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NUMERICAL SIMULATION OF THE MOLTEN STEEL FLOW IN THE TUNDISH OF CSC MACHINE

SYMULACJA NUMERYCZNA PRZEPŁYWU CIEKŁEJ STALI W KADZI POŚREDNIEJ URZĄDZENIA COS

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 one. 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 the convection term. One takes into consideration in the mathematical model the changes of thermophysical parameters depending on the temperature. The problem was solved by the finite element method. The one-strand slab tundish is used to casting slabs. The internal work space of the tundish was modified by flow control devices. The first device was a striker pad situated in the pouring tundish zone. The second device was a baffle with three holes. 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 visualization of 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: Continuous casting, tundish, molten metal flow, numerical simulation

W pracy przedstawiono model matematyczny i numeryczny przepływu ciekłej stali w kadzi pośredniej urządzenia ciągłego odlewania. Zadanie potraktowano kompleksowo. Pola prędkości otrzymano z rozwiązania równań Naviera-Stokesa i równania ciągłości przepływu, natomiast pola temperatury z rozwiązania równania przewodnictwa z członem konwekcyjnym. Uwzględniono zmianę parametrów termofizycznych od temperatury. Problem rozwiązano metodą elementów skończonych. Do rozważań wybrano jednowylewową kadź pośrednią przeznaczoną do odlewania wlewków płaskich. Przestrzeń robocza kadzi pośredniej została zmodyfikowana i zabudowana urządzeniami sterującymi przepływem ciekłej stali. Pierwszym urządzeniem był amortyzator kadzi pośredniej umieszczony w strefie jej zasilania. Drugim urządzeniem była przegroda z trzema oknami przelewowymi. Głównym celem użycia tych urządzeń było umieszczenie przeszkód na drodze przepływu stali wymuszających spokojne mieszanie cieczy metalicznej jak również ukierunkowanie płynięcia metalu w górę umożliwiające flotacyjne unoszenie wtrąceń do warstwy żużla. Wizualizacje oddziaływania zabudowy kadzi pośredniej na warunki hydrodynamiczne uzyskano na podstawie wyników otrzymanych z symulacji komputerowej przepływu ciekłej stali. W wyniku obliczeń numerycznych otrzymano pola prędkości i temperatury ciekłej stali. Badano w ten sposób wpływ modyfikacji wnętrza kadzi na pola prędkości w fazie ciekłej stali, które mają istotny wpływ na jakość wlewka ciągłego odlewania.

1. Introduction

Constantly increasing customers demands for the production of high-quality steels, cause the intensive technological development of their production. Today, the dominant method of global steel production is the continuous casting, hence the need for continuous improvement of this method. The production 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]. Important continuous casting device is the tundish, in which a stabilized steel flow has a crucial effect on the quality and efficiency conditions of the CSC process. In order to remove inclusions in the tundish, it is necessary

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to have a good understanding of fluid flow behaviour. Sometimes, the inertial or buoyancy forces may govern this behaviour. The inertial forces dominate the fluid behaviour when the liquid steel stream coming from the ladle shroud promotes high turbulence, which is transmitted to the bulk of the fluid and vice versa, when the turbulence is reduced, the buoyancy forces dominate the fluid flow behaviour. Under this flow regime, the tundish has the highest possibility of allowing the inclusions to float toward the free surface of the liquid bath. When the buoyancy forces are strongly dominant, the temperature plays a role of paramount importance. During a normal casting operation, the tundish inlet steel temperature continuously drops, due to the heat losses throughout the walls and the free surface to the environment of the ladle. During ladle change operations, the new and hotter steel is poured into the tundish and the inlet steel temperature is again increased. The buoyancy forces developed by the fluid density change contribute to the modification of the steel flow patterns. Furthermore, the steel in the tundish also loses heat through the walls and the free surface [3]. Flow behaviour in the tundish is governed mainly by the size and shape of the vessel and the location of flow-control devices, such as dams, weirs, filters, striker pad, baffles with holes and turbulence inhibitors. 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 also 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 [2, 4].

