ARCHIVES OF METALLURGY AND MATERIALS
Volume 58 2013 Issue 4
DOI: 10.2478/amm-2013-0134

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THE INFLUENCE OF THE SHAPE OF TURBULENCE INHIBITORS ON THE HYDRODYNAMIC CONDITIONS OCCURING IN A TUNDISH

WPŁYW KSZTAŁTU INHIBITORA TURBULENCJI NA WARUNKI HYDRODYNAMICZNE PANUJĄCE W KADZI POŚREDNIEJ

The article presents results of the research that was carried out taking into account the influence of the (impact pads) turbulence inhibitor geometry and its equipment of the working space on the hydrodynamic conditions occurring in T-type tundish. Four different turbulence inhibitors were discussed. They differ in shape and configuration of external walls. The research was conducted basing on the numerical simulations as well as on tests performed on physical water model. As a result of calculations the velocity field distribution, turbulence field and marker concentration distribution in the liquid steel for the tested geometrical variants of turbulence inhibitors were obtained. Worked out RTD curves (Residence Time Distribution) allowed to determine the kinetics of steel mixing (the range of transient zone was estimated), and the percentage participation of the particular flow zones. The test carried out on the water model concerned one of the tested turbulence inhibitors. Research was done to verify the parameter settings of the numerical model applied in calculations.

Obtained results gave valuable information about the work of the object after applying different turbulence inhibitors.

Keywords: tundish, continuous casting, numerical modeling, Residence Time Distribution

Artykuł przedstawia wyniki badań wpływu geometrii i sposobu zabudowy inhibitora turbulencji na warunki hydrodynamiczne panujące w przestrzeni roboczej kadzi pośredniej typu T. Rozpatrywano cztery warianty geometryczne inhibitora turbulencji. Inhibitory turbulencji różniły się kształtem i ukształtowaniem ścian wewnętrznych. Badania zrealizowano w oparciu o technikę modelowania numerycznego, oraz eksperyment na fizycznym modelu wodnym. W wyniku obliczeń uzyskano pola prędkości, turbulencji oraz rozkładu stężeń znacznika wprowadzonego do ciekłej stali w przestrzeni kadzi pośredniej dla rozpatrywanych wariantów geometrycznych inhibitora turbulencji. Opracowane charakterystyki RTD (Residence Time Distribution) umożliwiły określenie kinetyki mieszania stali (oszacowano zakres strefy przejściowej), oraz udziały procentowe poszczególnych stref przepływu. Badania uzupełniono o eksperyment na fizycznym modelu wodnym. Dotyczył on jednego z proponowanych wariantów inhibitora turbulencji. Wykonano je w celu weryfikacji doboru parametrów modelu numerycznego w przyjętych w obliczeniach.

Uzyskane wyniki dostarczyły cennych informacji o pracy obiektu po zastosowaniu różnych inhibitorów turbulencji.

1. Introduction

Tundish is a flow reactor, which is equipped with different flow control devices such as: baffles, notches, dams, impact pads, gaseous-permeable membranes or filters [1-4]. Today the most commonly used equipment of tundish seem to be turbulence inhibitors, also called subflux controllers of turbulence. Such devices are positioned in the axis of steel flux flowing into tundish. Turbulence inhibitors have different shapes; however their size and configuration of external walls have the essential meaning on the shaping of steel flow.

The devices mentioned above definitely influence flowing conditions in the working zone of a tundish. As a consequence they also influence the quality of obtained continuous casting ingot. In general the type, size and fitting place of the flow control device is chosen individually for a given tundish. This is caused by the fact, that in continuous casting (CC) machine different kinds of tundishes are applied, which are characterized by individual geometry, tonnage and amount of outlet nozzles [5-6]. Such features have great impact on forming the hydrodynamic conditions which are individual for every tundish. Therefore, it has also correlation with the individual view of a flow area, distribution of liquid steel temperature and behavior of nonmetallic particles. Additionally, the velocity of ingot casting and the amount of steel in the object influence the hydrodynamic conditions occurring in the tundish. So, all parameters mentioned above influence the participation of particular flow occurring in the tundish.

