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NUMERICAL MODEL OF THERMAL AND FLOW PHENOMENA THE PROCESS GROWING OF THE CC SLAB

MODEL NUMERYCZNY ZJAWISK CIEPLNO-PRZEPŁYWOWYCH PROCESU NARASTANIA WLEWKA COS

The mathematical and numerical simulation model of the growth of the solid metal phase within a continuous cast slab 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 and the solid phase volume fractions in the mushy zone. This formulation of the problem is called a complex model in contrast to the simplified model in which the conduction equation is solved only. The problem was solved by the finite element method. A numerical simulation of the cast slab solidification process was made for different cases of continuous casting mould pouring by molten metal. The influences of cases of the continuous casting mould pouring on the velocity fields in liquid phase and the solid phase growth kinetics of the cast slab were estimated, because these magnitudes have essential an influence on high-quality of a continuous steel cast slab.

Keywords: Solidification, molten metal flow, continuous casting, numerical simulation

W pracy przedstawiono model matematyczny i numeryczny narastania fazy stałej we wlewku 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 i od udziału fazy stałej w dwufazowej strefie przejściowej. Takie sformułowanie zadania nazwano modelem złożonym w przeciwieństwie do modelu uproszczonego, w którym rozwiązuje się tylko równanie przewodnictwa. Problem rozwiązano metodą elementów skończonych. Analizie poddano krystalizator o przekroju poprzecznym prostokątnym. Symulacje numeryczne procesu krzepnięcia wlewka wykonano dla różnych wariantów doprowadzenia ciekłego metalu do krystalizatora. Badano w ten sposób wpływ zalewania krystalizatora na pole prędkości w fazie ciekłej i kinetykę narastania fazy stałej wlewka, które mają istotny wpływ na jakość wlewka ciągłego odlewania stali.

1. Introduction

The continuous casting process of metals and alloys is today being frequently utilized in the metallurgical industry, and more general in material engineering. Typically, the molten matal flows into the continuous casting mould being cooled by cold water. The solidifying cast slab is pulled out of the system either by the withdrawal rolls. Below the continuous casting mould the side surface of the cast slab is very intensively cooled by the water flowing from the mould or being sprayed over the surface. Details of the particular technology depend on cast material [1]. The careful control of the cast slab cooling and the shell growth along the continuous steel caster is of central importance in continuous casting operation. These have a considerable influence on the formation of cracks and other defects which can form in the cast material. To ensure defect-free products, the cast slab has to be cooled down according to a pattern which depends on steel grade, product dimensions, casting speed, and continuous casting machine design. On the other hand, control of the liquid pool length is a key element in optimising the casting speed with respect to a good level of productivity [2]. Thus, heat transfer plays a very important role in continuous casting, especially when casting crack-sensitive steel grades. To study the thermal state of a continuously cast slab, two methods can be used: empirical correlation of numerous experimental results and mathematical simulation models supported by experimental results. It is dif-

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ficult and inaccurate to measure, at least inside the spray chamber, cast slab temperatures or shell thickness during casting. Moreover, the empirical models cannot be used to extrapolate the results outside the experimental range, and generally they cannot be used for simulation of transient casting conditions. Mathematical models, on the other hand, once verified are easy to use and comprehensive in simulating the thermal state of the cast slab [3]. During the last decades, many mathematical heat-transfer models for continuous casting have been developed [1-7]. However, some of these models can be used only for simulation of steady state casting operation in off-line. They give the cast strand temperature field as a function of casting parameters, such as the casting speed, superheat, mould heat removal, spray water flow rates, steel grade, and cast strand geometry. Although the steady state models provide important date for the operational limits of the continuous casting machine, they are not valid for simulation of transient casting conditions which occur rather frequently. In recent years, for better control of heat transfer over the whole continuous casting cycle, attention has recently been focused on developing real-time simulation models which are valid under transient casting conditions [3-7]. The computing time must, for instance, be short enough and the special process conditions, such as the start and the end of casting, must be included in the model. The great number of phenomena in the continuous casting process of steel, especially of large-size cast slabs, necessitates the need for continuous research in particular, in a cast of new steel grades. Thus, there is a need for the formulation of coupled mathematical models that take into account the many phenomena occurring in the continuous casting process of steel [4-5]. Fluid flow is very important to quality in the continuous casting of steel. With the high cost of empirical investigation and the increasing power of computer hardware and software, mathematical modeling is becoming an important tool to understand fluid flow phenomena [5-7]. These papers reviews developments in modeling phenomena related to fluid flow in the continuous casting mould region, and the resulting implications for improving the process. From the viewpoint of the intensity of a molten metal motion in the continuous cast slab, great important have a nozzle position relative to the axis of a continuous casting mould and a type of nozzle [7-9]. In these works were analysed various options for setting nozzles: a nozzle in the center of mould, an asymmetrical nozzle, two symmetrical nozzles and two types of nozzles: a straight nozzle (vertical) and a radial flow nozzle (horizontal). These investigators have shown that radial flow or bifurcated nozzles appear to provide the most favorable conditions for the flotation of inclusions.

