4 Instantaneous temperature field distribution, given in Kelvin, presented in cross-sections 1 and 2 for a) the RANS and b) the LES methods

ilar for both methods, the temperature distribution inside the tundish determined by both methods varies notably.

The numerical model allows analyzing working conditions and it provides a source of good knowledge about steel casting conditions.

CONCLUSIONS

In the present paper the results of liquid steel flow inside the tundish have been investigated with the RANS and the LES methods for turbulent flow. Comparisons of the results obtained from the two methods show differences in both velocity and temperature field distribution. In the case of the LES method, the turbulent natural convection flow with distinct vortex structures is present. This can be very important, especially, when investigations refer to the distribution of non-metallic inclusions in the tundish and their separation process from liquid steel.

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