Analysis of operating conditions both before and after modernization of working zone allows to choose the flow control devices appropriate for a given object. Not always however the designed flow control device measures up to the expec-

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tations. Very often the carried out analysis of tundish work indicates that the fixed flow control devices have a really poor influence on the flow hydrodynamics. That is why gaining information about the tundish work is so valuable and necessary. This information helps in taking a proper decision connected with the reconstruction of the tundish working zone.

The evaluation of the tundish work can be done by estimating the whole CC process in industrial conditions or carrying out the modelling research (physical model) or numerical simulations (mathematical model) [7-8]. In recent decade numerical modelling played an important role and became the basic tool applied by engineers when estimating the hydrodynamic conditions occurring in industrial object such as a tundish [9-10].

In this work the CFD techniques of numerical modelling were used to estimate the influence of turbulence inhibitors on the hydrodynamic conditions occurring in a tundish. Four different turbulence inhibitors were considered. Numerical simulations allow to obtain detailed hydrodynamic characteristics occurring in the object after installing different turbulence inhibitors. Basing on them the percentage participation of dead flow volume, well mixed flow volume and plug flow volume were calculated followed by the determination of the steel mixing kinetics.

2. Geometrical description of the tundish

A two-strand tundish designed for the continuous casting of slabs intended for small cross-section rolled products was under the study. It is a typical T-type tundish, which is used in the domestic metallurgical industry. This tundish is symmetrically relative to the transverse plane. The geometric dimensions and configuration of the industrial tundish are shown in Fig. 1.

The nominal capacity of the tundish was 10 Mg of liquid steel. Steel was poured into the tundish through a ceramic shroud positioned in the device plane of symmetry. The installation of turbulence inhibitors was proposed for technological reasons. Four different turbulence inhibitors were designed, which differ in shape and configuration of external walls. The possibilities of practical application was the main parameter taken into consideration in choosing the geometry of turbulence inhibitor and its way of installing in working zone of tundish. Thus, the proposed geometries of turbulence inhibitors could not be so complicated. The geometry of tundish also does not need the complicated shape of turbulence inhibitors. Fig. 2 shows the geometry of applied turbulence inhibitors.

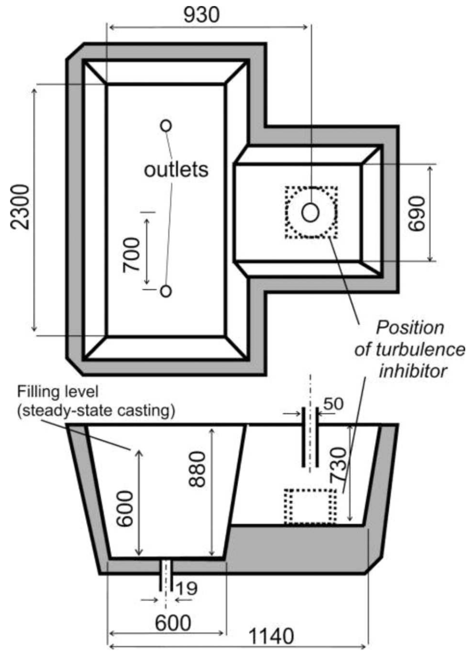

Fig. 1. Geometry of the studied industrial tundish, dimensions in [mm]

3. Methodology of the research

Presented research was carried out basing on the formulated mathematical model with the use of commercial computational program and also the tests on physical water model.

Commonly used research applied in estimating hydrodynamic conditions occurring in the tundish is based on determining the marker concentration distribution in the liquid steel and also working out the RTD curves.

The estimation of residence time distribution for the specific reactor (tundish) can be done experimentally or by means of numerical simulation of tracer distribution. Predominantly, the tracer is introduced in the inlet of the system, whereas in the outlet, continuous control of this tracer concentration is done.

