COMPARISON OF THE TEMPERATURE FIELD PREDICTION BY 2D AND 3D FINITE ELEMENT MODELS IN THE CONTINUOUS CASTING PROCESS

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Abstract

Continuous casting process of steel is very difficult to finite element modeling. Temperature computation is an important part of finite element software and has great influence on the solution accuracy. Computed temperature fields are generally qualitatively correct and it is not easy to eliminate wrong results. One of the possibilities to validate the temperature field gives the heat balance in the control volume. Two and three dimensional models of heat transfer have been tested. Stability of temperature field computation and fulfillment of heat balance have been studied for strand cooling in the continuous casting line. The two dimensional model gives the temperature only in the cross section of the strand. Three dimensional temperature field is obtained by moving the cross section into the casting direction. The three dimensional model uses steady solution to heat transfer in the control volume. Several computation tests have been carried out and the results have been compared.

1. INTRODUCTION

Heat transfer in the continuous steel casting process is very difficult to model. It is due to interaction of fluid flow and heat conduction. The problem can be treated as a steady state since there is no temperature change in time and can be well described by the convection-diffusion heat transfer equation. The finite element method is most widely used to compute the temperature field in many technical problems. However, in the case of convection dominated processes oscillatory solution are observed and convergence is not obvious. Several methods have been proposed to overcome this difficulties. One of the most popular formulation uses the non symmetric weighting functions instead of the linear shape functions. This formulation was first proposed in [1]. The method is efficient but in some cases solutions to the temperature field are not satisfactory [2]. Transient or iterative methods can be successfully employed but the computation time is generally high in the case of three dimensional problems. The internal heat source in the convection-diffusion heat transport equation makes the solution much more complicated. This issue has been addressed in work [3] and [4]. However, stable and good looking results may not be accurate. It makes the interpretation of the temperature computation results very difficult.

2. STEADY 3D HEAT TRANSFER MODEL

The heat transfer while continuous casting is a very rapid process, that involves cast metal, casting equipment and environment. To model such a process it is necessary to formulate suitable mathematical model. The most difficult is to define the boundary conditions for each type of cooling which take place in the continuous casting process. The strand temperature field while cooling in casting mould, in secondary cooling zones and in air was computed using steady solution to Fourier–Kirchhoff equation:

$$\frac{\partial T}{\partial \tau} + v_x \frac{\partial T}{\partial x} + v_y \frac{\partial T}{\partial y} + v_z \frac{\partial T}{\partial z} = \frac{\lambda}{\rho c}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + \frac{q_v}{\rho c} \tag{1}$$

where: T – temperature, K; τ – time, s; v_x, v_y, v_z – velocity field, m/s ;λ thermal conductivity, W/(m K); q_v – internal heat source, W/m^3; c – specific heat, J/(kg K); ρ – density, kg/m^3. Equation (1) describes the energy balance of a strand moving through the control volume. The internal heat source q_v represents the phase change and solidification heat. The more detailed description of the mathematical model of heat transfer has been presented in [5].

3. TRANSIENT 2D FINITE ELEMENT MODEL

The 2D finite element model is the transient solution to the heat transfer in the strand cross section:

$$\lambda\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)+q_v-\varrho c\frac{\partial T}{\partial \tau}=0 \qquad (2)$$

Three dimensional temperature field is obtained by moving the cross section from entry to exit of the control volume. The more detailed description of the 2D transient model has been presented in [6].

4. BOUNDARY CONDITIONS

Solutions to the heat transfer equations (1) and (2) require the boundary conditions on the strand surface. In the mold, on the steel – mold interface heat flux q_{sk} has been defined as:

$$q_{sk}=\alpha_{sk}(T_s-T_k) \qquad (3)$$

and below the mold as:

$$q_s=\alpha_s(T_s-T_p) \qquad (4)$$

where: T_s – strand surface temperature, T_p – air temperature or water spray temperature, T_k – mold surface temperature at the strand side , α_s – combined heat transfer coefficient for air or water spray cooling, α_{sk} – combined heat transfer coefficient on the strand – mold interface. Casting process consists of filling the mold with molten steel and its solidification. Below the meniscus level molten metal flows over the mold wall and convection is the main mechanism of heat transfer. Due to rapid cooling of the laminar layer of the liquid steel solidification starts and a gap between steel and mold is formed. For fully developed gap heat transfer mechanism changes to radiation. Thus, two boundaries for the heat transfer coefficient can be prescribed. The upper bound is defined by the convection heat transfer coefficient α_l if steel surface temperature T_s is greater than solidus temperature T_{so}. Below solidus temperature empirical equation has been employed:

$$\alpha_{sk}=\alpha_r+(\alpha_l-\alpha_r)exp^{\frac{T_s-T_{so}}{T_{so}-T_{za}}} \qquad (5)$$

where: α_r – radiation heat transfer coefficient, W/(m^2·K); T_{za} – temperature of the mold powder solidification, K. The value of α_r can be calculated taking into consideration radiation heat transfer between parallel plates:

$$\alpha_r=5.67\ 10^{-8}\frac{\varepsilon_s\varepsilon_k}{\varepsilon_s+\varepsilon_k-\varepsilon_s\varepsilon_k}\frac{T_s^4-T_k^4}{T_s-T_k} \qquad (6)$$

where: ε_s – emissivity of the strand surface; ε_k – emissivity of the mold surface.

Outside the mold in the secondary cooling zones strand is cooled by water sprays and the convection heat transfer coefficient α_s can be calculated from the equation published in [7]. For air cooling heat convection coefficient can be calculated from [8]:

$$Nu = \frac{\propto_s \lambda_p}{L} = 0{,}664\, Re^{1/2} Pr^{1/3} \left(\frac{Pr}{Pr_s}\right)^{0{,}19} \tag{7}$$

where: L – strand width, λ_p – air conductivity, Re – Reynolds number; Pr – Prandtl number, Pr_s – Prandtl number calculated for air temperature equal to strand surface temperature. Determination of the strand temperature field requires the mold surface temperature to be known. The mold temperature field can be calculated from the solution to the three dimensional heat conduction equation:

$$\frac{\partial T}{\partial \tau} = \frac{\lambda}{\rho c}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) \tag{8}$$

The mold is taking heat from the strand and is simultaneously water cooled on the outside surface. On the inner surface of mold the boundary condition has the form:

$$q_{sk} = \alpha_{sk}(T_k - T_s) \tag{9}$$

On the water cooled side of the mold heat flux is calculated from:

$$q_w = \alpha_w (T_{kz} - T_w) \tag{10}$$

where: T_w – the mean bulk temperature of water, T_{kz} – mold surface temperature at the water cooling side. Most relation for the heat transfer coefficient for turbulent flow are based on experimental studies. The Nusselt number due to Michiejew [8] can be used to calculate α_w:

$$Nu = \frac{\propto_w \lambda_w}{D} = 0.021 Re_w^{0.8} Pr_w^{0.43} \left(\frac{Pr_w}{Pr_s}\right)^{0.25} \tag{11}$$

where: λ_w – water conductivity, D – hydraulic diameter of the water cooling channel. Subscript s indicates that the Prandtl number Pr must be evaluated at the mold surface temperature and subscript w denotes that the Reynolds Re and Prandtl Pr numbers are to be evaluated at the mean bulk temperature of water.

5. ANALYSIS OF THE RESULTS

The computations have been performed for the tests which model heat transfer in the continuous casting line. The strand cross section of 100 mm × 100 mm and the mould length of 800 mm have been assumed for computations.The following chemical composition of steel has been assumed: 0.20% C, 0.50% Mn, 0.15% Si, 0.25% Cr and 0.35% Ni. Thermo physical properties of steel were selected on the ground of steel chemical composition. Strand moves with the constant velocity of 0.53 m/s. The inlet temperature of steel is 1550^{o}C. The computations have been performed for the following tests:

Test I – no solidification heat, the overall heat balance not stabilized.

Test II – solidification heat included but the overall heat balance not stabilized.

Test III – constant heat transfer coefficient α = 1000 W/(m^2·K) on the strand surface and the overall heat balance stabilized.

Test IV – boundary conditions as described in paragraph 4 and the overall heat balance stabilized.

In figure 1 the results of transient 2D and steady 3D solutions have been compared. The models have given almost identical solutions but the heat of solidification was not computed. The solidification heat increases the strand temperature at the end of casting line by about 100°C (fig. 1, right). The difference between the models results is not very significant. In order to estimate the accuracy of the methods the heat balance in the control volume has been calculated. This integral of the heat balance represents the error of the numerical solution to the heat transfer problem. At the end of casting line the temperature should be higher by about 250°C, as has been shown in figure 2 (right). Coupling between heat transfer boundary conditions and the strand surface temperature results in significant differences between transient 2D and steady 3D solutions. Steady solution gives the possibility to improve boundary conditions iteratively and the results are much more accurate.