The tundish provides a continuous flow of metal from the batch ladle operation to the continuous casting machine. It also serves as an important metallurgical reaction vessel, where quality can be improved, maintained or lost. The flow objective in the tundish is to encourage uniformity and inclusion removal, while avoiding flow-related problems. Tundish flow problems include surface turbulence, short-circuiting, dead zones and vortexing. 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 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 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 [4, 5]. An important mechanism for inclusion elimination from liquid steel is that of 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 a 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. Gas bubbles have higher rise velocities than inclusions as a result of being less dense and typically larger in size. Thus, particle/bubble attachment is an important topic in the enhancement of inclusion separation in a tundish [6, 7].

The common way to control the flow is by designing and placing devices inside the tundish. This is commonly carried out experimentally using physical or using mathematical models. Two different techniques are normally applied when the design is made experimentally. The first method is based on the addition of a tracer as an impulse in an analogue water model. The second method is based on a temperature step input change in the ladle shroud of a water model. The two methods can be reproduced using a mathematical model and numerical simulations. Mathematical modelling was a very useful tool, since most of the cases are experimentally difficult to carry out [3, 6, 8, 9].

The aim of the paper is to estimate, by numerical simulation method, the modification effect of the internal space of tundish by flow control devices on the molten metal flow and the temperature field within the tundish. The molten steel flow behaviour characterized by mathematical modelling in the bare tundish and in the tundish equipped with a baffle was analyzed in this work. In each case of a study, the velocity and temperature distribution were obtained. 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. The thermal field inside the tundish depends on the fluid flow, varying temperature of the liquid steel stream coming from the ladle, heat losses through refractory lining and heat losses from top surface of the liquid steel and slag. Mathematical and numerical models of the molten metal motions within a tundish in which we took into consideration the changes of thermophysical parameters depending on the temperature are presented in this paper. For the flowing liquid metal, the constant flow intensity on the inlet to the tundish is assumed, and has been used to calculate the outlet speed. The velocity field is obtained by solving the Navier-Stokes equations, whereas the thermal field is calculated by solving of Fourier-Kirchhoff equation with the convection term. It was assumed that the solidification front is mushy, i.e. the liquid metal solidifies within the range of liquidus/solidus temperature. The assumption of such model (the mushy zone) allowed us to introduce the phase transformation enthalpy to the effective thermal capacity in the Fourier-Kirchhoff equation in the problem solution. The problem was solved by the finite element method [9-13].

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 equation describes the heat transfer in the region of a tundish is based on solving the Fourier-Kirchhoff equation with the convection term [8-15]. The superheated metals and their alloys in the liquid state can be treated as Newtonian fluids [9, 13, 15], therefore in the paper is used the system of equations which describe the flow of viscous incompressible fluid (the Navier-Stokes equations and the continuity equation). The mathematical model is based on the solution of the following system of differential equations [9-13, 15]:

– the energy equation

$$\nabla \cdot (\lambda \nabla T(\mathbf{x}, t)) - C_{ef}\frac{\partial T}{\partial t} - C_{ef}\nabla T \cdot \mathbf{v} = 0, \tag{1}$$

– the momentum equations

$$\rho\frac{d\mathbf{v}}{dt} = -\nabla p + \mu\nabla^2\mathbf{v} + \rho\mathbf{g}\beta(T - T_{in}), \tag{2}$$

– the continuity equation

$$\nabla \cdot \mathbf{v}(\mathbf{x}, t) = 0, \tag{3}$$

where: T – the temperature [K], t- time [s], $\rho = \rho(T)$ – the density [kg/m^3], λ – the thermal conductivity coefficient [W/(mK)], $\mathbf{v}(u, v)$ – the velocity vector of a molten metal flow [m/s], $\mathbf{x}(x, y)$ – the coordinates of the vector of a considered node's position [m], $\mu(T)$ – the dynamical viscosity coefficient [Ns/m^2], C_{ef} ($C_{ef} = \rho_{LS}c_{LS} + (\rho_S L)/(T_L\text{-}T_S)$ [14]) – the effective heat capacity of the mushy zone [J/(m^{3}K)], L – the latent heat of solidification [J/kg], c_{LS} – the specific heat of the mushy zone [J/(kgK)], p – the pressure [N/m^2], $\rho_S, \rho_L, \rho_{LS}$ – the density of solid phase, liquid phase, and mushy zone, respectively [kg/m^3], $\mathbf{g}$ – the vector of the gravity acceleration [m/s^2], β – the volumetric thermal expansion coefficient [1/K], T_{in} – the initial temperature (tundish inlet) [K].

