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MODELLING OF FLOW BEHAVIOUR IN A SIX-STRAND CONTINUOUS CASTING TUNDISH

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Mathematical modeling has been extensively used to study the fluid flow phenomena taking place in continuous casting tundish. The article presents an analysis of the hydrodynamic properties of a real industrial facility - a six-strand tundish of a capacity of 30 Mg liquid steel. As a result of numerical computations carried out, spatial distributions of the velocity vectors, fields of turbulence kinetic energy, temperature of steel flowing in the tundish and characteristics called RTD (Residence Time Distribution) were get. Calculations were carried out by commercial computer program FLUENT. The geometry and nodal point grid were generated in the GAMBIT program. Results of computer simulation were verificated on the industrial tundish.

Key words: *steel, tundish, mathematical modeling, fluid dynamics*

Modeliranje ponašanja tijeka taline u razdjelnom loncu šest-žilnog konti-lijeva. Matematičko se modeliranje intezivno upotrebljava za proučavanje fenomena tijeka tekućina koji se događaju u razdjelnom loncu konti-lijeva. Predstavlja se analiza hidrodinamičkih svojstava realnog industrijskog postrojenja s šestožilnim razdjelnim loncem kapaciteta 30 Mg tekućeg čelika. Kao rezultat provedenih numeričkih proračuna, dobivene su prostorne distribucije vektora brzine, polja turbulencijske kinetičke energije, temepratura čelika koji teče u razdjelnik i karakteristika zvana RTD (Residence Time Distribution). Proračuni su provedeni komercijalnim računalskim programom FLUENT. Geometrija i mreža čvorova generirani su programom GAMBIT. Rezultati računalske simulacije provjereni su na industrijskom lijevanju uz upotrebu razdjelnika.

Ključne riječi: *čelik, razdjelni lonac, matematičko modeliranje, dinamika fluida*

INTRODUCTION

The working spaces of contemporary tundishes have been diversified and increasingly better adapted the requirements of the continuous casting process. Indeed, they depend on the tundish capacity, casting time, the physical properties of steel being cast, the number and cross-section of moulds, their arrangement in relation to each other and liquid metal demand by each of them.

A tundish should also provide a reserve of liquid steel of a specified temperature, thus enabling the exchange of the main ladles and carrying out of sequential casting. Efforts are being made worldwide to obtain the most favorable shapes of tundish interior by using dams, overfills and partitions, which favour nonmetallic inclusions floating into the slag, and also reduce the share of dead zones. Numerous model studies are being carried out with the aim of explaining the effect of the tundish working space shape and steel flow conditions on the inclusion floating processes.

The primary purpose of the investigation carried out was to present the characteristics describing the transitory zone in a real tundish, as well as on a numerically modeled facility. The curve F describing the transitory zone was examined using a marker. The numerical modeling enabled also the visualization of the liquid steel flow characteristics.

TUNDISH DESCRIPTION

The object of the study is a “delta”-type tundish. The tundish is symmetrical relative to the transverse plane and has six strands. Figure 1. shows half of the device with most important dimensions indicated. The nominal capacity of the tundish was 30 Mg of liquid steel. Steel is poured into the tundish through a ceramic screen positioned in the device’s plane of symmetry. Table 1. gives technological parameters of tundish operation.

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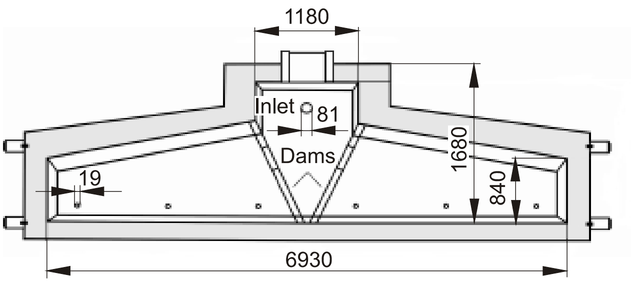

Figure 1. **Schematic diagram showing tundish geometry, dimensions in mm**
Slika 1. **Shematski dijagram dimenzija razdjelnika [mm]**

MATHEMATICAL MODEL

Fundamental equations of flow. In the considered case, the mathematical model for liquid steel flow includes differential equations of the continuity of flow and the conservation of momentum, as well as an equation describing the turbulence of liquid steel motion in the tundish. Calculations (3D) of steel flow in the tundish was performed by using the commercial program FLUENT 6.0. The equations are represented in the Cartesian coordinate system and index notation.

