ARCHIVES

Of

FOUNDRY ENGINEERING

Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences

ISSN (1897-3310)
Volume 11
Special Issue
2/2011
199–202

39/2

Effect of nozzle outlet angle on flow and temperature field in a slab continuous casting mould

L. Sowa
Institute of Mechanics and Machine Design, Częstochowa University of Technology,
73 Dąbrowskiego str. 42-200 Częstochowa, Poland
Corresponding author. E-mail: sowa@imipkm.pcz.czest.pl

Received 11.04.2011; Approved for print on: 26.04.2011

Abstract

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. 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 effect of nozzle outlet angle on the velocity fields in liquid phase and the solid phase growth kinetics of the cast slab were investigated, because these magnitudes have essential an influence on high-quality of a continuous steel cast slab.

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

1. Introduction

The continuous casting process is now well recognized as a standard process in the production slabs in most steelmaking plants. This process has been developed rapidly because it has better productivity and heat effectiveness. However, the solidified shell is subjected to varying thermal and mechanical load during the solidification process, which can cause a number of defects in the cast products. It is possible to improve the quality of the steel by evaluating the effects of the process variables such as the casting speed, casting temperature, and the cooling condition and solving the problems form these effects [1]. On the other hand, control of the liquid pool length is a key element in optimizing the casting speed with respect to a good level of productivity. Thus, heat transfer plays a very important role in continuous casting, especially when casting crack-sensitive steel grades. Mathematical models, on the other hand, once verified are easy to use and comprehensive in simulating the thermal state of the cast slab [2]. During the last decades, many mathematical heat-transfer models for continuous casting have been developed [1-8]. However, some of these models can be used only for simulation of steady state casting operation in off-line. 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 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 [3,4]. 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 modelling is becoming an important tool to understand fluid flow phenomena and the resulting implications for improving the process [4-6]. 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 [6-8]. In these works were analyzed various options for setting nozzles: a nozzle in the centre 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 favourable conditions for the flotation of inclusions.

The aim of the paper is to estimate, by numerical simulation method, the effect of molten metal motion and manners of pouring (three angles of nozzle outlet) on the thermal field and the solid phase growth kinetics, within the rectangular cast slab in successive stages of its formation. 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 momentum 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 problem was solved by the finite element method [3,6,9,10].

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

The proposed model for numerical simulation of the solid phase growing process within continuous casting mould is based on solving the Fourier-Kirchhoff equation with the convection term [3,6,7,9,10]. This equation describes the heat transfer in the region of a continuous casting machine, solid phase and liquid phase respectively (Fig. 1):

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

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 [4,6-9]:

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

where: $C_{ef}(T)=\rho_{LS}c_{LS}+\rho_S L/\left(T_L-T_S\right)$ - 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].

The superheated metals and their alloys in the liquid state can be treated as Newtonian fluids [7,9-12], 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) [5-8,10-11]:

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

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].

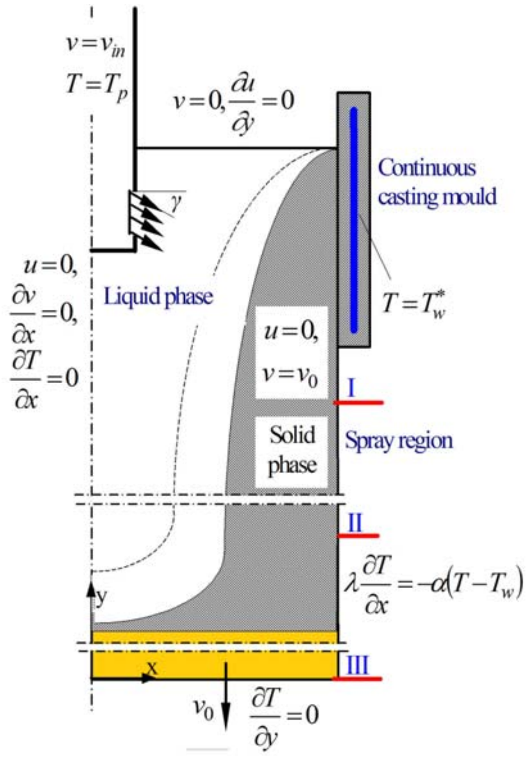

Fig.1. Region and boundary conditions assumed in the problem under study

In this paper the closed and coupled system of equations 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. Example of numerical calculations

