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EFFECT OF STEEL FLOW CONTROL DEVICES ON FLOW AND TEMPERATURE FIELD IN THE TUNDISH OF CONTINUOUS CASTING MACHINE

WPŁYW URZĄDZEŃ STERUJĄCYCH PRZEPŁYWEM STALI NA POLE PRĘDKOŚCI I TEMPERATURY W KADZI POŚREDNIEJ URZĄDZENIA CIĄGŁEGO ODLEWANIA

The mathematical model and numerical simulations of the liquid steel flow in a tundish are presented in this paper. The problem was treated as a complex and solved by the finite element method. One takes into consideration in the mathematical model the changes of thermophysical parameters depending on the temperature. The single-strand tundish is used to casting slabs. The internal work space of the tundish was modified by flow control devices. The first device was a pour pad situated in the pouring tundish zone. The second device was a dam. The third device was a baffle with three holes. The dam and baffle were placed in the tundish at different positions depending on the variant. The main purpose of using these was to put barriers in the steel flow path as well as give directional metal flow upwards which facilitated inclusion floatation. The interaction of flow control devices on hydrodynamic conditions was received from numerical simulations. As a result of the computations carried out, the liquid steel flow and steel temperature fields were obtained. The influences of the tundish modifications on the velocity fields in liquid phase of the steel were estimated, because these have essential an influence on high-quality of a continuous steel cast slab.

Keywords: Numerical simulation, molten metal flow, continuous casting, tundish

W pracy przedstawiono model matematyczny i wyniki symulacji numerycznych przepływu ciekłej stali w kadzi po-średniej urządzenia ciągłego odlewania. Zadanie potraktowano kompleksowo rozwiązując go metodą elementów skończonych. Uwzględniono zmianę parametrów termofizycznych od temperatury. Do rozważań wybrano jednowylewową kadź pośrednią przeznaczoną do odlewania wlewków płaskich. Przestrzeń robocza kadzi pośredniej była modyfikowana i zabudowywana urzą-dzeniami sterującymi przepływem ciekłej stali. Pierwszym urządzeniem była kształtka podwylewowa umieszczona w strefie zasilania kadzi pośredniej. Drugim urządzeniem była tama a trzecim przegroda z trzema oknami przelewowymi. Tama i przegroda były umiejscawiane zamiennie w różnych położeniach zależnie od wariantu. Głównym celem zastosowania tych modyfikacji było wymuszenie spokojnego mieszania cieczy metalicznej oraz ukierunkowanie płynięcia metalu w górę, które wspomaga flotacyjne unoszenie wtrąceń do warstwy żużla. Wpływ zastosowanych w kadzi pośredniej urządzeń sterujących na warunki hydrodynamiczne przepływu ciekłej stali oceniano na podstawie symulacji komputerowych. W wyniku obliczeń numerycznych otrzymano pola prędkości i temperatury ciekłej stali. Analizowano wpływ modyfikacji wnętrza kadzi na rozkłady prędkości w fazie ciekłej stali, które mają istotny wpływ na jakość wlewka ciągłego odlewania.

1. Introduction

The method of continuous casting of steel is now often used in the metallurgical industry, due to the increasing demand for the production of high-quality steel. There is therefore a need for continuous improvement of this method by proposing of new technical solutions in different elements of the continuous casting machine. The obtainment of quality steel from a continuous casting machine is dependent on a large number of interlinked process parameters of main ladle, tundish and continuous steel casting (CSC) mould [1]. Molten steel at an appropriate temperature is poured from the main ladle to the tundish at a preset rate and then flows over this vessel and fills it up to a specified height. Next, the steel flows out through the openings in the tundish bottom to the CSC mould [2]. An important device of continuous casting machine is the tundish, in which a stabilized steel flow has a crucial affect on the quality and efficiency conditions of the continuous casting process. The paper mainly focuses on the analysis of flow and thermal phenomena occurring in the tundish. Nowadays, tundish is not only a storage vessel which guaranty the continuous casting of steel, but it become an additional metallurgical stage where other operation are performed. These operations are for example the temperature control of alloy and chemical composition, the melt flow control to enable the non-metallic inclusion separation and transport them to the slag layer. Flow behaviour in the tundish is governed mainly by the size and shape of the tundish and the location of flow control devices,

