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ANALYSIS OF HEAT TRANSFER AND FLUID FLOW IN CONTINUOUS STEEL CASTING

ANALIZA WYMIANY CIEPŁA I RUCHU CIEKŁEJ STALI W PROCESIE CIĄGŁEGO ODLEWANIA STALI

The paper presents three mathematical and numerical models of heat transfer during continuous steel casting. The models differ from each other in the description of convection heat transfer in the liquid steel. The calculated temperature profiles in the strand and casting mould are compared and discussed. The first model involves the total mass movement of the continuous strand expressed by the average velocity equal to casting speed. In the second the convection heat transfer is simulated by the equivalent (increased) thermal conductivity of the non solidified steel, while the third includes the two dimensional steel movements in the liquid region of the continuous strand. For temperature calculations Fourier Kirchhoff equation has been applied. The velocity profile in the liquid region and in the solidifying shell has been calculated from the Navier Stokes equations coupled with the mass continuity equation. The calculations have been performed for the square strand 160×160mm in side. The problem has been solved using the finite element method.

Keywords: continuous steel casting, numerical modeling, finite element method

W artykule przedstawiono trzy modele wymiany ciepła zachodzącej podczas procesu ciągłego odlewania stali. Modele różnią się od siebie opisem konwekcyjnej wymiany ciepła w ciekłej stali. W pierwszym uwzględniono ruch masy wlewka ciągłego na podstawie średniej prędkości odlewania. W drugim efekt konwencji symulowano na drodze zastosowania tzw. efektywnego współczynnika przewodzenia ciepła w fazie ciekłej, zaś w trzecim obliczano pole prędkości na podstawie uproszczonego modelu numerycznego. Pola temperatury wyznaczono z równania Fouriera – Kirchhoffa, a pola prędkości z równań Naviera – Stokesa. Porównano i poddano analizie wyznaczone z ich wykorzystaniem pola temperatury we wlewku i krystalizatorze. Obliczenhia przeprowadzono dla krystalizatora o wymiarach 160 × 160 mm. Problem został rozwiązany metodą elementów skończonych.

1. Introduction

The solidification of the continuous strand during continuous steel casting is the complex process of heat and mass transfer. Many mathematical models has been developed to investigate the various phenomena accompanying steel solidification [1,2]. One of the most important parameters affecting these phenomena is temperature. Therefore all the models must take temperature under consideration in calculations.

Heat from the liquid steel is transferred by the solidified shell and the gap to the mould surface and subsequently to the cooling water. The superheated metal is poured into a mould and intensifies convection heat transfer due to the mass movement along with the conduction in the liquid region. Afterwards conduction takes place in the shell and mixed radiation conduction model is usually used for heat transfer in the air gap. Convection-conduction interaction in the liquid pool can be described by the Fourier – Kirchhoff and Navier – Stokes equations. Solution of the set of differential equations allows to get the temperature and velocity profiles, but such a way of modeling creates difficulties in numerical calculations. To avoid this some simplifications are usually involved in the mathematical models. The most popular is to include the convective heat flow into conduction mechanism by using the arbitrary increased thermal conductivity (effective conductivity) and assuming velocity profile equal to zero in the Fourier Kirchhoff equation [3, 4]. Sometimes the average velocity of the steel movement equal to the casting velocity is involved into the mathematical model [5].

In order to determine the influence of simplifications in considering heat convection in liquid pool on the temperature profile in the strand and the mould three mathematical models of heat flow are discussed. The re-

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sults of numerical simulations are presented. They were obtained using the developed by the authors computer program based on finite element method.

2. Mathematical formulation

2.1. The temperature profile in the strand

The temperature profile in solidifying steel has been calculated from the equation of heat conduction with the convective component. Assuming thermal conductivity λ constant against temperature it can be written in the following form

$$\frac{\partial T}{\partial \tau} + \vec{v} gradT = \frac{\lambda}{c\rho}\nabla^2 T + \frac{q_v}{c\rho}, \tag{1}$$

where T – temperature, τ – time, v – velocity, λ – thermal conductivity, q_v – internal heat generation per unit volume (heat of solidification), ρ – density, c – heat capacity.