Table 1. **The technological conditions of tundish operation**
Tablica 1. **Tehnološki uvjeti lijevanja uz upotrebu razdjelnika**

Total steel mass	30 Mg
Number of tundish nozzles	6
Bath level	780 mm
Inlet velocity	1,6 m·s^{-1}
Inlet temperature	1550 °C
Liquid steel density	7010 kg·ms^{-3}
Specific heat	821 J·kg^{-1}·K^{-1}
Thermal conductivity	30,5 W·m^{-1}·K^{-1}
Liquid steel viscosity	0,007 kg·m^{-1}·s^{-1}

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

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

The equation of the conservation of momentum is defined as follows:

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

where:

μ_{eff} - effective viscosity, $\mu_{eff} = \mu + \mu_t$,
μ - dynamic viscosity,
ρ - density,
u_i, u_j - velocity components,
g_i - gravitational acceleration,
P - pressure,
t - time.

The dynamic coefficient of turbulent viscosity is defined by the following formula:

$$\mu_t = C_\mu \rho \frac{k^2}{\varepsilon}, \tag{3}$$

where:

C_μ - model constant (= 0,09),
k - kinetic turbulence energy.

For the modeling of turbulence, the K-ε semi-empirical double equation model proposed by Launder and Spalding [1] was employed, which is commonly used in the analysis of engineering problems. Constants used in the k-ε Model shown in $c_{1\varepsilon} = 1,44$; $c_{2\varepsilon} = 1,92$; $c_\mu = 0,09$; $\sigma_k = 1,0$; $\sigma_\varepsilon = 1,3$.

Residence Time Distribution characteristics. An additional measure of the correctness of tundish construction are characteristics called RTD (Residence Time Distribution). These represent the curve of response (in the form of concentration at the tundish outlet) to the pulse input of a tracer introduced to the tundish. To calculate the distribution of tracer concentration in the tundish, it is necessary to complement the model equation by adding a further differential equation in the form of:

$$\frac{\partial\left(\rho C\right)}{\partial t}+\frac{\partial\left(\rho u_j C\right)}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\rho D_{eff}\frac{\partial C}{\partial x_j}\right), \tag{4}$$

where the effective diffusion coefficient (D_{eff}) is the sum of diffusion coefficient and turbulent diffusion coefficient

$$D_{eff} = D_m + D_t. \tag{5}$$

MODELLING NUMERICAL

For the presented system of differential equations describing the model of flow in the tundish, proper boundary conditions should be set. The system under consideration is spatial and symmetrical, since the tundish geometry is symmetrical relative to the plane passing through the gate axis. The result is the zeroing of the first derivatives in relation to the direction normal to the plane of symmetry. The flow in the boundary layer was modelled using the so called "wall function". This method enables a considerable reduction in computational outlays, as it uses an analytical solution for the description of the field of velocities in the boundary region, which permits a much smaller number of nodal points to be used in this region. On the system border corresponding to the pouring gate the medium (steel) inflow velocity was assumed to be equal to 1,2 m/s, which is equivalent to casting rate in the order of 3,6 m/min with a turbulence intensity of 5 %. The velocity of flux outflow from the tundish results from the mass balance. The upper surface of the device, i.e. the contact of the liquid steel with the air, was assumed to be a free surface, which was assumed further to be a flat surface.

In order to develop concentration characteristics corresponding to normalized conditions, the boundary condition was applied on the pouring gate in the form of a stepwise change of concentration ($C = 1$).

An important element in the numerical computation is the distance of the first computation grid node from the wall. In the program, this problem is described by the dimensionless parameter y^+ which, according to the instruction manual of the Fluent software [2], should be contained in the range from 30 to 60 for the model (*Standard Wall Functions*). This parameter is calculated from the following formula:

$$y^+ \equiv \frac{\rho \mu_T y}{\mu}. \tag{6}$$

Target design of the computational grid includes 350000 control volumes, condensed in the vicinity of the gate and at the tundish strands.