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such as dams, weirs, filters, pour pad, baffles with holes and turbulence inhibitors [3, 4]. These devices are designed to allow the implementation of the main objective of the flow in the tundish which is to ensure uniformity and inclusion removal, while avoiding flow-related problems. Tundish flow problems include the surface turbulence, short-circuiting, dead zones and vortexing. An excessive flow directed across the top surface can produce turbulence and lead to reoxidation and slag entrainment. Short-circuiting allows incoming steel from the ladle to exit prematurely into the CSC mould with insufficient time for inclusion flotation. Dead zones are stagnant, colder regions that inhibit inclusion removal and can slowly mix and contaminate the new steel flowing through the tundish. If the liquid level is too shallow, high-speed, asymmetric flow may produce vortexing, which can entrain surface slag down into the CSC mould. Generally summarize, for the designing of a tundish arrangement, it is necessary to look for the highest plug flow volume fraction with a minimum dead volume and perfect mixing zones [2-5]. An important mechanism for inclusion elimination from liquid steel is a simple flotation, whereby the particle is separated if it rises as the result of its buoyancy to contact the slag and is then absorbed by the slag. However, the efficiency of inclusion removal by simple flotation in the tundish is generally limited by the residence time of liquid metal as it flows through a tundish and the rise velocity of the buoyant particles. The rise velocity of a particle is a function of its size, smaller particles are harder to remove [6-8]. The flow pattern is also affected by the steel flow rate and its temperature distribution. Thermal buoyancy tends to lift up the hotter, lower-density flowing steel, while colder steel tends to flow down the walls and along the bottom. A temperature difference of only a few degrees is enough to lift the jet flowing beneath the weir and completely reverse the flow direction in the tundish. Flow in the tundish is greatly affected by the ladle-tundish nozzle geometry and gas in the ladle stream. Problems related to surface turbulence can be reduced by avoiding excessive argon levels in the ladle stream and by using fully-shrouded and immersed nozzles [5-7]. Empirical studies of the liquid metal flow in the tundish, due to the high temperatures and a lack of optical access, are almost impossible. For this reason, the numerical modelling is currently the main tool for analyzing the phenomena of continuous casting process [1-6, 8-10]. In the present study, the numerical simulation was used.

The mathematical and numerical simulation model of the liquid steel flow in a tundish is presented in this paper. The problem was treated as a complex and solved by the finite element method [8-11]. The velocity fields are obtained by solving the momentum equations and the continuity equation, whereas the thermal fields are calculated by solving the conduction equation with convection term. The internal work space of the tundish was modified by the flow control devices. The main purpose of using these devices was to cause a quiet liquid mixing as well as give directional metal flow upwards which facilitated inclusion floatation. The interaction of flow control devices on hydrodynamic conditions was received from numerical simulation. As a result of the computations carried out, the liquid steel flow and steel temperature fields were obtained. The influence of the tundish modification on velocity fields in the liquid phase of steel was estimated, because these have an essential influence on high quality of a continuous steel cast slab.

2. Mathematical model of the heat-transfer during the molten metal motions

The mathematical model of a molten metal flow in the tundish has been proposed. The superheated metals and their alloys in the liquid state can be treated as Newtonian fluids [5, 6, 8-12], therefore in the paper is used the system of equations (2, 3) which describe the flow of viscous incompressible fluid. The equation (1) describes the heat transfer in the region of a tundish is based on solving the Fourier-Kirchhoff equation with the convection term [5, 6, 8-14]. It was assumed that the solidification front is mushy [8-14], but sometimes it is assumed that it can be sharp [15, 16]. The assumption of such model (the mushy zone) allowed us to introduce the phase transformation enthalpy to the effective thermal capacity in the energy equation in the problem solution. The mathematical model is based on the solution of the following system of differential equations [8-12]:
– the energy equation

$$C_{ef}\left(\frac{\partial T}{\partial t} + v_j \frac{\partial T}{\partial x_j}\right) = \frac{\partial}{\partial x_j}\left(\lambda \frac{\partial T}{\partial x_j}\right), \qquad (1)$$

– the momentum equations

$$\rho\left(\frac{\partial v_i}{\partial t} + v_j \frac{\partial v_i}{\partial x_j}\right) = \frac{\partial}{\partial x_j}\left(\mu \frac{\partial v_i}{\partial x_j}\right) - \frac{\partial p}{\partial x_i} + \rho g_i \beta (T - T_{in}) + \rho g_i, \qquad (2)$$