The aim of the paper is to estimate, by numerical simulation method, the effect of a molten metal motion and the manner of pouring on: the thermal field and the solid phase growth kinetics, within the rectangular cast slab in successive stages of its formation. Mathematical and numerical models of growth of solid metal phase within a cast slab in which we took into consideration the molten metal motion and the changes of thermophysical parameters depending on the temperature and the solid phase volume fractions in the mushy zone are presented in this paper. For the flowing liquid metal, the constant flow intensity on the inlet to the continuous casting mould is assumed, and has been used to calculate the casting 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. The thermal and fluid flow phenomena, which proceed in the considered system from the moment of continuous casting mould pouring by molten metal until the starter bar leaves the cast slab control area, were analysed. 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 solution of the problem. Continuous cast strand of rectangular cross-sections was analysed. The problem was solved by the finite element method [3,4,7,10,11].

2. Mathematical heat-transfer model

The proposed model for numerical simulation of the solid phase growing process within continuous casting mould is based on solving the Fourier-Kirchhoff system of equations with the convection term [3,4,7,10,11]. These equations describe the heat flow in the region $\Omega_C \cup \Omega_S \cup \Omega_L$ (continuous casting machine, solid phase, liquid phase) (Fig. 1):

$$\rho c \left(\frac{\partial T(\mathbf{x}, t)}{\partial t} + \nabla T \cdot \mathbf{v} \right) = \nabla \cdot (\lambda \nabla T) + \dot{Q} \tag{1}$$

where: T – the temperature [K], t – time [s], $\rho = \rho(T)$ – the density [kg/m^3], $\dot{Q}$ – the volumetric efficiency of the internal heat source [W/m^3], c - the specific heat [J/(kgK)], 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].

In the used model of solid phase growth, in the equation of heat conductivity the internal heat sources do not come forth evidently, therefore differential equation (1) assumes in the form [5,7-9]:

$$\nabla \cdot (\lambda \nabla T) - C_{ef}\frac{\partial T}{\partial t} - C_{ef}\nabla T \cdot \mathbf{v} = 0, \tag{2}$$

where: $C_{ef}(T) = \rho_{LS}c_{LS} + \rho_S L/(T_L - T_S)$ – 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)], ρ_S,ρ_L,ρ_{LS} – the density of solid phase, liquid phase, and mushy zone, respectively [kg/m^3].