In computations, the segregated solver and the following numerical procedures were used: Discretization Pressure - Body Force Weighted, [2], Discretization Pressure-Velocity Coupling - SIMPLEC [3], Discretization Momentum - upwinding of order II [2].

EXPERIMENTAL

The tests were carried out in industrial conditions on a continuous steel casting stand. A method of step chemical disturbance, which was the flowing out, through the tundish nozzle, of steel from the next melt in the sequence, that differed in chemical composition, was used in the experiment. The samples were not taken from the typical „agitation zone" between two different steel grades, but instead from the „agitation zone" of two melts being cast in the same grade, but with some differences in chemical composition. Melts in grade S235JRG2-Bu, as cast into the 130 × 130 mm profile, were analyzed during the tests. Chemical composition of these melts is given in Table 2. [4].

The tests involved the tracking of the effects of disturbance in copper concentration by assaying the chemical composition of samples taken from continuous castings as a function of variation in casting time. Samples were taken from continuous castings 1, 2 and 3. The role of the marker element was performed by Mn and Cu. The chemical analysis of samples cut out from strands was made based on chips taken by spot drilling of each sample. The analysis was performed on a "Spectro FLA" spectrometer supplied by SPECTRO. The assayed concentration of Mn and Cu enabled the determination of variation in the content of the respective element in casting time. Thus plotted response curve provides a basis for the determination of the transitory zone after applying an appropriate selection criterion.

Table 2. **Chemical constitution composition melts**
Tablica 2. **Kemijski sastav talina**

	Chemical constitution / %								
	C	Mn	Si	P	S	Cr	Ni	Cu	Al
melt A	0,12	0,49	0,17	0,015	0,017	0,02	0,02	0,07	0,004
melt B	0,13	0,53	0,18	0,014	0,021	0,02	0,02	0,05	0,004

COMPUTATION RESULTS

As a result of computations, spatial distributions of the vectors of velocities and the field of turbulence intensities were obtained for preset conditions in a steady state. To illustrate the computed fields of variables, useful in the evaluation of steel movement within the tundish, the obtained results are presented in two planes: the vertical plane, *A*, passing through the tundish nozzles, and the horizontal plane, *B*, passing at a level of 480 mm below the steel table.

The distribution of the vectors of velocities within the tundish is shown in Figures 2., 3. Figure 2. illustrates the steel movement in the nozzle outlet region, whereas, for a better illustration of velocities in the tundish interior, the velocity range has been narrowed and the vectors at

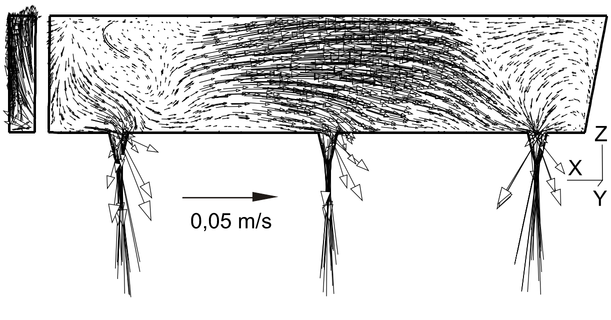

Figure 2. **Velocity fields of steel (profiles) in plane (*A*) of the tundish**
Slika 2. **Polja brzine (m/s) čelika (profili) u ravnini (*A*) razdjelnika**

the tundish nozzles have been cut off. A relatively small share of ascending streams (except for the pouring gate zone) is visible in the diagram, which might not favour the floating of nonmetallic inclusions to the slag phase. These diagrams indicate that a horizontal steel circulation starts to predominate in the region of nozzle 2, with a distinct vortex around this nozzle. Such a configuration might promote the formation of an agitation zone in the tundish, which is more effective in the vicinity of the nozzle of strand 2. In the pouring gate zone (separated from the nozzle zone by partitions with overfalls), a horizontal and a vertical circulations occur, and three distinct horizontal vortexes form, see Figure 3. The greatest values of velocity exist in the tundish nozzle outlets. The maximum steel velocity at the tundish nozzles does not exceed 3,86 m/s, with the average value on the nozzle cross-section being 3,53 m/s.