– the continuity equation

$$\frac{\partial v_i}{\partial x_i} = 0, \qquad (3)$$

where: T – the temperature [K], t – time [s], $\rho = \rho(T)$ – the density [kg/m³], λ – the thermal conductivity coefficient [W/(mK)], x_j – the coordinates of the vector of a considered node's position [m], v_i – the velocity vector of a molten metal flow [m/s], $\mu(T)$ – the dynamical viscosity coefficient [Ns/m²], C_{ef} ($C_{ef} = \rho_{LS}c_{LS} + (\rho_S L)/(T_L\text{-}T_S)$ [8]) – the effective heat capacity of the mushy zone [J/(m³K)], L – the latent heat of solidification [J/kg], c_{LS} – the specific heat of the mushy zone [J/(kgK)], p – the pressure [N/m²], $\rho_S, \rho_L, \rho_{LS}$ – the density of solid phase, liquid phase, and mushy zone, respectively [kg/m³], g_i – the vector of the gravity acceleration [m/s²], β – the volumetric thermal expansion coefficient [1/K], T_{in} – the initial temperature (tundish inlet) [K].

The equation of heat conductivity (1), the Navier-Stokes equations and continuity equation (2, 3) create a closed, coupled system of equations describing the molten metal flow. This system of equations is completed by the appropriate initial conditions and the classical boundary conditions [8-18].

The initial conditions for velocity fields and temperature fields are given as:

$$\mathbf{v}(x_i, t_0) = \mathbf{v}_0(x_i), \qquad T(x_i, t_0) = T_0(x_i) . \qquad (4)$$
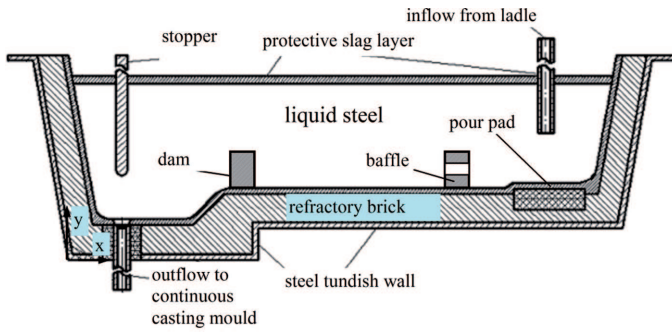
Fig. 1. A schematic illustration of the single-strand tundish containing the flow control devices

The boundary conditions, on the indicated surfaces (Fig. 1), specified in the considered problem were as follows:
– at the inflow nozzle

$$v_y = v_{in}, \quad v_x = 0, \quad T = T_{in}, \qquad (5)$$

– at the tundish wall

$$v_x = v_y = 0, \quad \lambda \frac{\partial T}{\partial n} = -\alpha_t (T - T_a) \qquad (6)$$

– at the slag layer

$$v_y = 0, \quad \lambda \frac{\partial T}{\partial n} = -\alpha_s (T - T_a) \qquad (7)$$

– at the outflow nozzle

$$v_x = 0, \quad \frac{\partial T}{\partial n} = 0 \qquad (8)$$

where: T_a – the ambient temperature [K], α_t – the heat-transfer coefficient between the steel tundish wall and ambient [W/(m^{2}K)], n – the outward unit normal surface vector.

The above problem was solved by the finite element method in the weighted residuals formulation [8-11, 15-17].