The equations above (1-3) create a closed, coupled system of equations describing the molten metal flow. The equation of heat conductivity (1), the Navier-Stokes equations and continuity equation (2, 3) are completed by the appropriate initial conditions and the classical boundary conditions [8-15] which are shown in Fig. 1. The above problem was solved by the finite element method in the weighted residuals formulation [9-13].

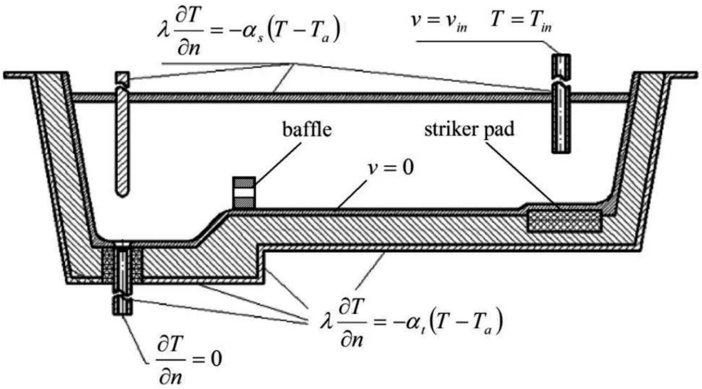

Fig. 1. Region and boundary conditions assumed in the problem under study

3. Numerical simulations

The calculations were performed for the tundish with a cross-section 3.3×1.44 and the length 4.7 m. The overheated steel with temperature T_{in}= 1906 K was poured with velocity v_{in}= 0.45 m/s into the tundish with the initial temperature T_t= 1300 K. The thermophysical properties of the cast steel and tundish were taken from works [1, 6, 8, 10, 13] and calculations were made according to relationships shown in work [6, 15]. The characteristic temperatures of the molten steel were equal to: T_L= 1810, T_S= 1760 K and ambient temperature T_a= 305 K. The heat-transfer coefficient (α) between the tundish and ambient was equal α_t = 30 W/(m^{2}K) and between the slag and ambient α_s = 3 W/(m^{2}K) [1, 12, 13]. The thermal and fluid flow phenomena proceeding in the considered system were analyzed. The internal work space of the tundish was modified by the location of flow control devices, such as the striker pad and baffle with three holes. 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 non metallic inclusion separation and give directional metal flow upwards which facilitated inclusion floatation. In numerical calculations, two tundish variants – the first without a baffle and second with the baffle – were taken into account. Examples of calculation results are shown in the form of the temperature and velocity fields (Figs 2-7). The calculation results for the first variant shown in Figs 2-5 present the successive stages of achieving the steady state by phenomena into account. However, the results obtained from second variant are shown with only two figures indicating that reach the steady state takes place in a time comparable to that obtained in the simulation of the first variant (c.f Figs 4-7).