3. Mathematical model of a liquid metal flow

The superheated metals and their alloys in the liquid state can be treated as Newtonian fluids [7,9-12], therefore the authors of the paper use the system of equations which describes the laminar flow of the viscous incompressible fluid (the Navier-Stokes equations and the continuity equation) [6,7,9-12]:

$$\rho\frac{d\mathbf{v}}{dt} = \rho\mathbf{g} - \nabla p + \mu\nabla^2\mathbf{v}, \qquad \nabla \cdot \mathbf{v} = 0\ , \tag{3}$$

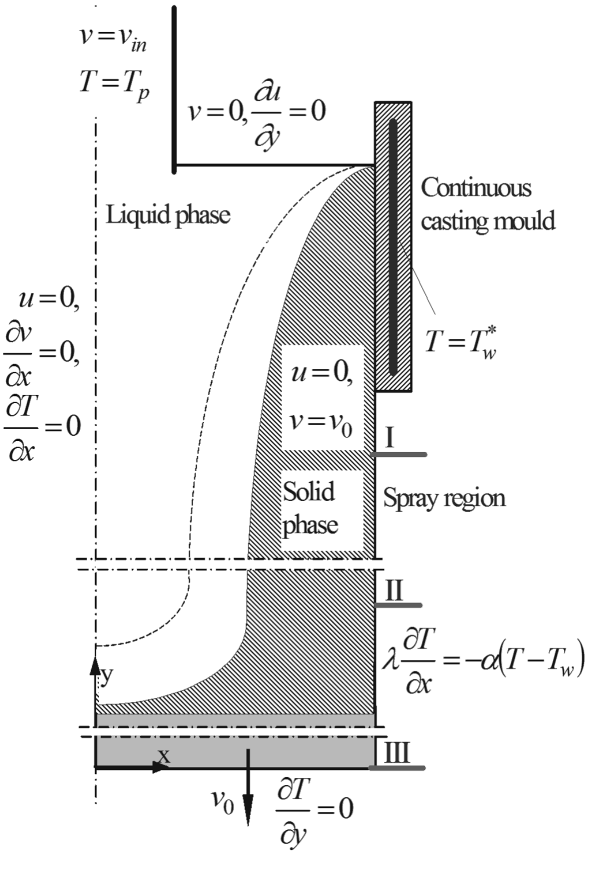

Fig. 1. Region and boundary conditions assumed in the problem under study

where: p – the pressure [N/m^2], $\mu(T)$ – the dynamical viscosity coefficient [Ns/m^2], $\mathbf{g}$ – the vector of the gravity acceleration [m/s^2].

The equations above and the equation of heat conductivity (2) create a closed, coupled system of equations describing the laminar flow of the fluid. In the paper this system is uncoupled when: the velocity field $\mathbf{v}=\mathbf{v}(\mathbf{x},t)$ is obtained from equation 3, whereas the thermal field $T=T(\mathbf{x},t)$ is calculated from equation 2. The equation of heat conductivity (2), the continuity equation and Navier-Stokes equations (3) are completed by the initial conditions and the classical boundary conditions which are shown in Figure 1.

4. Numerical simulations

The calculations were performed for the continuous casting mould with rectangular cross-section (0.3x1), length (0.7[m]) and the control length of the continuous cast slab equals to 2.9[m]. Assuming casting speed v_0 = 0.01[m/s], the liquid steel velocity (v_{in}) on the inlet to the continuous casting mould was calculated from the continuity condition. The thermophysical properties of a cast steel were taken from works [9-11]. The characteristic temperatures of a molten steel were equal to: T_p=1820[K], T_L =1800[K], T_S =1760[K], whereas the cooling water T_w^*=303 [K], T_w =300 [K]. The heat-transfer coefficient (α) between cast slab and cooling water changed depending on length of the cast slab in range value as α =1100-750[W/(m^{2}K)] [4,7,10]. The thermal and fluid flow phenomena, proceeding in the considered system from the moment of continuous casting mould pouring by molten metal until the starter bar leaves the cast slab control area, were analysed. The authors examined the the effect of a molten metal motion and the manner of pouring on: the thermal field and the solid phase growth, within the rectangular cast slab in successive stages of its formation. This problem was analysed by a complex model (Figs 2-7) and the simplified model (Fig. 8) in which the conduction equation was solved only. A numerical simulation of the cast slab solidification process was made for three cases of a continuous casting mould pouring by molten metal: the horizontal-central pouring (Figs 2,3), the vertical-central pouring (Figs 4,5) and the vertical-non central pouring (Figs 6,7) respectively. We studied also the penetration depth of the jet issuing from the horizontal and vertical nozzles. The influences of cases of the continuous casting mould pouring on the velocity fields in liquid phase and the solid phase growth kinetics of the cast slab were estimated, because these magnitudes have essential an influence on high-quality of a continuous steel cast slab [6,8,9]. Information concerning solid phase growing rate allows one to predict also the type of the casting steel structure. Examples of calculation results are shown in the form of the temperature and velocity fields.