3. Numerical simulations

The calculations were performed for the tundish with a cross-section 3.3×1.44 and the length 4.7 m (Fig. 1). The height of the dam and baffle was equal to 0.27 m. The overheated steel with temperature $T_{in} = 1900$ K was poured with velocity $v_{in} = 0.45$ m/s into the tundish with the initial temperature $T_t = 1400$ K. The thermophysical properties of the cast steel and tundish were taken from works [2, 4, 6, 11 - 14]. The linear change of the density (ρ) and thermal conductivity (λ) were assumed in the $T_L - T_S$ temperature interval. The variability of the dynamical viscosity coefficient (μ) with respect to temperature was determined according to the exponential relationship in range $0.003 - 10^5$ [Ns/m^2] [19, 20]. The characteristic temperatures of the molten steel were equal to: $T_L = 1810$, $T_S = 1760$ K and ambient temperature $T_a = 303$ K. The heat-transfer coefficient (α) between the tundish and ambient was equal $\alpha_t = 30$ W/(m^{2}K) and between the slag and ambient $\alpha_s = 3$ W/(m^{2}K) [1, 9]. The thermal and fluid flow phenomena occurring in the considered system were analyzed. The internal working space of the tundish has been modified by the location of added flow control devices, such as the pour pad, dam and baffle with three holes. In numerical calculations five variants location of the flow control devices inside the tundish, were taken into account. In I variant the pour pad was used only in the inflow zone. In II variant the dam was used additionally in the outflow zone. In III variant the baffle with three hols was located in the outflow zone. In IV variant the dam and baffle ware used together. In V variant the two baffles were applied. An influence of the interaction of this flow control devices on the velocity fields in the liquid phase of steel were estimated. The main objective of the velocity field change was to enable the separation of non-metallic inclusions and directed metal flow upwards which facilitated the floatation of inclusions. Examples of calculation results are shown in the form of the temperature and velocity fields (Fig. 2-9).
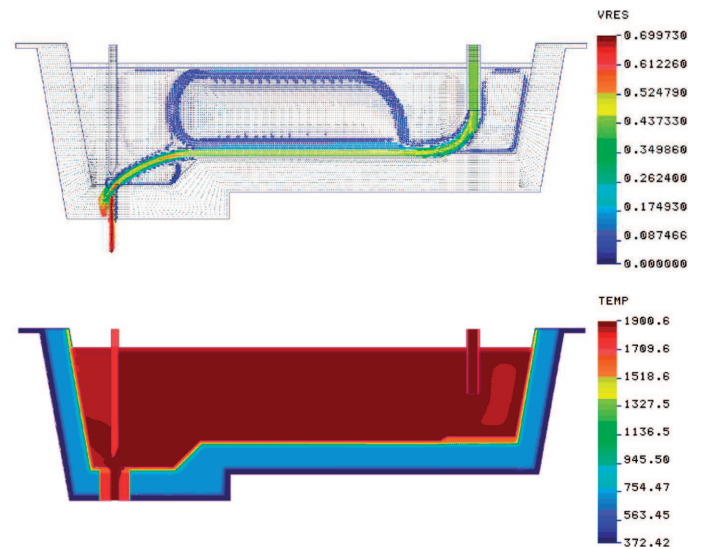

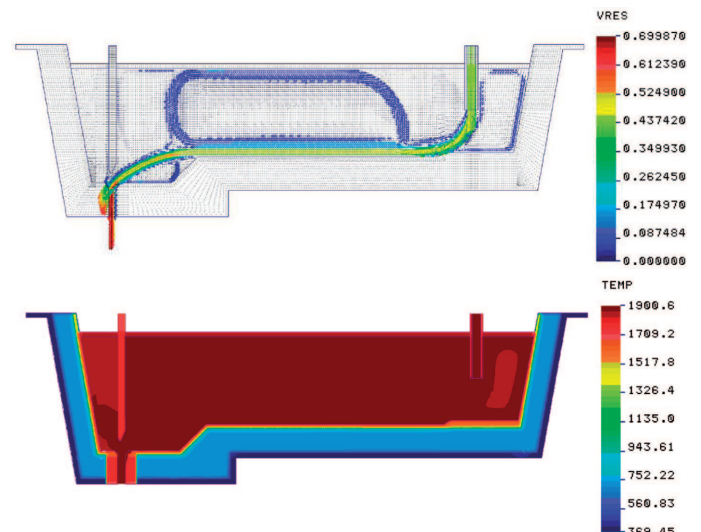Fig. 2. Velocity vectors and temperature field after time 720 s, I variant

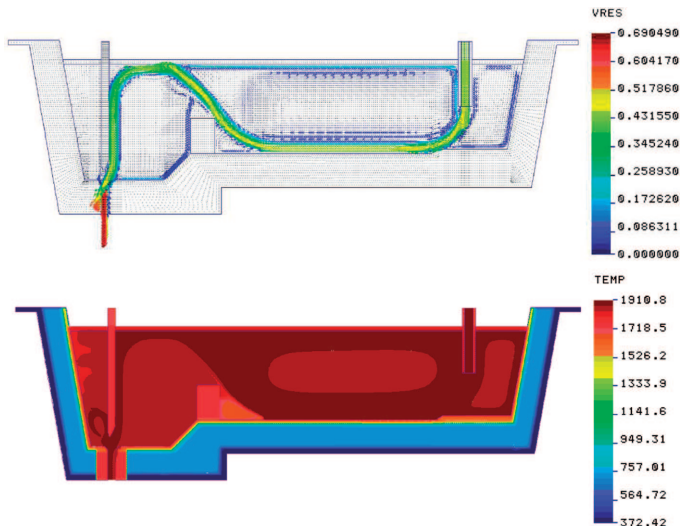Fig. 3. Velocity vectors and temperature field after time 840 s, I variant