To estimate the flow in the reactor two types of signals in the inlet to the system are applied: signal in the form of impulse (Dirac's function) and single step function (Heaviside's function) [11]. Fig. 3 presents the concept for measurement.

In numerical simulation the impulse signal in the inlet to the system can be directly introduced by means of analytical function of concentration change on time in the form of the following expression:

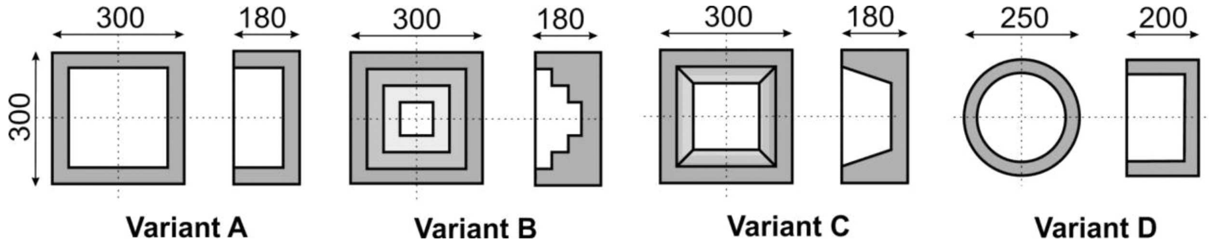

Fig. 2. Different variants of (impact pads) turbulent inhibitors studied in this work

$$c = c_{out} \cdot \exp[-(t-3)^2] \tag{1}$$

where: c – concentration of the tracer, c_{out} – concentration of the tracer in the outlet.

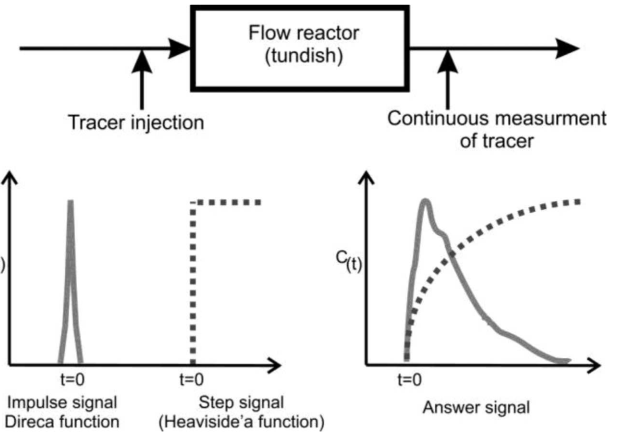

Fig. 3. Scheme of experimental designation of RTD curves for a flow reactor

When the small amount of tracer m_{tr} is once introduced to the reactor with the volume V and the flow rate Q and concentration c_{imp} is registered on the outlet from the system, the answer function in the form of dimensionless concentration $C(\Theta) = c_{imp}/c_0$ responds to the function of the residence time distribution (curves E(Θ) type). Then concentration c_0 can be expressed as a ratio of m_{tr}/V or as the surface under curves (*concentration = f(time)* and time axis; this can be written in the form:

$$c_0 = \int_0^{\infty} c_{imp}(\Theta)d\Theta = \frac{1}{t}\int_0^{\infty} c_{imp}(t)dt \cong \frac{1}{t}\sum_i c_i\Delta t \tag{2}$$

where:c_0 – dimensionless concentration, c_{imp} – concentration of the tracer in the outlet stream (impulse signal), t – time.

If the research is conducted with the step signal on the inlet to the system, the change of concentration c_{step}/c_0 is registered on the outlet and as a result the cumulative function of distribution F-type is obtained, because:

$$F(\Theta) = c_{step}/(\dot{m}/Q) = c_{step}/c_0 \tag{3}$$

where: c_{step} – concentration of the tracer in the outlet stream (step signal), $\dot{m}$ – rate of tracer feeding on the outlet, Q – flow rate.