The velocity profile has been obtained from Navier-Stokes equations coupled with continuity equation. Generally, they are as follows

$$\rho\frac{d\left(\vec{v}\right)}{d\tau} = \rho\,\vec{g} - gradp + \mu\vec{\Delta}, \quad v\nabla\vec{v} = 0 \tag{2}$$

where p – pressure, $\vec{v}$ – velocity, τ – time, ρ – density, μ – dynamic viscosity, g – acceleration of gravity.

In the analysis the action of the steel stream in the nozzle on the liquid pool has been considered, so the component containing gravity might been omitted.

To investigate the temperature and velocity profiles the 3 D transient FEM model has been developed by the authors. The symmetry of the solidification process has been assumed, so the calculations have been limited to the one quarter of the strand volume.

The third order boundary condition has been declared for temperature calculations. The heat flux densities at the strand mould (q_{sm}) and the strand surrounding (q_{sf}) interfaces were obtained from the simple relations

$$q_{sm} = \alpha_{sm}(T_s - T_m) \in \mathrm{S}_{sm} \tag{3}$$

$$q_{sf} = \alpha_{sf}(T_s - T_f) \in \mathrm{S}_{sf}, \tag{4}$$

where: α_{sm} – heat transfer coefficient at the strand-mould interface, T_s – strand surface temperature, T_m – mould surface temperature, S_{sm} – area of interfacial heat transfer in the mould, α_{sf} – heat transfer coefficient at the strand sorroundings interface in the spray region, T_f – ambient temperature, S_{sf} – area of interfacial heat transfer in the spray region.

Heat transfer in the air gap between the mould and solidified steel shell has been modeled considering radiation between the strand and mould surfaces and conduction through the gap.

The total heat transfer coefficient in the gap α_{sm} is a sum of the radiation α_r and the conduction α_c components

$$\alpha_{sm} = \alpha_r + \alpha_c. \tag{5}$$

The radiation component has been calculated from Stefan Boltzmann law for the infinite parallel planes

$$\alpha_r = 5.67 \cdot 10^{-8}\frac{\varepsilon_s + \varepsilon_m - \varepsilon_s\varepsilon_m}{\varepsilon_s\varepsilon_m}\frac{T_s^4 - T_m^4}{T_s - T_m} \tag{6}$$

and the conduction one – from the empirical equation [6]

$$\alpha_c = (\alpha_l - \alpha_r)\exp\left(\frac{T_s - T_{so}}{200}\right), \tag{7}$$

where ε_s – strand surface emissivity, ε_m – mould surface emissivity, T_{so} – solidus temperature, K.

At the liquid metal-mould interface the constant value of the heat transfer coefficient equal to α_l = 1500 W/(m^2·K) [7] has been declared. The steel meniscus is assumed to have temperature equal to t_{in}=1520°C. The boundary conditions involved in the model for the velocity profile determination are shown in Figure 1.