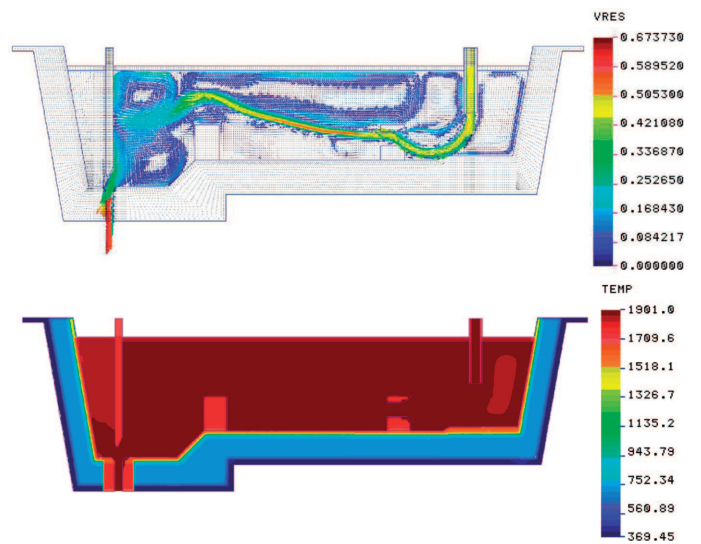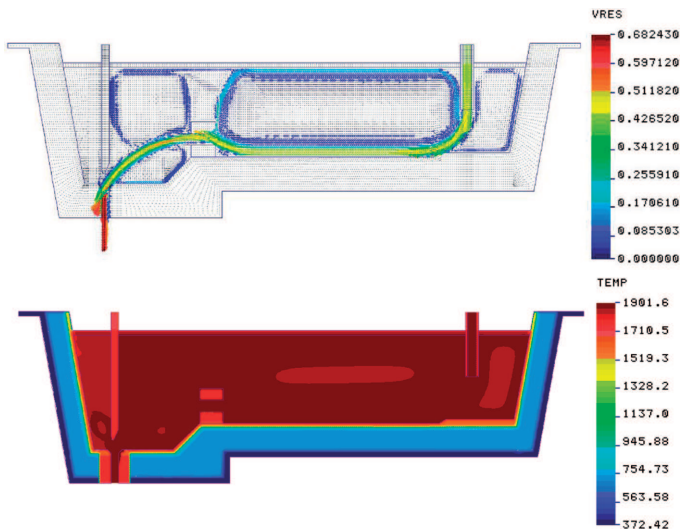Fig. 4. Velocity vectors and temperature field after time 720 s, II variant