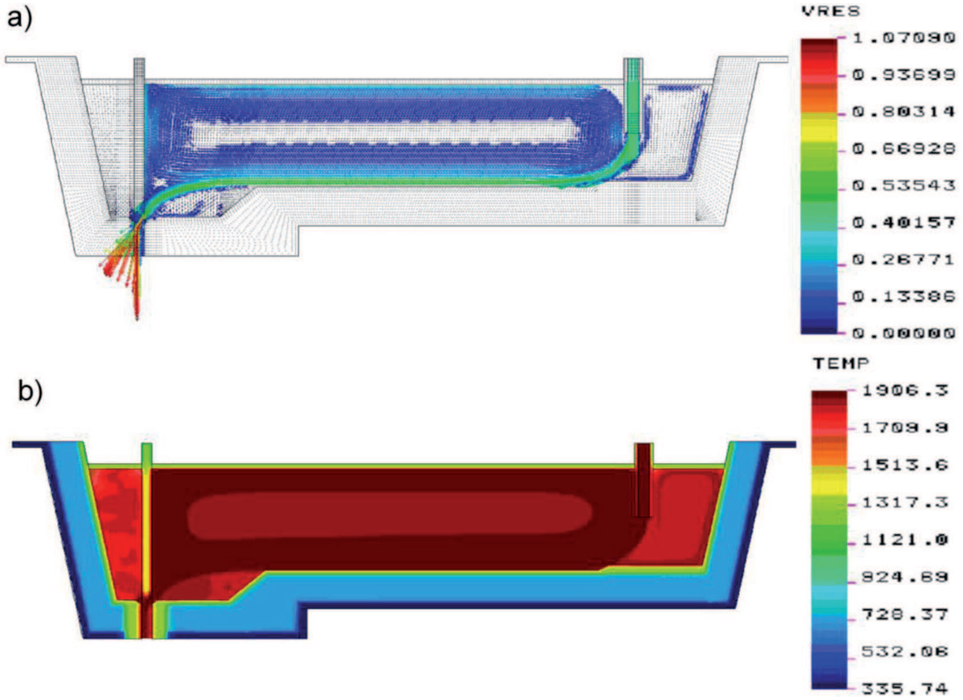

Fig. 2. Velocity vectors (a) and temperature field (b) after time 180 s, I variant

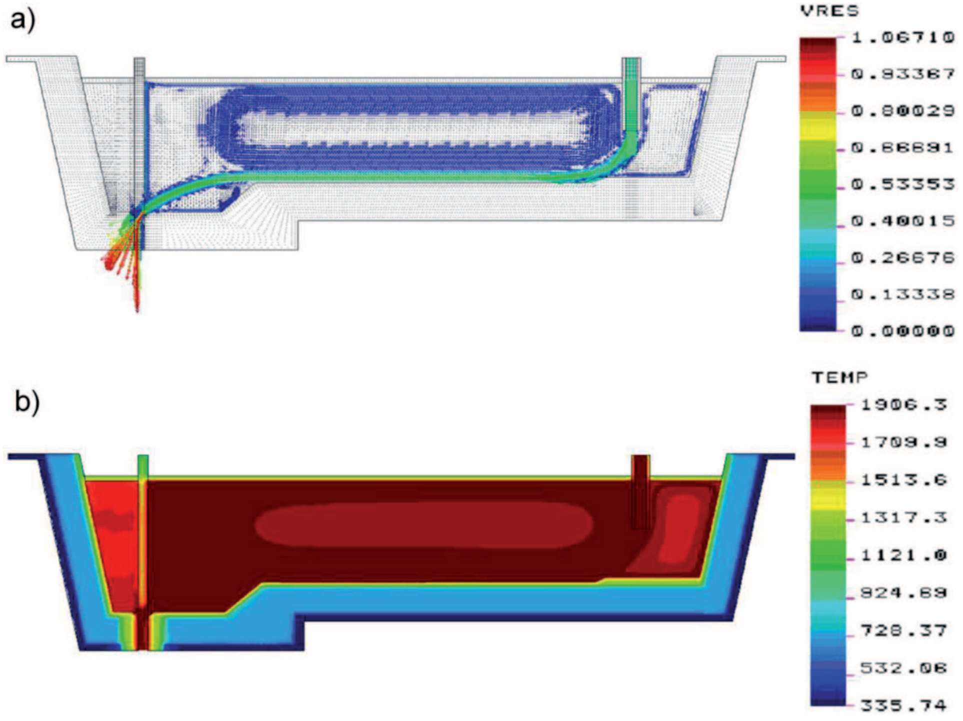

Fig. 3. Velocity vectors (a) and temperature field (b) after time 360 s, I variant