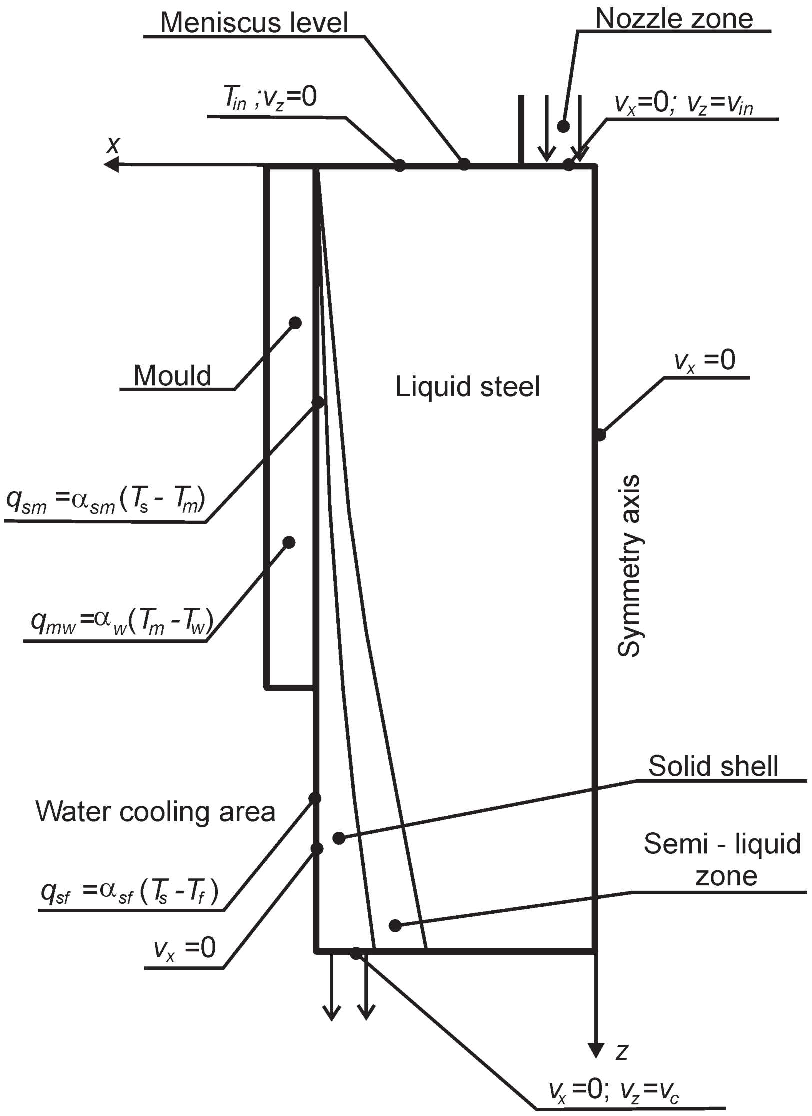

Fig. 1. Schema of the control volume and applied boundary conditions

3. The temperature profile in the mould

Determination of the boundary conditions at the strand mould interface requires temperature of the mould surface to be known. It can be calculated from Fourier-Kirchhoff equation (1) assuming velocities and heat generation equal to zero. The transferred heat flux densities were obtained using the relation (3) for strand-mould interface and (8) for mould cooling water interfaces respectively.

$$q_{mw} = \alpha_{mw}(T_m - T_l) \in \mathrm{S_w}, \tag{8}$$

where: α_{mw} – heat transfer coefficient at the mould cooling water interface, T_m – water-cooled mould surface temperature, T_w – cooling water temperature, S_w – area of the water cooled mould surface.

Heat transfer coefficient mw has been determined from the well known relation governing forced convection in tubes [6]

$$Nu = 0.021\mathrm{Re}_l^{0.8}\,\mathrm{Pr}_l^{0.43}\left(\frac{\mathrm{Pr}_l}{\mathrm{Pr}_k}\right)^{0.25}, \tag{9}$$

where subscript k refers to the water-cooled mould surface temperature, subscript l to the cooling water temperature. Water temperature was assumed to be equal to 30°C, water flow velocity in the mould channel – 4.5m/s and geometrical dimension of the channel – 4mm.

In the applied algorithm it is possible to simulate various geometrical distribution of the cooling channels made in a copper block of a continuous casting mould. The performed numerical tests allowed to fit the thermally proper design of the cooling system [8]. In the presented calculations it has been assumed, that there is one ring-shape channel around the copper block and the whole surface of the mould is cooled with the water. This condition is hard to be accomplished due to difficulties in practical realization of a cooling channel of this type, but ensures uniform and intensive transport of heat from the mould surface to cooling water. Additionally this solution affects on the temperature decrease of the copper block and elongation of working life of a caster.