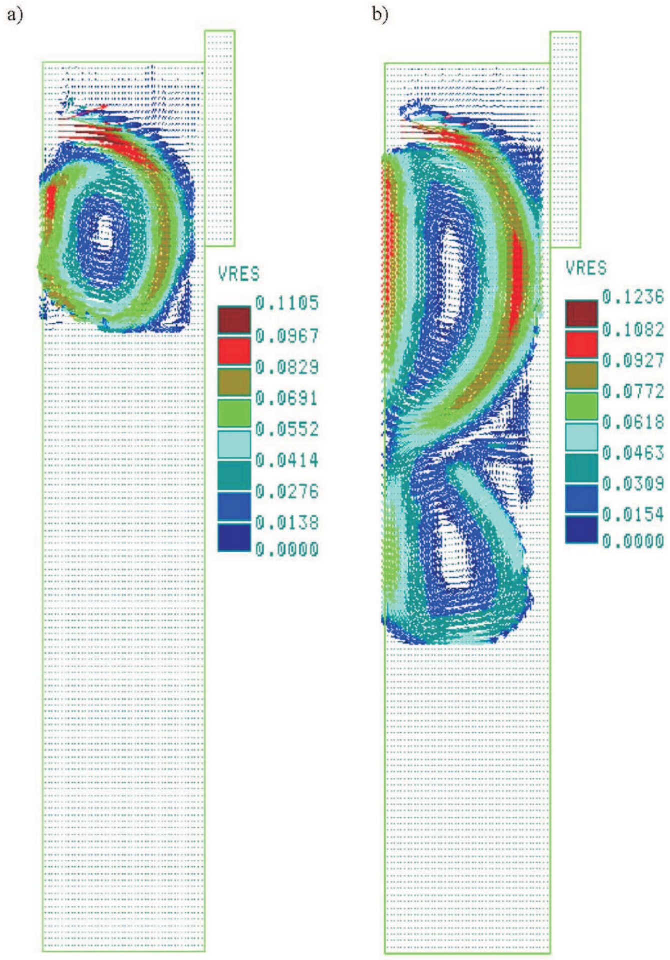

Fig. 2. Velocity vectors when the face of melt metal reached: a) I level (t=100s), b) II level (t=200s); horizontal-central pouring, complex model