Mathematical model, that is used in calculation, describing the flow and mixing of liquid steel in the tundish is based on the Navier-Stokes‘ differential equations, mass and energy conservation equations and k-ε models of turbulence [12]. These equations were presented in detail in works [13-14].

To calculate the tracer concentration in the tundish, it is necessary to complete the system of equations mentioned above by adding a differential equation written in the following form:

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

where: $D_m + D_t = D_{eff}$ – the effective diffusion coefficient, D_m – molecular diffusion coefficient, D_t – turbulent diffusion coefficient.

To solve the differential equation system suitable initial and boundary conditions were assumed. On the edge of the system corresponding to the inlet hole the speed of steel flow was assumed to equal the casting speed (1.0 m·min^{-1}), when the turbulence intensity was 5%. The speed of steel outflow from the tundish came from the mass balance.

To evaluate the distribution of tracer concentration in the steel during the casting process, two types of boundary conditions were set at the inlet:

– at the moment t = 0, a one-off tracer addition was X_{tr} = 0.00015 of mass fraction (Dirac‘s function),

– the tracer concentration was uniform and normalized (C=1) in the whole period of measurement (Heaviside’s function).

Detailed boundary and processing conditions, which correspond to the conditions of the industrial process, can be found in another article [15].

The analyzed system is three-dimensional and symmetrical. Because of the object symmetry, only half of the tundish was considered in the numerical computation. The computational space discretization was made with use of the computational mesh consisting of 350 000 control volumes. The mesh was denser in the inlet and outlets regions.

The flow in the boundary layer was modelled by means of so-called “wall function”. This method allows to reduce computational time considerably, as it uses an analytical solution for the description of the velocities field in the boundary region. It is possible, because it permits a much smaller number of nodal points to be used in this region. In the computations, the steel free surface was assumed as a flat surface – a wall with zero shear stresses. The SIMPLEC numerical algorithm was used to solve those equations. During iteration, the convergence was assumed to reach a point where all the normalized residuals were smaller than 10^{-6}. Computations were carried out for both steady and unsteady conditions. Unsteady calculations were only performed to determine the curves of steel mixing characteristics and residence time distribution curves (RTD). The time intervals of recorded concentration were constant in the entire testing range, being equal to Δt=0.05 s. The range in which continuous recording was performed was 2500 s. The mathematical simulations were run on an INTEL CORE i7 processor computer with the CFD software AnsysFlunet.

The test conducted on the physical water model concerned one of the designed variants of turbulence inhibitors. The main aim of such research was to verify the parameter settings of the numerical model applied in calculations.

4. Results and discussion

As a result of the numerical computations conducted for different analyzed variants of tundish equipment, forecasted fields of flow velocity, temperature and steel tracer concentration were obtained. The present paper is limited to showing only hydrodynamic conditions prevailing in the tundish under study. Fragments of the research presented in this article were also described in works [16,17].

Fig. 4 shows the characteristics of steel flow (velocity vectors) in the tundish on the plane intersecting it in the inlet axis.

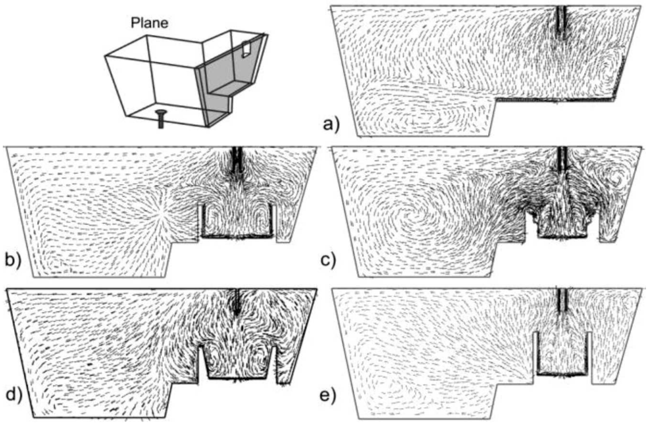

Fig. 4. Velocity vectors of liquid steel: a) tundish without impact pads, b) variant A, c) variant B, d) variant C, e) variant D