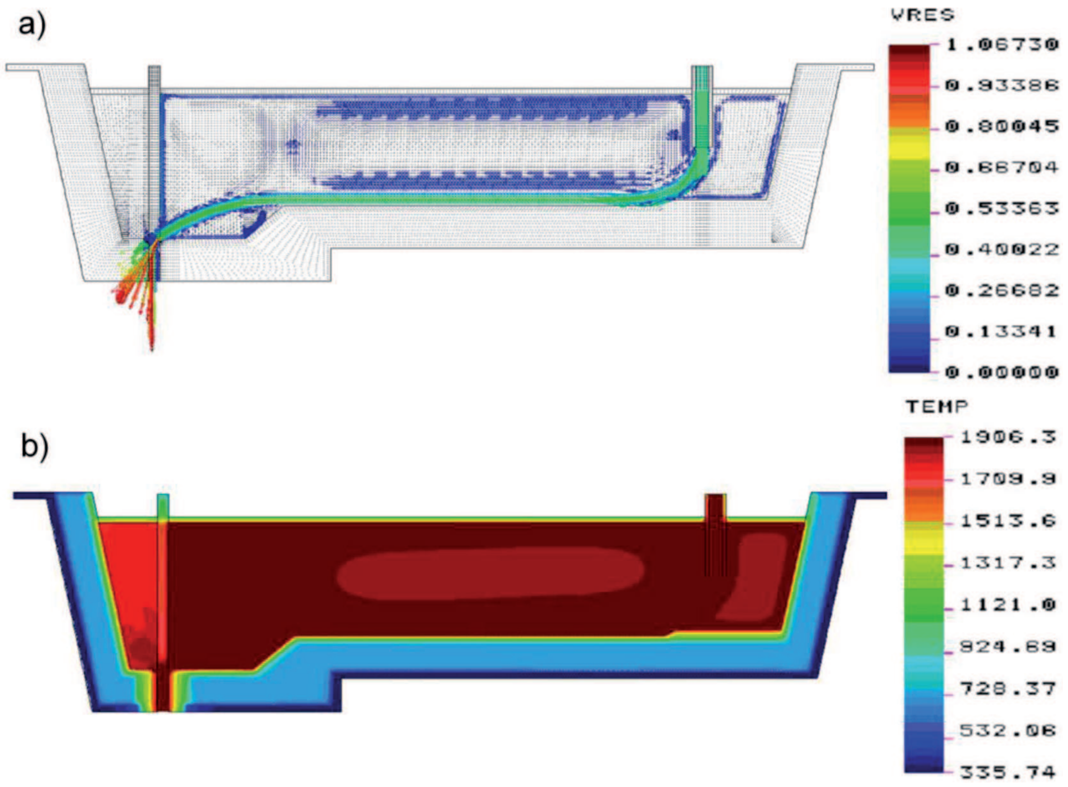

Fig. 4. Velocity vectors (a) and temperature field (b) after time 720 s, I variant