4. Solution procedure

The finite element method FEM has been used to solve the presented temperature and velocity problems [9, 10]. The self developed computer program consists of the two basic elements. The temperature module based on the solution of Fourier – Kirchhoff equation (1) and the mechanical module, where velocity profiles are calculated from the Navier – Stokes equations (2).

The calculations has been performed for the square ingot 160×160mm. The 1m long part of steel ingot has been considered; 0,7m inside the mould and 0,3m below it (sprayed with water). The mould corner radius equal to 15mm has been set. The casting nozzle has been put in a central position referring to the mould. The carbon content in steel equal to C=0.35%, the solidus temperature $\mathrm{t_{so}}$=1430°C and the liquidus temperature t_{liq}=1480°C have been assumed in computations. The casting velocity applied in the computations was set to v_o=1.5m per minute. The water flux density equal to W=3dm^3/(m^2·s) has been set in a spray region. The boundary condition were refreshed at every time step $\Delta\tau$.

The computations has been carried out for the three mathematical models varying in the description of convection in liquid steel region of the strand. First model involved the case, when convection in the liquid steel has been limited to the average strand mass movement along to the mould (***model No.* I**). Strand velocity in the axial direction (z) equal to casting speed v_o has been set. Velocity vectors in the remaining directions were put equal to zero. The second model (***model No.* II**) has been extended by including to the model No I. the artificially increased thermal conductivity in the liquid pool according to the relation [3].

$$\lambda_e = \lambda_l \lfloor (1 + 6(1 - f_s)^2 \rfloor, \tag{10}$$

where λ_e is the equivalent (increased) thermal conductivity of non solidified steel, λ_l is thermal conductivity of liquid steel, f_s is a fraction of solidified steel in semi liquid region. In the third, the most expanded option (***model No.* III**), the velocity profiles are computed from the solutions of Navier – Stokes equations. To reduce the computation time the velocity profiles were refreshed at every 50 time steps of computations. The thermal conductivity of the liquid steel has been put equal to "molecular" value, like in the model No. I.

5. Results and discussion

The axis and surface temperature for the various models of heat transfer in liquid pool are presented in Figure 2. Temperature does not change along the strand axis applying models No. I and No. III. When using model No. II the temperature drop along the distance from the steel meniscus equal to about 40K can be observed. The differences in results are more evident for the strand surfaces. The highest discrepancies occur in the upper part of the mould and reach about 80K for the model No. II and No. III. It can be also seen that the temperature profiles predicted using effective thermal coefficient (model No. II) are noticeably different regarding shape and values when compared to the remaining models. The analysis of temperature profiles allows to track the solidification process. For the model No. I the formation of steel shell begins at the distance of 4mm and ends at about 11mm from steel meniscus (Figure 3), for the model No. II 12mm and 38 mm and for the model No. III 3mm and 7mm respectively. The increase of the thickness of solidified steel shell and the shape and volume of semi liquid region are strongly affected by the applied model of convection movements in steel. The distance between solidus and liquidus lines at the 1m distance from the meniscus varies between 15mm and 18mm when models No. I and No. III were used for calculations respectively. Results of computations applying model No. II show, that the semi liquid region fills up the whole cross section of the strand (except the solidified shell). The temperature and velocity profiles along the strand longitudinal section are plotted in Figures 3 and 4. Figure 5 presents the predicted temperature profile in the transverse section of the strand at the 0,7m distance from steel meniscus which is equal to the total length of the mould. The profile of solidus and liquidus lines show that the circumferential thickness of the semi liquid region evaluates from the uniform one for the model No. I, through its slight variations for the model No. II up to noticeable changes for model No. III, depending on the position at the cross section. In the last case the calculated thickness of the mushy zone in the mould corner is about twice of this obtained at the flat part of the mould wall. The neglect of liquid mass movements in model No. I and/or application of equivalent thermal conductivity of the non solidified steel (model No. II) has led to the disturbances in the determination of liquid steel volume, range of the semi liquid zone and the thickness of the solidified shell. In conclusion, results of presented calculations show, that the quality of the temperature profile determination in the continuous strand can be improved when the velocity profile is taken under consideration.