In the tundish, which is equipped with the turbulence inhibitors, two zones are created: near-inlet and off-outlet. They differ distinctly in the structure of steel movement. In a near-inlet zone the area of intensive mixing is observed, so the circulation is generated (with the considerable participation of ascending component). In this zone the flow is really intensive, so forces of forced convection determine the flow direction. As a consequence the flux of steel, which is flowing into tundish, is directed to the contact surface: slag/metal. Then flux is held in. The flow in the off-outlet zone is definitely muted. It is characterized by the smaller values of velocity, and as a result the risk of the refractory lining erosion of the tundish is also lower. The situation, which is presented in Fig. 4 (variant A-D) can also influence the improvement of steel refining conditions as well as kinetics of steel mixing (extent transient zone) in the tundish.

The state of steel movement in the analyzed variants of the tundish can be complemented by the characteristics of flow turbulence. Fig. 5 shows the forecasted distribution of liquid steel kinetic turbulent energy (k) for analyzed variants.

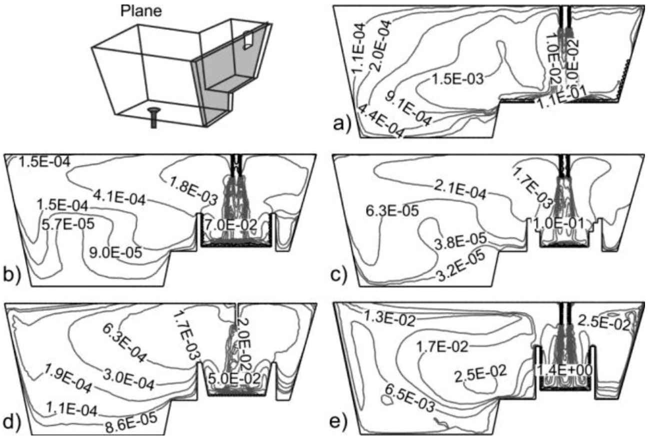

Fig. 5. Isolines of steel kinetic turbulent energy (m^2/s^2): a) tundish without impact pads, b) variant A, c) variant B, d) variant C, e) variant D

Fig. 5 clearly shows the differences between particular variants of turbulence inhibitors. The presented results indicate that applying turbulence inhibitors limits the area with the raised turbulence in the working space of turbulence inhibitors. Then, the flow turbulence in the remaining parts of the object also decreases (the off-outlet zone).

The presented results have pictorial character, so to make detailed estimation of the influence of used turbulence inhibitor on the casting condition of steel the additional calculations were carried out. The distribution tracer concentration in liquid steel and RTD curves (F and E-type) were made. Numerical simulations were done for earlier determined velocity field, assuming unsteady conditions. Fig. 6 presents the forecasted view of distribution tracer concentration in steel after 100 s. Characteristics presented in Fig. 6 confirmed the earlier observation concerning the improvement of steel mixing conditions in the tundish after applying turbulence inhibitors. It also revealed that tracer in steel is moving mainly as a result of forced convection coming from applied variant of turbulence inhibitor. The conditions occurring in a tundish without impact pads seem to be most unfavorably.

Between curves (see Fig. 7) describing kinetics of steel mixing (time of mixing) for analyzed variants, only slight difference is observed; they are most visible for tundish without impact pads and variant D. This is caused by forming the flow near the neighborhood of outlet nozzles. The presented characteristics allow to state that in all cases (so tundish without impact pads and all analyzed variant of turbulence inhibitors) the flow participation with well mixing is dominating.