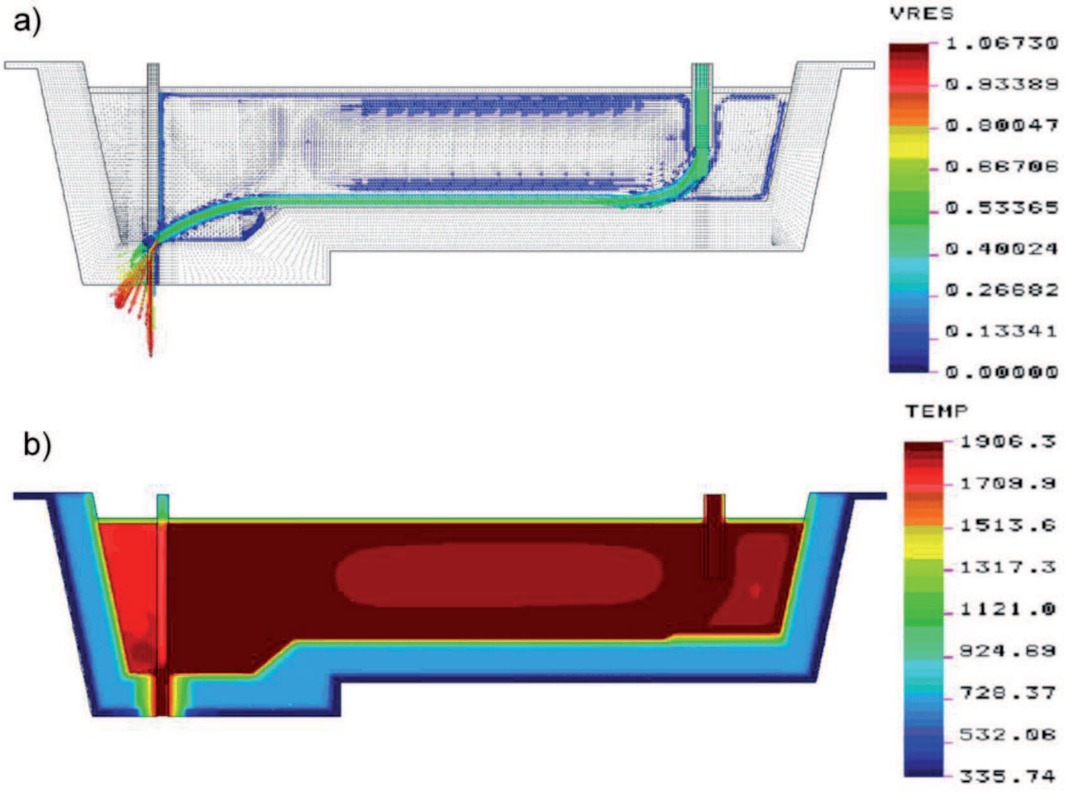

Fig. 5. Velocity vectors (a) and temperature field (b) after time 840 s, I variant

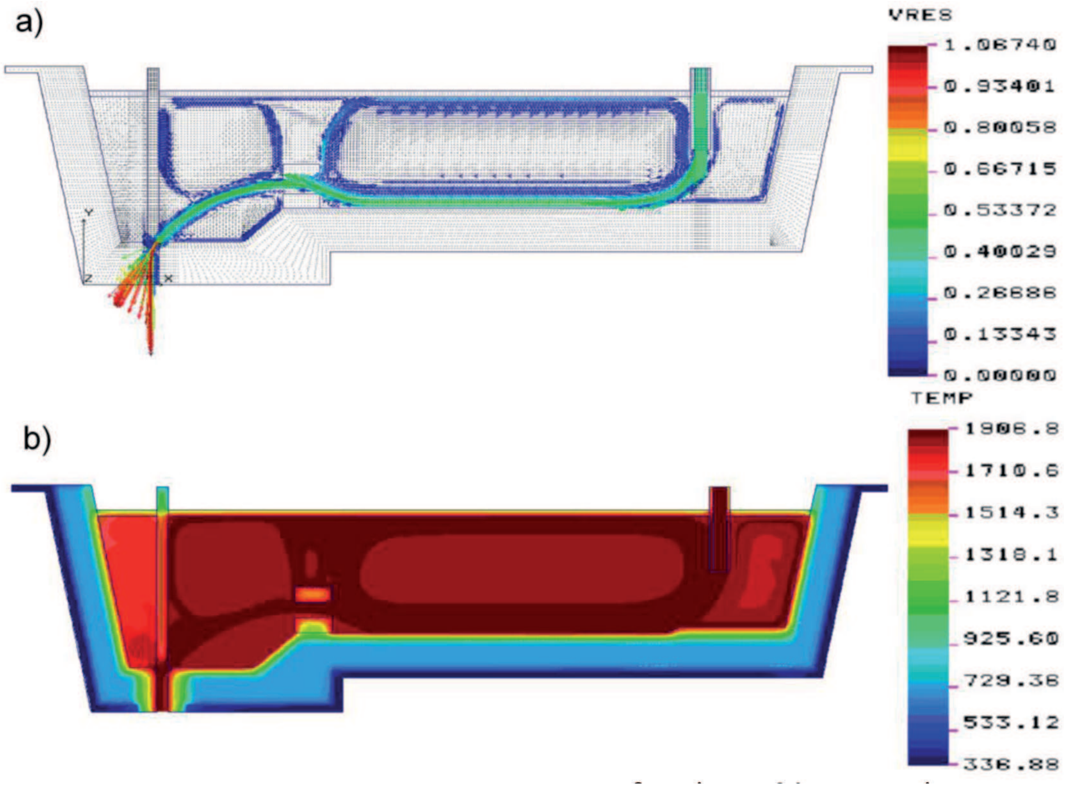

Fig. 6. Velocity vectors (a) and temperature field (b) after time 720 s, II variant