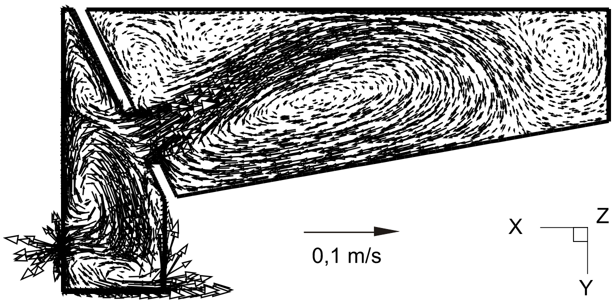

Figure 3. **Velocity fields of steel (profiles) in plane (*B*) of the tundish**
Slika 3. **Brzina polja čelika (profila) u ravnini (*B*) razdjelnika**

The disturbance in the structure of liquid steel flow in the tundish, forced by the partition, is clearly visible in the diagram illustrating the spatial distribution of the energy of steel turbulence intensity. The distribution of the energy of turbulence intensity is shown in Figure 4. The turbulence intensity, represented in these diagrams, is defined by the expression

$$I \cong \frac{\sqrt{\frac{2}{3}k}}{\upsilon_{ref}},$$

where:

k - kinetic turbulence energy,
υ_{ref} - steel velocity reference = steel velocity in inlet.

The vectors of intensities, shown in Figures 2., 3., and the field of turbulence intensities, presented in Figure 4., clearly indicate that the metal movement is equalized and the predominating horizontal circulation is initiated at the overfall window boundary. The distribution of the vectors of velocities and turbulence energy in the tundish provide an important knowledge of steel casting conditions; however, these characteristics do not give a direct answer to the question of whether the tundish conditions is appropriate, or not, for the removal of nonmetallic inclusions and for agitation processes during the sequential casting of different steel grades. Reaching the answer to this question is greatly facilitated by concentration distribution curves, the so called RTD (*Residence Time Distribution*) curves. On the basis of experimental tests (carried out on a real facility) and numerical computations, based on a developed mathematical model, a curve (F) representing variation in marker element concentration in the steel during the casting process has been plotted. The detailed results of the experimental tests are given in work [4]. This characteristic has been represented in dimensionless coordinates and is shown in Figure 5.

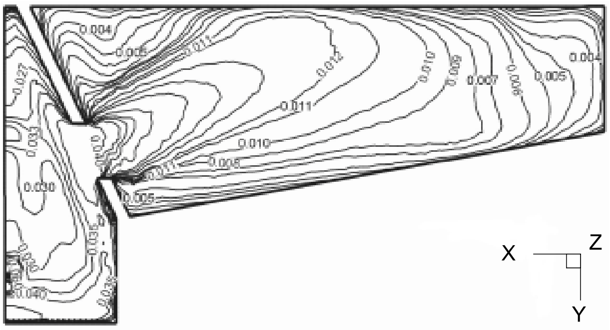

Figure 4. **Isolines of steel intensity turbulence (*I*) in the plane *B***
Slika 4. **Izolinije intenziteta turbulencije čelika (*I*) u ravnini *B***

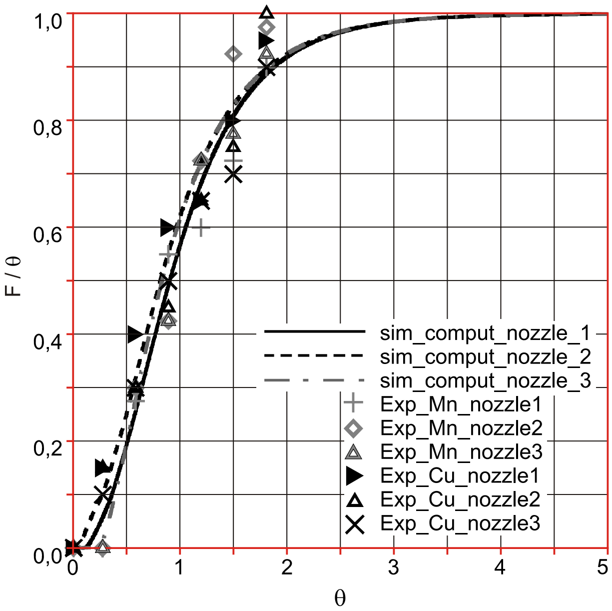

Figure 5. **Mixing-time characteristics as determined for three tundish discharge nozzles**
Slika 5. **Karakteristike vremena miješanja koje su određene za tri ispusne mlaznice razdjelnika**