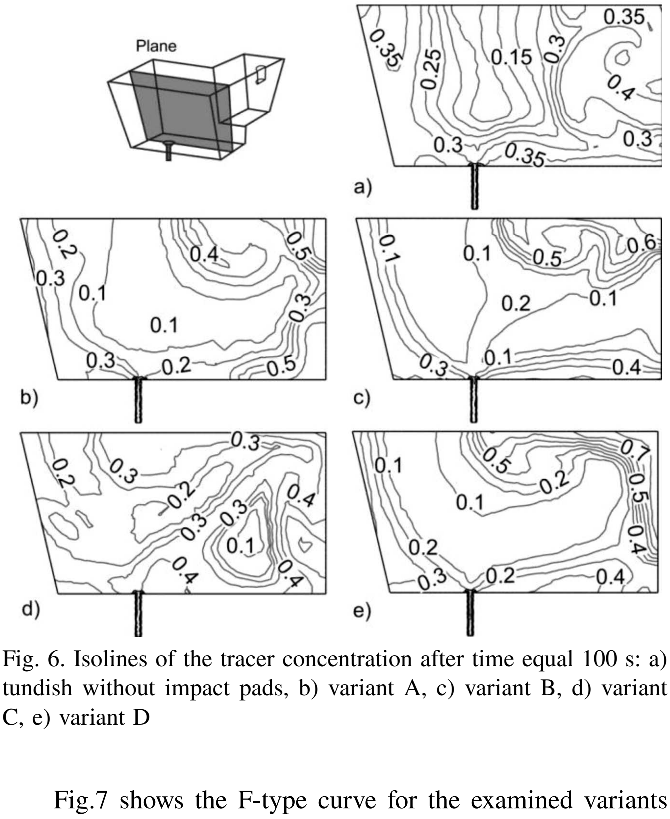

Fig. 6. Isolines of the tracer concentration after time equal 100 s: a) tundish without impact pads, b) variant A, c) variant B, d) variant C, e) variant D

Fig.7 shows the F-type curve for the examined variants of tundish equipment.

Determined curves of F-type (see Fig. 7) also give possibility to estimate quantitatively the kinetics of steel mixing in examined object. As a comparative range the time interval Δt (transient zone) was estimated necessary to obtain 20% and 80% of maximum concentration. The smallest values of Δt, the better condition of mixing. Table 1 presents obtained results.

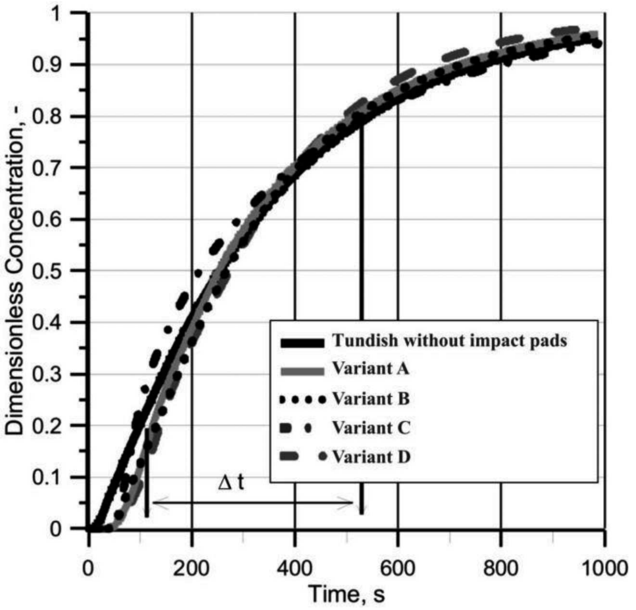

Fig. 7. RTD curves (F – type) for different studied configurations of tundish equipment

TABLE 1
Kinetics of steel mixing (transient zone) in the range of 20 to 80% of the maximum tracer concentration

Tundish configuration	Kinetics of steel mixing Δt, s
Tundish without impact pads	443.5
Tundish with turbulence inhibitors (variant A)	391
Tundish with turbulence inhibitors (variant B)	387.5
Tundish with turbulence inhibitors (variant C)	451.5
Tundish with turbulence inhibitors (variant D)	389.6

Values presented in Table 1 give the practical information about the usability of the tundish to cast different sort of steel in one casting sequence. The best parameters are connected with the work of turbulence inhibitors variant B and D.