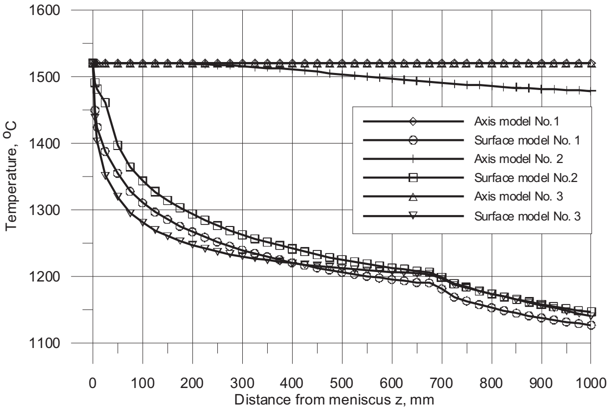

Fig. 2. Temperature profiles at the surface centerline and axis of the strand

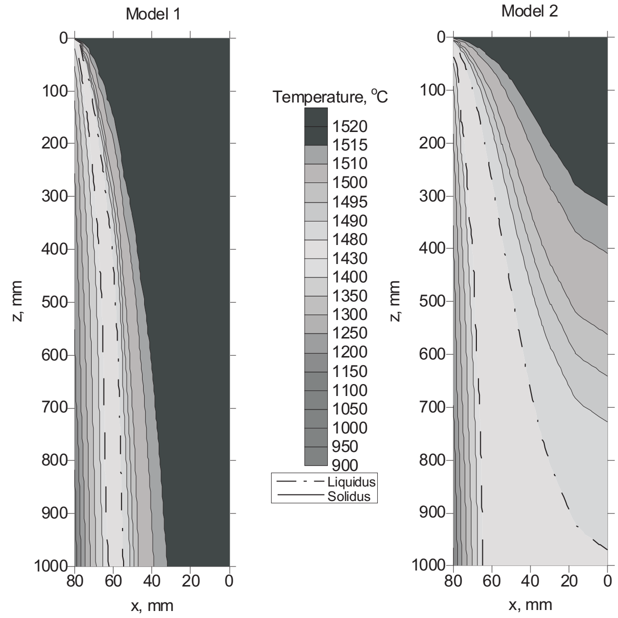

Fig. 3. Temperature profiles at the longitudinal cross section of the continuous strand obtained from models No. I and No. II

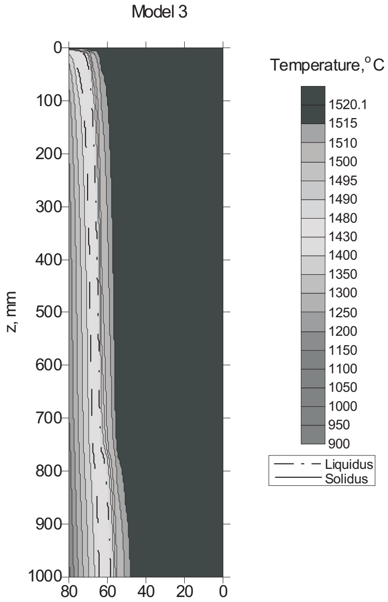

Fig. 4. Temperature profiles at the longitudinal cross section of the continuous strand obtained from model No. III