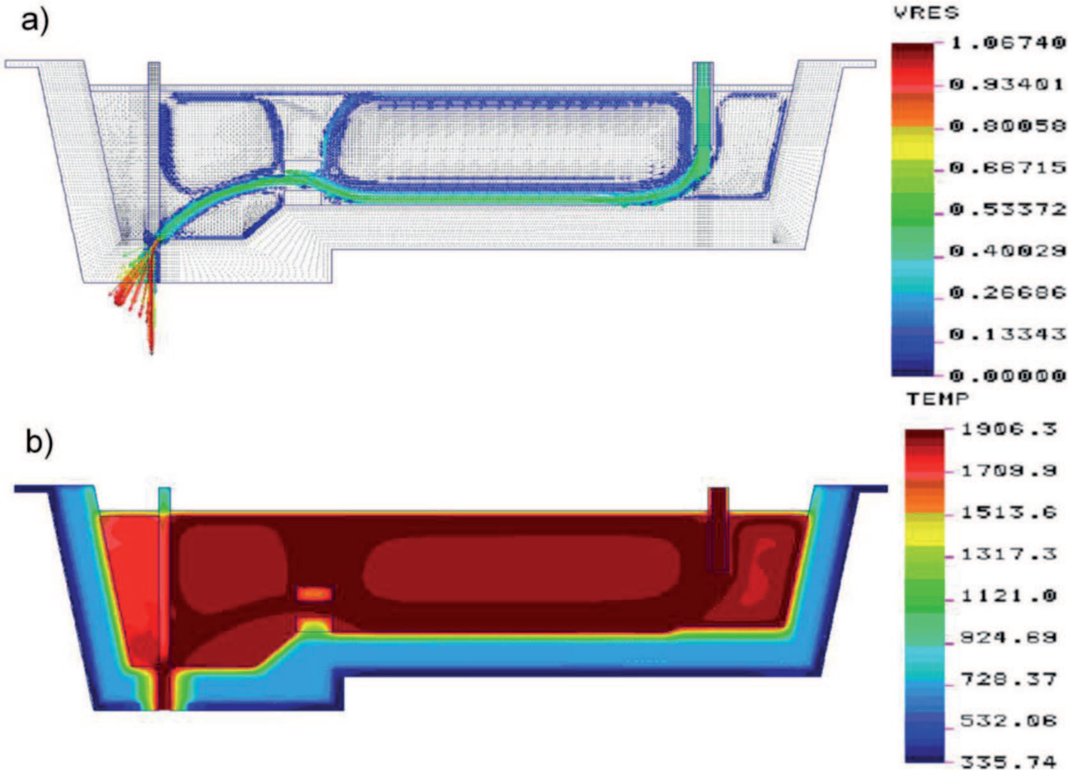

Fig. 7. Velocity vectors (a) and temperature field (b) after time 840 s, II variant

4. Conclusions

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 control of melt temperature, composition and melt flow control to enable non-metallic inclusion separation. 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, what in this study was presented.

This paper presents the coupled model of solidification for the transient evaluation of fluid flow and heat transfer in the tundish during continuous casting processes. The problem was analysed by a complex model. 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 (c.f Figs 4-5). Numerical analysis included the forced molten metal flow and the convectional motions of a molten metal. In numerical calculations, two modification variants of the internal work space of a tundish – the first without a baffle and second with the baffle – were taken into account. The influence of the flow control devices inserted to inside of the tundish on the temperature and velocity distribution were estimated. It was noticed, that second variant of the built-in inside the tundish turned out to be better, to enable non metallic inclusion separation (Fig. 7). In this variant, the minimum dead volume is visible because the baffle gives a directional metal flow upwards allowing the inclusions to float toward the slag layer (c.f Figs 5-7). It has an essential influence on obtain high-quality of the continuous steel cast slab. Furthermore, can concluded that numerical studies indicate that flow conditions beneficial in the removal of non-metallic inclusions in the tundish can be created by inserting appropriate flow-modification devices. It is very important for the practice casting.

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