Applying mathematical relationship (5-7) basing on the obtained RTD curves of E-type the percentage participations of flow (dispersed plug flow volume, well mixed flow volume and dead flow volume) [18] were calculated for the analyzed variants of equipment. Fig. 8 presents graphically calculated participation of the flow in analyzed tundish.

$$V_d = 1 - \frac{\dot{V}_a}{\dot{V}}\Theta_{av} \tag{5}$$

$$V_{dp} = \frac{\left(\Theta_{\min} + \Theta_{peak}\right)}{2} \tag{6}$$

$$V_m = 1 - V_d - V_{dp} \tag{7}$$

where: V_{dp} – dispersed plug flow volume, V_m – well mixed flow volume, V_d – dead flow volume, θ_{av} – mean dimensionless time, θ_{min} – minimal dimensionless time, θ_{peak} – peak dimensionless time, $\dot{V}$ – volumetric rate of flow trough the active region of the tundish.

Fig. 8 shows that comparing to the tundish without impact pads the percentage participation of dead flow volume is clearly decreased and in the same time there is an increase of well mixed flow volume for analyzed turbulence inhibitors. For A to C variants the participation of dispersed plug flow volume is lower. This, however, is not beneficial, because the dispersed plug flow favour the floating of nonmetallic inclusions from liquid steel.

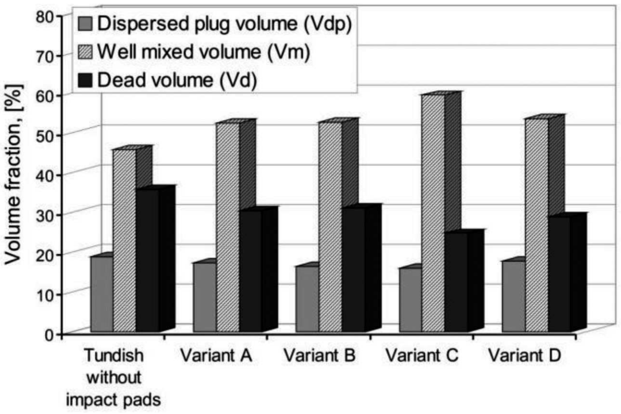

Fig. 8. RTD parameters and volume participation of flow

According to the rule concerning the correctly modernized tundish, which says that to improve the refining capacity of a tundish the dead zone should be minimized and the dispersed plug flow volume should be increased even at the cost of well mixed flow volume, the most effective seems to be geometry of turbulence inhibitor variant D.

5. Additional measurements on the water model

To identify the obtained results (settings of mathematical model parameters) the experimental tests were carried out for one of the analyzed variants of turbulence inhibitors. The physical model of CC process (at the scale 1:2) has the character of water segment model and was built according to the rules coming from the theory of similarity [19].

The construction of the model allow to determine RTD curves of F-type describing the way liquid steel flows through the tundish taking into account the hydrodynamics of steel mixing. As a tracer the water solution of $KMnO_4$ was used. Optoelectronics sensors were installed on the particular outlet from the model of the tundish. This is an original solution, and its construction and principle of operation were described in work [20].

To compare directly the results coming from the water model (at 1:2 scale) to results from numerical calculations (at 1:1 scale) the time was converted using Froude‘s criteria of similarity:

$$t_{wm} = t_{num} \cdot \sqrt{S_L} \tag{8}$$

where: S_L – dimensional scale of model, t_{wm} – time in water model, $t_{,num}$ – time in numerical simulation.

Fig. 9 presents changes of dimensionless tracer concentration for the water experiment and numerical simulation as a function of time for the turbulent inhibitor – variant A. Agreement between results of water experiment and numerical simulation can be stated. This as a consequence confirms the correctness in choosing mathematical model and setting of model parameters.