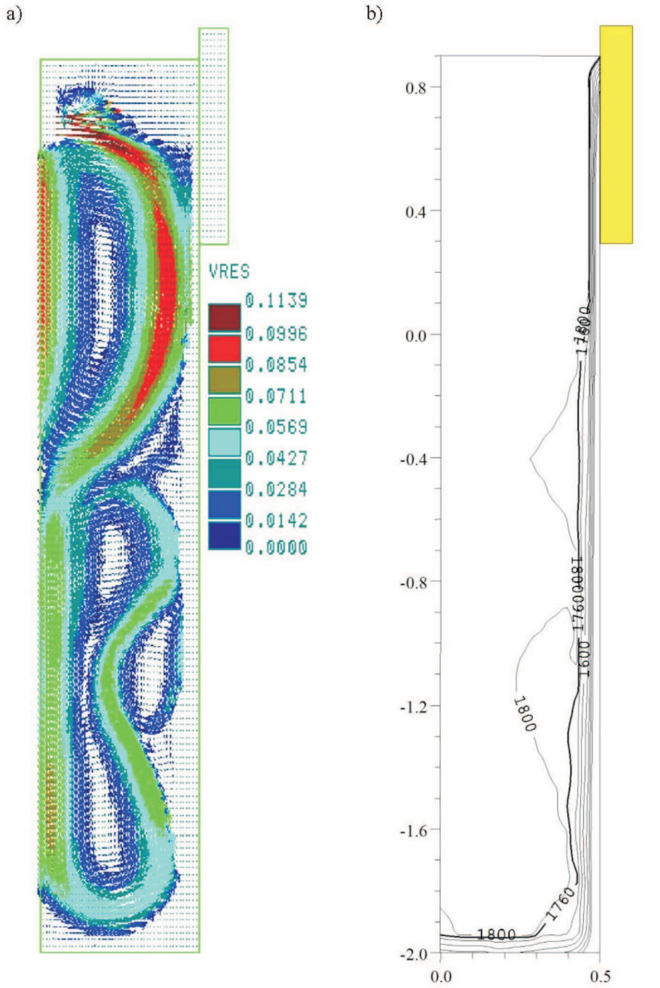

Fig. 3. Velocity vectors (a) and temperature isolines (b) when the face of melt metal reached III level (t=300s); horizontal-central pouring, complex model

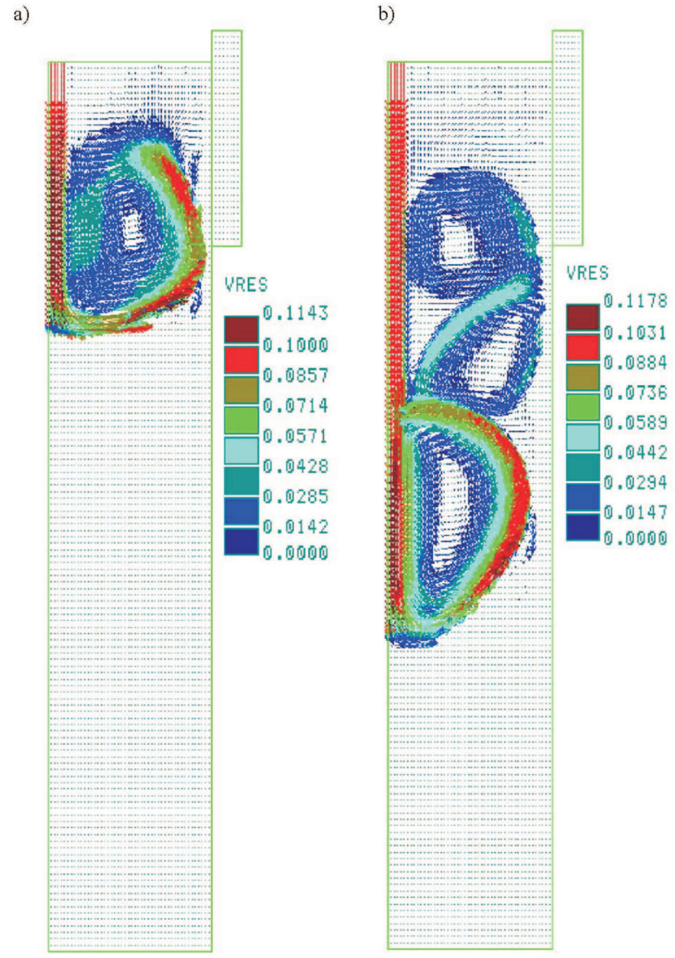

Fig. 4. Velocity vectors when the face of melt metal reached: a) I level (*t*=100s), b) II level (*t*=200s); vertical-central pouring, complex model