It can been seen from the diagram that there is a good agreement between the experimental results and the model computation results. This is evidence for the proper choice of the boundary conditions of the mathematical model. Figures 6., 7. illustrate the distribution of marker concentration within the tundish during the casting process for two situations: after a time of 100 and 500 seconds, respectively, from the point of starting the casting of steel of a changed chemical composition.

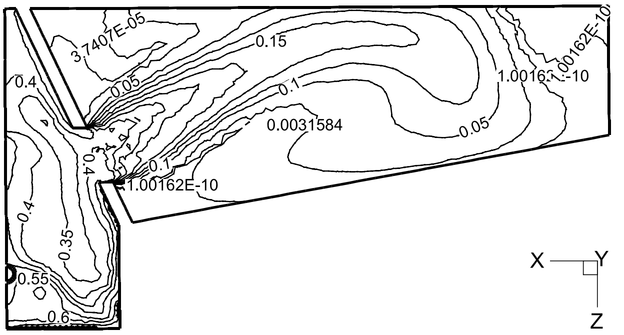

Figure 6. **Computed distribution of concentration (normalized, 0→1) in the planes after 100 sec from the moment of filling with a new steel grade**

Slika 6. **Proračunata raspodjela koncentracije (normalizirana, 0→1) u ravninama nakon 100 sekundi od trenutka punjenja novim tipom čelika**

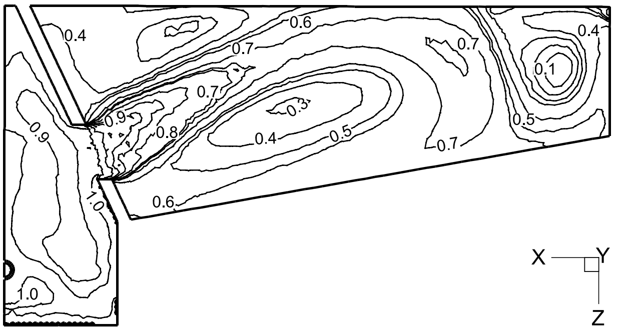

Figure 7. **Computed distribution of concentration (normalized, 0→1) in the planes after 500 sec from the moment of filling with a new steel grade**

Slika 7. **Proračunata raspodjela koncentracije (normalizirana, 0→1) u ravninama nakon 500 sekundi od trenutka punjenja novim tipom čelika**

CONCLUSIONS

The presented investigation results concern the following problems: the evaluation of the state of tundish operation in terms of hydrodynamic and refining properties and the assessment of the consistence of the model computations with the experimental tests. On the basis of the investigation carried out, the following findings can be outlined and conclusions drawn:

1. The developed mathematical model can be regarded as correct, considering the consistence of the computer simulation results with the results of experimental testing;
2. The distribution of the field of velocities and turbulence intensities is significantly influenced by the partition placed in the tundish and, more specifically, the overfall which it incorporates, which directs the liquid steel flow in the tundish;
3. Partitions used in the tundish cause two regions to clearly constitute in the tundish, i.e. a pouring gate region and a nozzle region, which differ in the intensity and structure of steel movement;
4. Such a shape of the internal tundish space might have an adverse effect on the refractory lining of the tundish bottom (causing leaching) and on the partitions positioned in the tundish (damaging). This is caused by a high intensity of flow in the pouring gate zone;
5. In the nozzle zone, which has a lower intensity of turbulence energy, the role of the gravity mechanism of increasing nonmetallic inclusions grows;
6. The transitory agitation zone starts at strands 2 and 5, at the earliest.

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