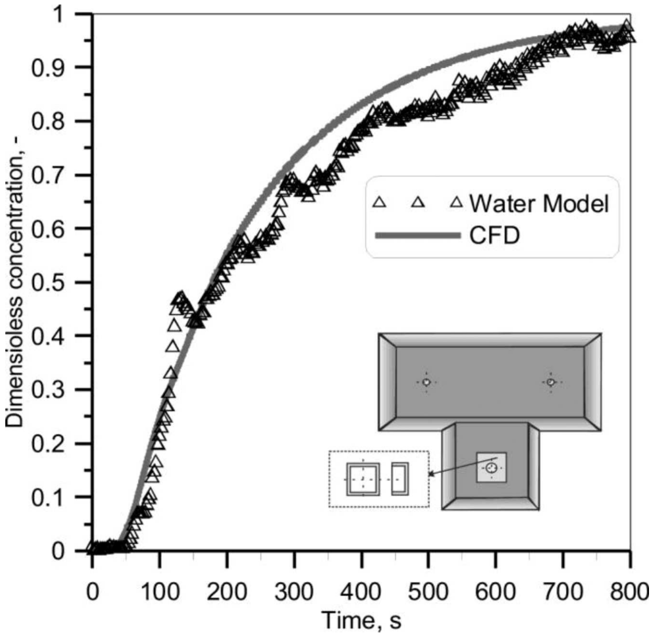

Fig. 9. Results coming from water model and CFD – mixing-time characteristics for turbulence inhibitor variant A

6. Summary and conclusions

Presented results concern only a fragment of a bigger research project. It is connected with the flow and with mixing liquid steel in tundishes which differ in the flow control devices.

To verify settings of numerical model the obtained results were juxtaposed with data gained from physical model (see Fig. 9). There is an agreement between them, so the correctness of chosen method is confirmed.

Observations collected during the investigations can be summarized in the following manner:

- Applying turbulence inhibitor limits the dynamics of steel flux coming into tundish, then the flow of steel becomes more uniform (lower profile of velocity). It gives better control over the steel flow.
- Turbulence inhibitors have beneficial influence on durability of refractory lining in near-inlet zone, therefore the consumption of such lining during the process of filling the tundish with liquid steel is lower.
- Comparing with the tundish without impact pads, application of the turbulence inhibitor makes the liquid steel better mixed. This improvement is based on increasing the dynamics of liquid steel mixing, so then the zone of intensive mixing is also bigger. Such situation favours floating the nonmetallic inclusions to the slag and their absorption. This concerns all analyzed variants of turbulence inhibitors.
- Applying turbulence inhibitors decrease the percentage participation of dead zones (see Figure 8). However, it is not possible to eliminate them. Areas most susceptible to this flow disturbance are the ones near back wall of the tundish in a near-slag zone.
- Turbulence inhibitors influence shaping the zone of intensive mixing, but forming the zone of dispersed plug in a channel part of the tundish is rather difficult. This is caused by the movement of liquid downwards after being reflected from the slag. However, the time the tracer reaches particular outlets is rather similar. So, it can be assumed that the course of casting process will be correct.
- The shape of turbulence inhibitor (square – variant A or round – variant D) does not influence the kinetics of steel mixing and also the ratio of percentage participation of particular flow volume in the tundish (Table 1, Fig. 8).
- Formation of inner space of turbulence inhibitor influences the flow and kinetics of steel mixing and also the ratio of percentage participation of particular flow volume in the tundish (Table 1, Fig. 8).
- According to the rule concerning the correctly modernized tundish, which says that to improve the refining capacity of a tundish the dead zone should be minimized and the dispersed plug flow volume should be increased even at the cost of well mixed flow volume, the most effective seems to be geometry of turbulence inhibitor variant D.

To sum up, turbulence inhibitor fixed in the tundish is advantageous to the hydrodynamic conditions of steel flow. However, the shape and inner space of this inhibitor have to be individually chosen to particular geometry of the tundish.

Acknowledgements

To the State Committee for Scientific Research (MNiSW) for financial support (project N N508 390337).

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Received: 10 April 2012.