The calculations were performed for the continuous casting mould with rectangular cross-section (0.3x1), length (0.7[m]) and the control length of a continuous cast slab equals to 2.9[m].

a) b)

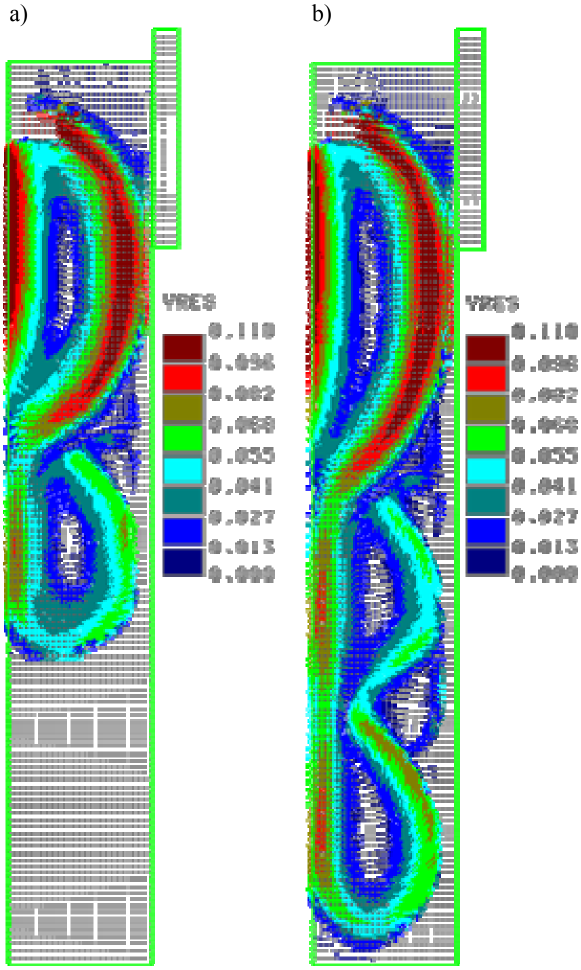

Fig.2. Velocity vectors when the face of melt metal reached: a) II level (t=100s), b) III level (t=200s); $\gamma=0^0$

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 [8-11]. The characteristic temperatures of molten steel were equal to: T_p=1830[K], T_L =1810[K], T_S =1760[K], whereas the cooling water T_w^*=303 [K], T_w=300 [K]. The heat-transfer coefficient (α) between the cast slab and cooling water changed depending on length of the cast slab in range value as α=1100-750[W/(m^{2}K)] [3,6,9]. 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 liquid steel motion in the casting mould caused by the dynamic forces resulting from the liquid steel leaving the submerged nozzle has been computed. In this study, three nozzle outlet angles (γ) were evaluated. They were equal to 0^0, 30^0 and -30^0 (Fig.2, 3). We studied also the penetration depth of a metal jet flowing from the horizontal and vertical nozzles [6]. 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 [5,7,8]. 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 velocity fields (Fig.2,3).

a) b)

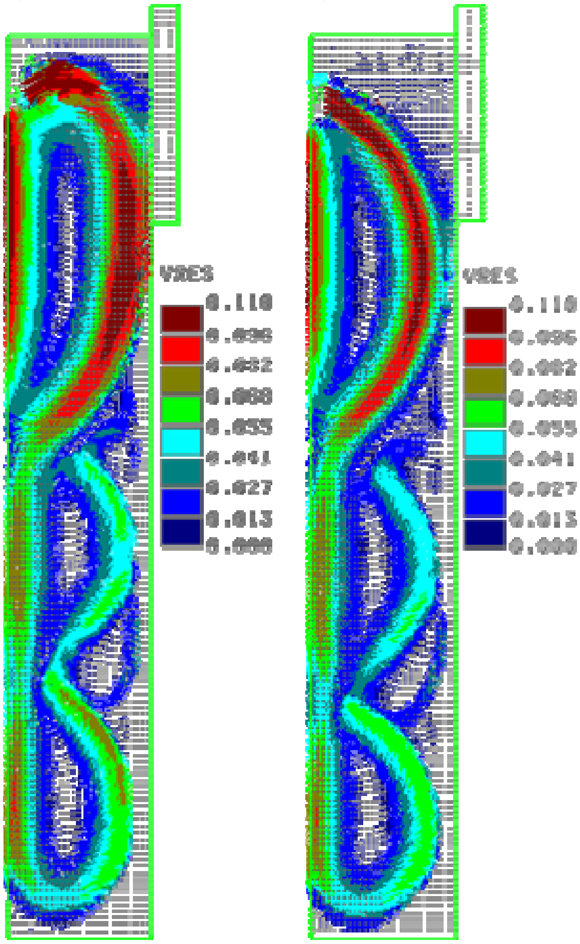

Fig.3. Velocity vectors when the face of melt metal reached level III (t=200s): a) $\gamma=+30^0$, b) $\gamma=-30^0$