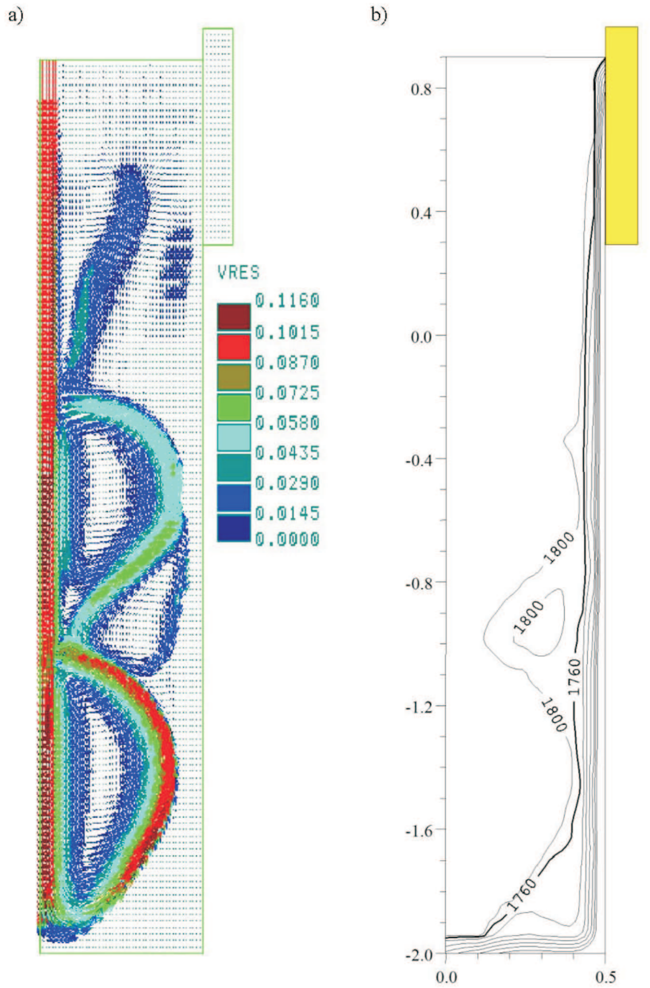

Fig. 5. Velocity vectors (a) and temperature isolines (b) when the face of melt metal reached III level (*t*=300s); vertical-central pouring, complex model

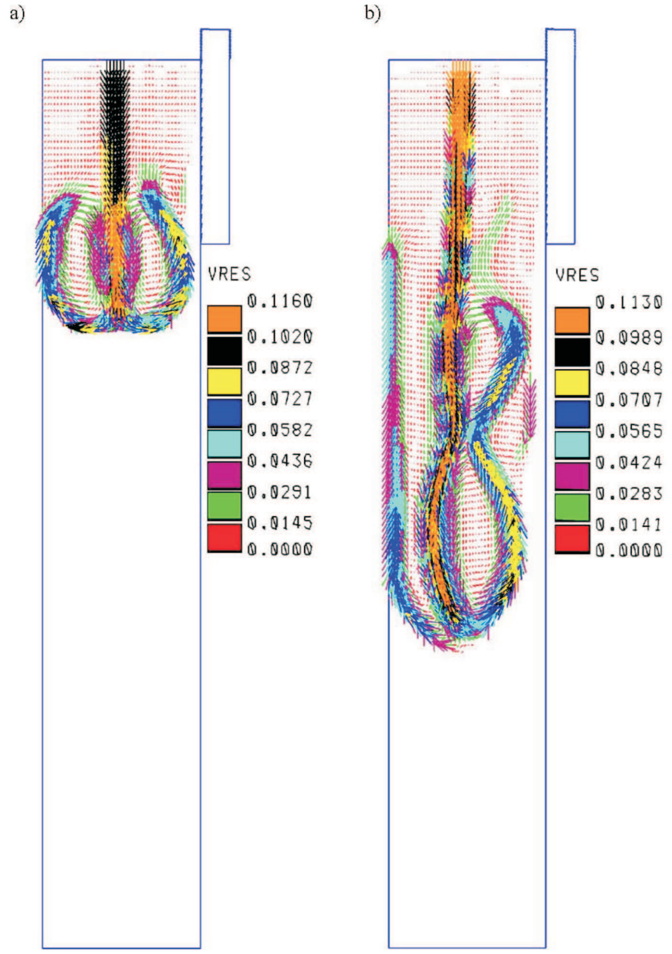

Fig. 6. Velocity vectors when the face of melt metal reached: a) I level (*t*=100s), b) II level (*t*=200s); vertical-non central pouring, complex model