Fig. 5. Velocity vectors and temperature field after time 720 s, III variant

Fig. 6. Velocity vectors and temperature field after time 720 s, IV variant

Fig. 7. Velocity vectors and temperature field after time 840 s, IV variant

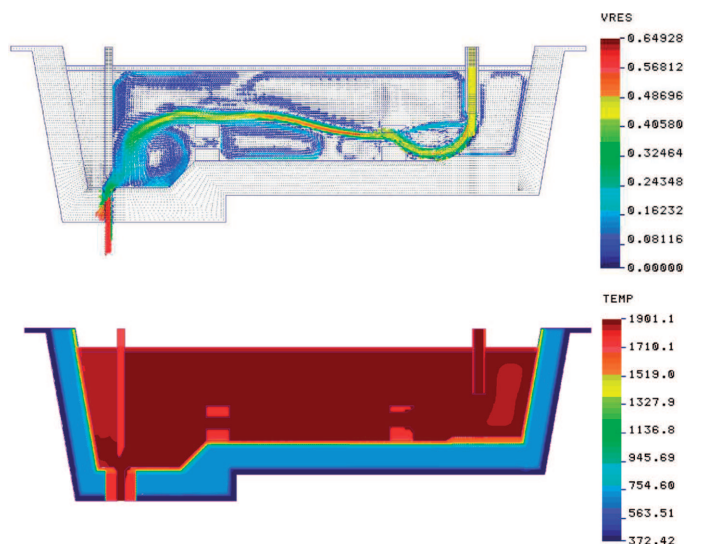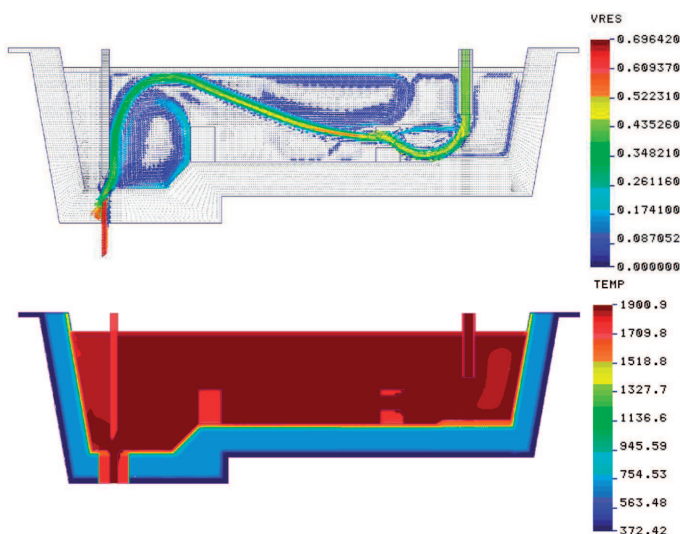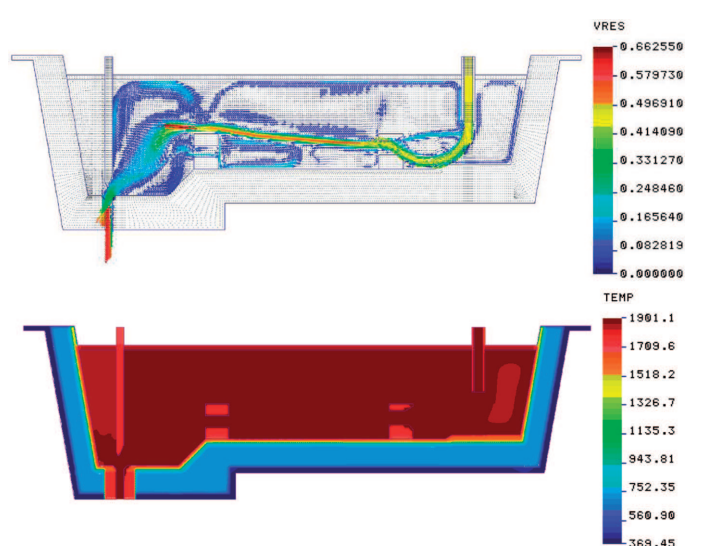Fig. 8. Velocity vectors and temperature field after time 720 s, V variant

Fig. 9. Velocity vectors and temperature field after time 840 s, V variant

4. Conclusions

The paper mainly focuses on the analysis of flow and thermal phenomena occurring in the tundish. Investigations of the steel flow or inclusions separation process at the industrial plant are nearly impossible because of the high temperature and a lack of optical accessibility. For this reason the numerical modelling is becoming an important tool to analyze all phenomena of the continuous casting process. This paper presents the coupled model of the fluid flow and heat transfer in the tundish during continuous casting processes. The problem was treated as a complex and solved by the finite element method. Numerical simulation results are shown in the form of the temperature and velocity fields (Fig. 2-9). It was noted, that the velocity field of a liquid phase has a significant influence on the temperature field. A small intensity of the molten metal motion near the slag layer causes the formation of dead zones and the local temperature drop in the inflow and outflow tundish zone (Fig. 2, 3). Next, four modification variants of the internal work space of the tundish were performed (Fig. 4-9). In the second variant, the dam causes the excessive flow directed to the top surface what can lead to the reoxidation and slag entrainment down into the continuos casting mould (Fig. 4). In this case, the small movements of the liquid phase in the central zone of the tundish occur because the main stream of liquid metal flows after the bottom of it. The use of the baffle with three holes causes the liquid metal moves return and reducing dead zones (Fig. 5). In the fourth variant, when the dam and baffle are used together, the appropriate directed flow of molten metal was obtained. The main directed flow slightly to the top surface causes the circulating movements of molten metal in the whole tundish allow flowing of the non-metallic inclusions to the slag layer (Fig. 7). Similarly, satisfying results were obtained in case of a fifth variant. In this case, the minimum dead volume is visible because the baffle gives a directional metal flow upwards allowing the inclusions to float toward the slag layer (Fig. 9). Generally summarize, the flow field inside the tundish is frequently unsteady and is an important mechanism for inclusion elimination from liquid steel allowing the inclusions to float toward the slag layer. It has an essential influence on obtain high-quality of the continuous steel cast slab. It is very important for the practice casting.

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