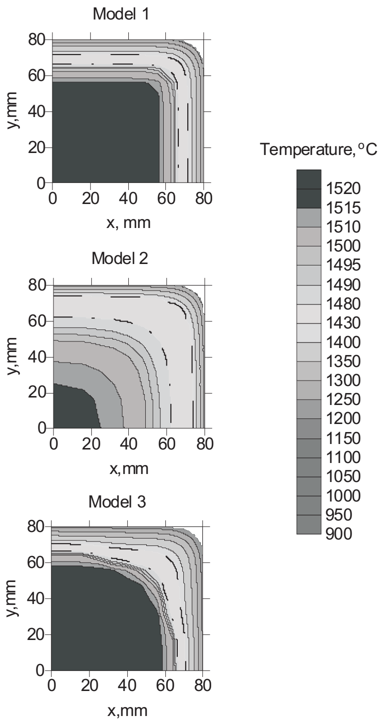

Fig. 5. Temperature profiles at transversal cross section of the strand for z=700mm.

In Figure 6 the temperature profiles in axial section of the mould are presented. The highest values of temperature equal to about 200°C are observed at the liquid mould interface for all discussed models. The air gap formation implicates the change of interfacial thermal resistance and rapid temperature drop of the mould surface along the strand axis.

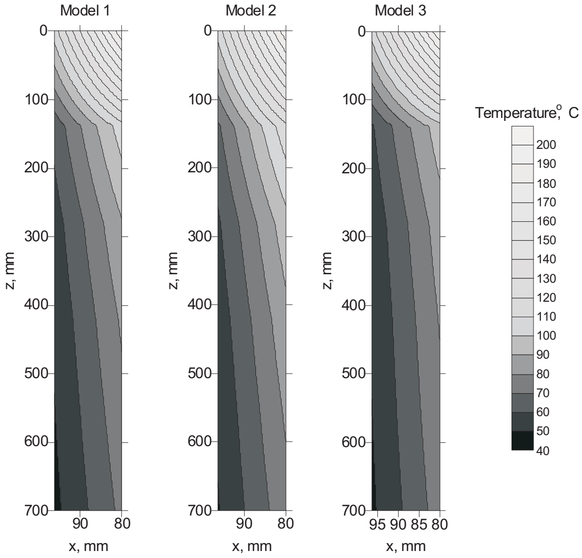

Fig. 6. Temperature profiles at longitudinal cross section of the mould

The inner surface temperature of the mold results from the surface temperature of the strand for the steady heat transfer coefficient at the mould cooling water interface. The highest mold temperature values are observed applying model No. II (Figure 7), when the thermal conductivity of the liquid phase has been increased according to the formula (10). The highest difference in mould surface temperatures has been observed at the distance of 150mm below the steel meniscus. The mould surface temperature equal to 118°C has been obtained from the model No. II, while model No. III gave the value of 95°C, which makes the 23K difference at that point. Next, the temperature difference become lower reaching the value of 4K at the mould exit.