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 numerical 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. A numerical simulation of the cast slab solidification process was made for different cases of continuous casting mould pouring by molten metal as a result of the various nozzle outlet angles. 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 and horizontal pouring. 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, 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 [6-8]. The magnitude of rotations and the level of velocity values are also dependent on the casting rate [5]. We studied also the penetration depth of the metal jet issuing from the submerged nozzle. It was noted that vertical flow nozzles were found to penetrate the lequd 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 horizontal flow nozzles appears to be preferable for promoting the flotation of inclusions.

Acknowledgements

This work has been supported by Ministry of Science and Higher Education.

References

[1] A. Fic, A.J. Nowak, R. Bialecki, Heat transfer analysis of the continuous casting process by the front tracking BEM, Engineering Analysis with Boundary Elements, vol. 24, (2000) 215–223.

[2] S. Louhenkilpi, M. Makinen, S. Vapalahti, T. Raisanen, J. Laine, 3D steady state and transient simulation tools for heat transfer and solidification in continuous casting, Materials Science and Engineering, A413-414, (2005) 135-138.

[3] L. Sowa, Numerical analysis of solid phase growing in a continuous steel caster, ZAMM, vol. 76, (1996) 491-492.

[4] S.K. Choudhary, D. Mazumdar, Mathematical modelling of transport phenomena in continuous casting of steel, ISIJ International, vol. 34, No. 7 (1994) 584-592.

[5] B.G. Thomas, L. Zhang, Mathematical modelling of fluid flow in continuous casting, ISIJ International, vol. 41, No. 10 (2001) 1181–1193.

[6] A. Bokota, L. Sowa, Numerical modelling of solidification of the cast slab at the beginning of continuous casting process, Acta Metallurgica Slovaca, vol. 8, No. 2 (2002) 245-249.

[7] W. Kapturkiewicz, A.A Burbelko, Modelling of semicontinuous and continuous casting of steel with using of own and professional programs, Archives of Foundry, vol. 1, No. 2 (2001) 185-192 (in Polish).

[8] B. Zhao, B.G. Thomas, S.P. Vanka, R.J. Omalley, Transient fluid flow and superheat transport in continuous casting of steel slabs, Metallurgical and Materials Transactions B, vol. 36, (2005) 801-823.

[9] B. Mochnacki, J.S. Suchy, Numerical methods in computations of foundry processes, Polish Foundrymen's Technical Association, Krakow 1995.

[10] L. Sowa, N. Sczygiol, Computer simulation of the filling and solidification of a gravity die casting, Solidification of Metals and Alloys, vol. 2, No. 44 (2000) 329-334.

[11] T. Telejko, Z. Malinowski, M. Rywotycki, Analysis of heat transfer and fluid flow in continuous steel casting, Archives of Metallurgy and Materials, vol. 54, No. 3 (2009) 837-844.

Wpływ kąta wypływu dyszy na pole prędkości i temperatury w krystalizatorze ciągłego odlewania wlewków płaskich

Streszczenie

W pracy przedstawiono model matematyczny i numeryczny narastania fazy stałej we wlewku ciągłego odlewania. Zadanie potraktowano kompleksowo. Pola prędkości otrzymano z rozwiązania równań pędu 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. Problem rozwiązano metodą elementów skończonych. Analizie poddano krystalizator o przekroju prostokątnym. Symulacje numeryczne procesu krzepnięcia wlewka wykonano dla różnych wariantów doprowadzenia ciekłego metalu do krystalizatora (różne kąty wypływu strumienia ciekłego metalu z dyszy wylewu zanurzonego). Badano wpływ zalewania krystalizatora na pole prędkości w fazie ciekłej i kinetykę narastania fazy stałej wlewka ciągłego odlewania.