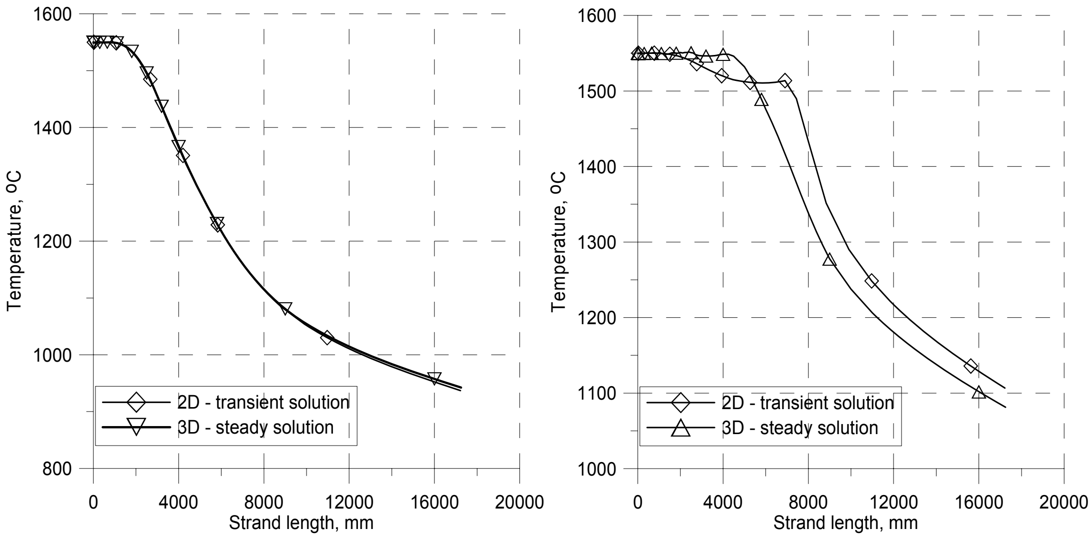

Fig. 1. Temperature distributions at cast strand axis computed without solidification heat (left, Test1) and with solidification heat (right, Test 2). The overall heat balance not stabilized.

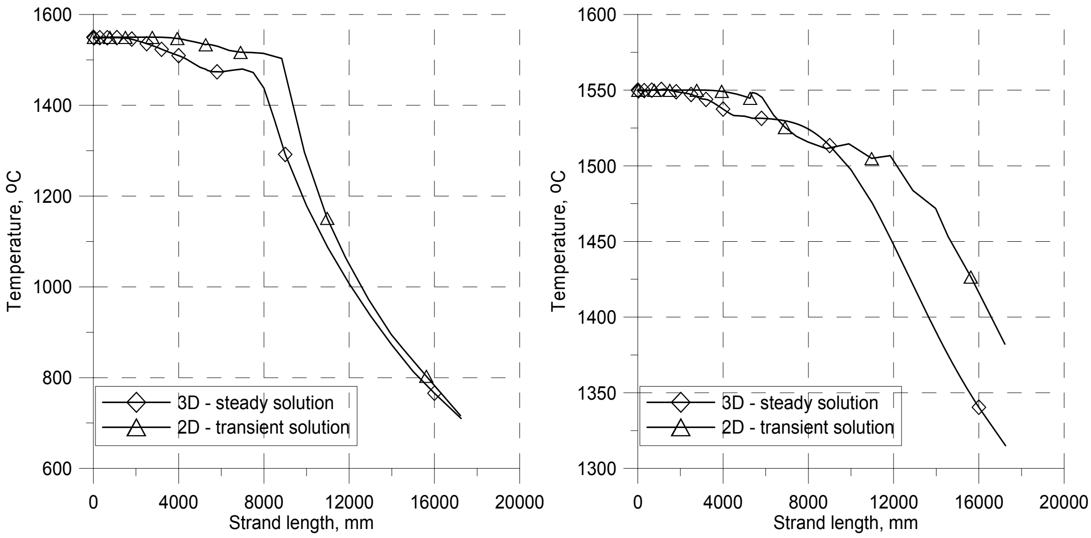

Fig.2. Temperature distributions at cast strand axis computed with the overall heat balance stabilization. (left, Test 3), (right Test 4).

6. CONCLUSIONS

Accuracy of the finite element solution to the temperature field of the cast strand has been analyzed. Two dimensional transient solution and three dimensional steady formulation have been compared. In the lack of solidification heat all methods have given very similar results. The solidification heat has significant influence on the temperature filed computed with transient 2D and steady 3D solution. But the differences between models results are not very important. The major problem lies in the overall heat balance discrepancy. It is necessary to include the overall heat balance calculation in the finite element solutions in order to improve solutions accuracy.

ACKNOWLEDGEMENTS

The work has been financed by the Ministry of Science and Higher Education of Poland, Grant No N R07 0018 04.

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