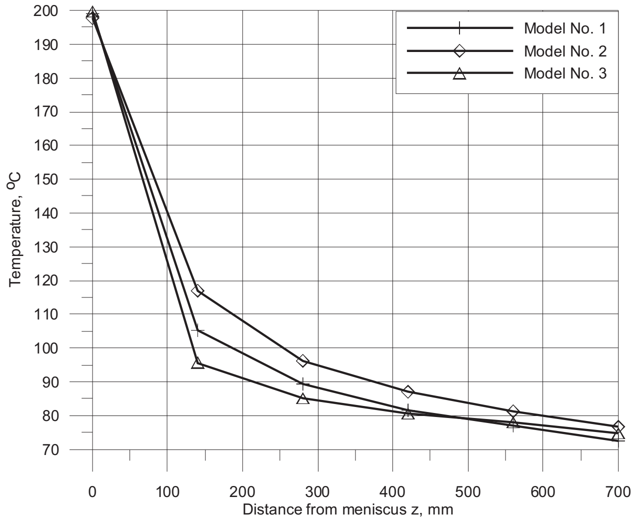

Fig. 7. Temperature profile at the surface centerline of the mould

Figure 8 shows the temperature profiles in a transverse section through the mould taken at 140mm below the meniscus. It can be noted, that the highest temperature values are predicted for the calculations performed using model No. II. In this case the surface temperature in the center line of the mould wall reaches ~117°C. The temperature in the corner is noticeably lower and equal to ~84°C. For the remaining models calculated surface mould temperature values are equal ~105°C in the center and ~80°C in the corner for model No. I and ~95°C in the center and ~71°C in the corner for model No. III respectively. The shapes of temperature curves shown in Figures 6 and 8 are similar but the different values at the respective geometrical points are observed for the various models of heat transfer in the liquid regions of the continuous strand. This confirms the impact of simplifications in modeling liquid steel flow in the continuous strand both on temperature profile in the strand itself and for temperature profiles in the mould.

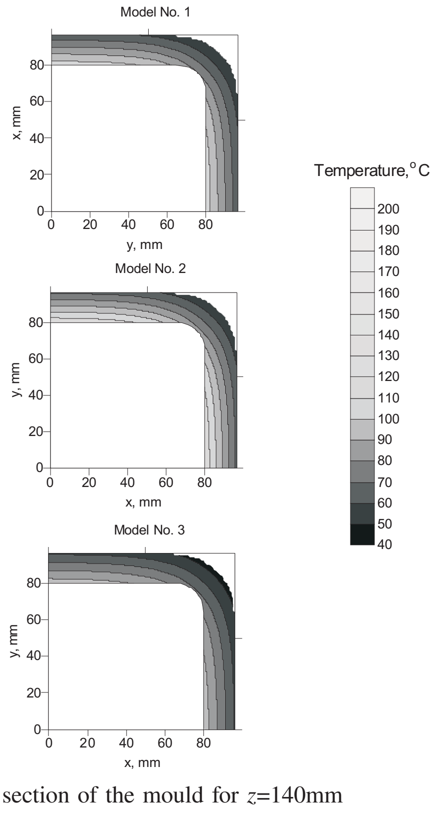

Fig. 8. Temperature profiles at transversal cross section of the mould for z=140mm

6. Conclusions

The impact of heat transfer modeling in the liquid core of the continuous strand on the temperature calculations has been discussed in the paper. Three heat transfer models have been analyzed. First the convection heat transfer in liquid steel has been considered taking into account the average velocity of the steel movement equal to the casting velocity – model No. I. In the second model convection mechanism has been intensified by arbitrary increasing the thermal conductivity of the liquid steel – model No. II. The third model is based on the solution of the velocity profile from Navier Stokes equations coupled with the temperature profile calculated from the Fourier-Kirhchoff equation- model No. III. The presented analysis clearly indicated that the temperature profile strongly depends upon the mathematical model of heat transfer in the liquid core of the continuous strand. The calculation of the velocity profile seems to be fundamental for the correctness of the temperature profiles in the strand and the mould. The simplest and popular way of simplification of the convection mechanism applied in the second model leads to noticeably different calculation results than for remaining models, including the shape and the range of the liquid and semi liquid regions. For the presented calculations the maximum disagreement in temperature exceeds 40K in the strand axis and 80K at the strand surface. This induces the differences in the thickness of the non solidified zone, which varies from the 15÷18mm at the strand centerline for models No. I and No. III up to the more than 60mm for model No. II. The results regarding thickness are given for the 1m distance from the steel meniscus.

The differences has been also observed comparing the computations for the models No. I and III. It is easy to predict that the more precise evaluation of the velocity profiles in a non solidified region of the strand shall increase the accuracy of the results of temperature profile calculations, both in the strand and in the mould. If the velocity profile in the liquid region is not available, the model involving the average mass movement gives better results and should be used to calculate the strand and mould temperature during continuous steel casting.

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