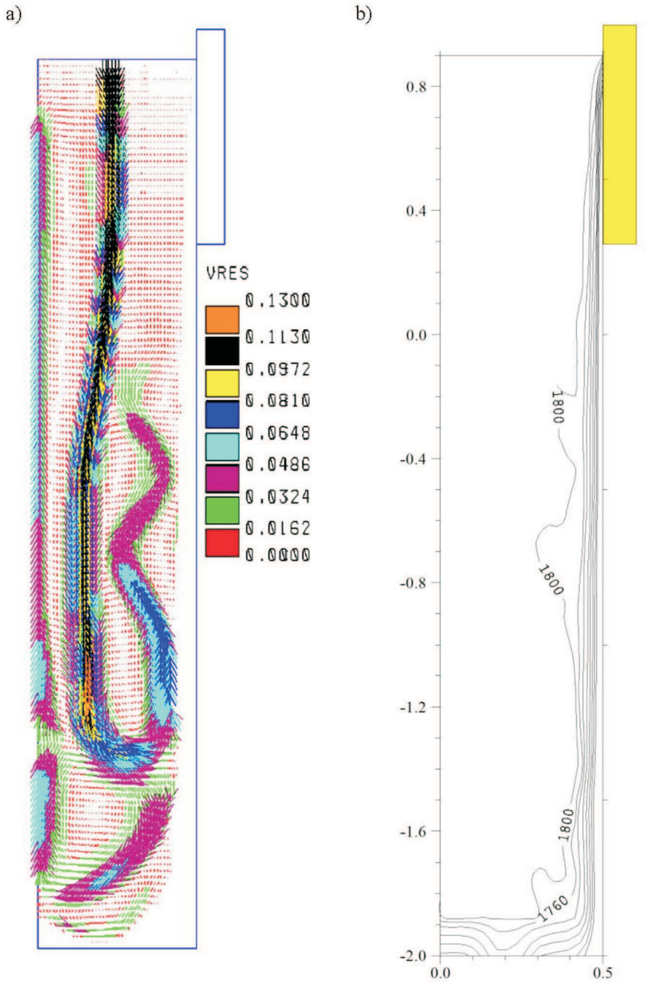

Fig. 7. Velocity vectors (a) and temperature isolines (b) when the face of melt metal reached III level (*t* =300s); vertical-non central pouring, complex model

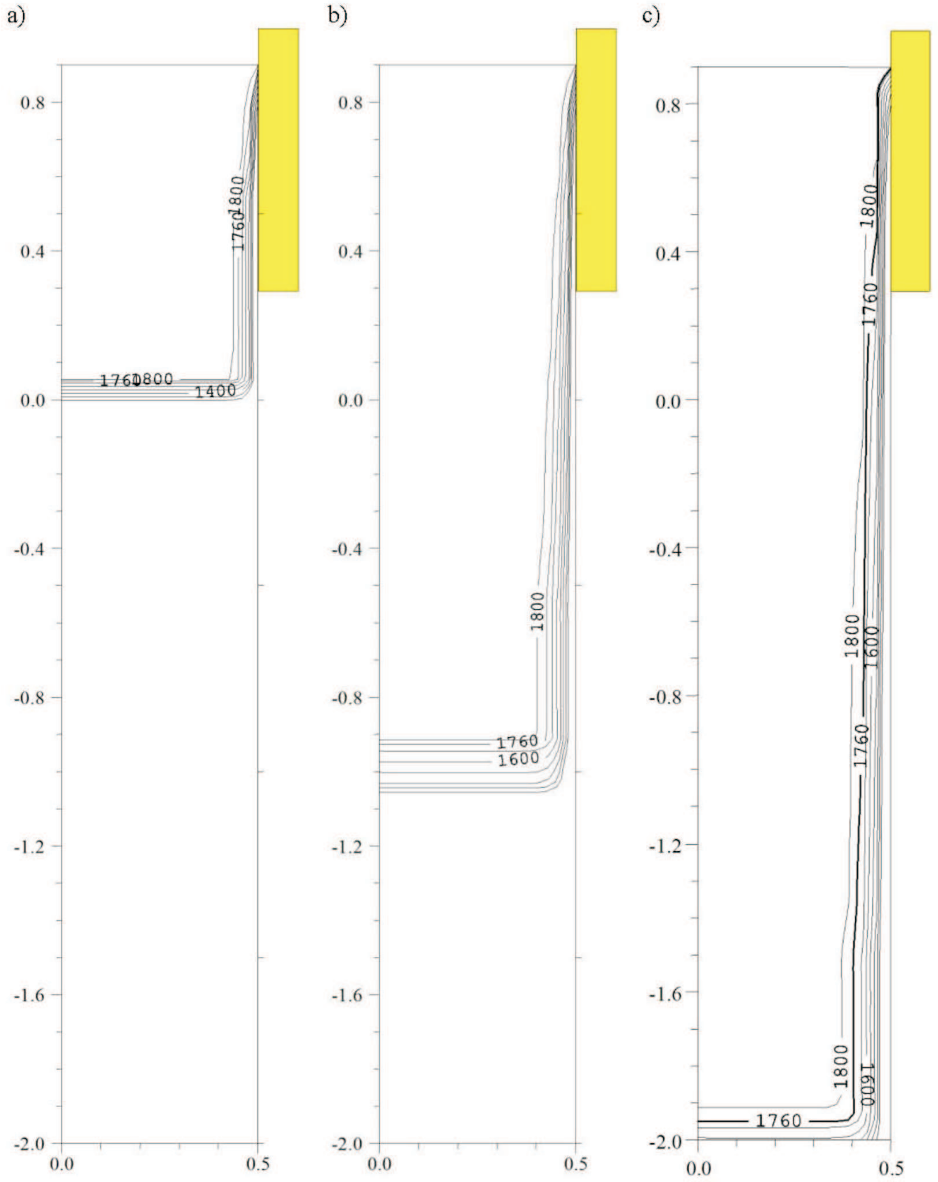

Fig. 8. Temperature isolines when the face of melt metal reached: a) I level (*t*=100s), b) II level (*t*=200s), c) III level (*t*=300s); simplified model

5. Conclusions

This paper presents the coupled model of solidification for the transient evaluation of fluid flow and heat transfer during continuous casting processes. This problem was analysed by a complex model and the simplified model. It was noted that the velocity field of a liquid phase has a significant influence on the temperature field and thus the formation of the solid phase in the continuous cast slab. The solidified layer has a thickness non-uniform in the length of continuous cast slab, which is caused by fluid movement. Using the simplified model does not notice this phenomenon, which can be mistaking in the assessment of solid phase thickness by using only those results (Figs 3,5,7 and 8).

A numerical simulation of the cast slab solidification process was made for different cases of continuous casting mould pouring by molten metal. The influences of cases of the continuous casting mould pouring on the velocity fields in liquid phase and the solid phase growth kinetics of the cast slab were estimated. On the base of a numerical simulation of a solid phase growth in the continuous cast slab, we can draw the conclusion that there are no essential differences in the shape and thickness of the solid phase set on the continuous casting mould walls in the case of the vertical-central pouring and horizontal-central pouring (Figs 3,5 and 7). Changes in the pouring manner of the continuous casting mould result in different character of the liquid metal movement/flow within an area of the continuous cast slab (Figs 3,5,7), thereby changing the distribution of non-metallic inclusions and a slag in the cast slab. This has a considerable effect on the state of the surface and mechanical properties of the obtained cast strand [7-9]. The magnitude of rotations and the level of velocity values are also dependent on the casting rate [6]. We studied also the penetration depth of the jet issuing from the horizontal and vertical nozzles. It was noted that vertical flow nozzles were found to penetrate the liquid phase to a much greater depth and led to the undesirable downward flow of the metal. The actual numerical data on the velocities indicate that the flow field in the horyzontal flow nozzles appears to be preferable for promoting the flotation of inclusions.

Acknowledgements

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