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Modelling of three-dimensional thermal field in mould during continuous casting of steel

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In this work the three-dimensional numeric analysis inside the mould, during the continuous casting of low carbon steel is presented. In the numeric simulation the field of temperatures and the thickness of the solid shell were computed. For the computation the finite elements method with the enthalpy convention was applied.

1. INTRODUCTION

The solidification with phase change and the temperature distribution inside the billet, during continuous casting of steel can by described by the three-dimensional unsteady-state heat conduction equation

$$\rho(T)c(T)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k(T)\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k(T)\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k(T)\frac{\partial T}{\partial z}\right) + \dot{q} \tag{1}$$

where: T - temperature (°K), t - time (s), x,y,z - rectangular coordinates (m), $k(T)$ - thermal conductivity (W/mK), $c(T)$ - specific heat (J/kgK), $\rho(T)$ - density (kg/m^3), $\dot{q}$ - latent heat source (W/m^3). In the equation (1) the heat flow provided by the convection is not taken into consideration. For simulation the convection effects the liquid phase thermal conductivity is adopted several times greater than the solid (figure 1) [1].

The latent heat is generated during phase change between liquidus and solidus temperatures and is expressed by following equation

$$\dot{q} = \rho(T)_s L \frac{\partial f_s}{\partial t} \tag{2}$$

where: L - latent heat of fusion (J/kg), f_s - solid fraction, $\rho(T)_s$ - density of solid (kg/m^3).

For simplification of the equations (1,2), the enthalpy formulation is used [2]. In the enthalpy convention the non-linear parameters as specific heat, latent heat and density can be replace by one parameter

$$\frac{\partial H(T)}{\partial t} = c(T)\rho(T)\frac{\partial T}{\partial t} - \rho(T)_s L \frac{\partial f_s}{\partial t} \tag{3}$$

where $H(T)$ is enthalpy (J/m^3).

Finally the heat conduction equation (1) can be described by expression

$$\frac{\partial H(T)}{\partial t} = \frac{\partial}{\partial x}\left(k(T)\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k(T)\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k(T)\frac{\partial T}{\partial z}\right) \tag{4}$$

or in the simplest form (with the nabla operator)

$$\frac{\partial H(T)}{\partial t} = \nabla\left(k(T)\nabla T\right) \tag{5}$$

2. NUMERICAL SIMULATION

For the simulation the mould region was chosen. For the numerical solution of equation (5), the commercial system ANSYS® which based on finite elements method was used [4]. The material properties as thermal conductivity and enthalpy in figures 1,2 are showed (0,3 wt% C steel). In the table 1, the casting parameters are showed [3]. The boundary conditions in figure 3 are presented. Because the rectangular billet have two axis of symmetry (figure 3b), only one quarter for analysis was used. In this way, time of calculation is smaller. The heat flux from billet to mould is described by the Newton equation

$$-k(T)\frac{\partial T}{\partial z} = h\left(T_{surf} - T_{amb}\right) \tag{6}$$

where: h - heat transfer coefficient (W/m^{2}K), T_{surf} - temperature of billet surface (°K), T_{amb} - ambient temperature (°K).

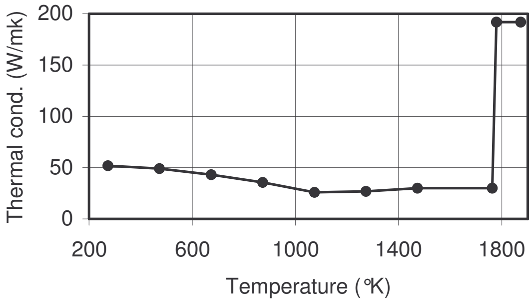

Figure 1. Thermal conductivity

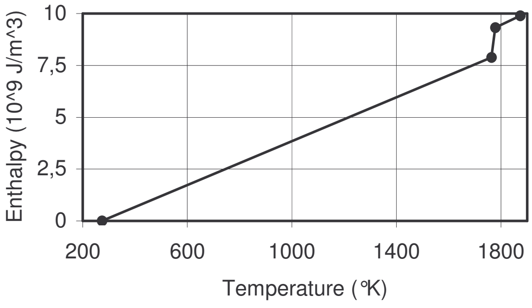

Figure 2. Enthalpy

Table 1
Casting conditions (0.3 wt% C steel)

mould dimensions	0.2 x 0.2 x 0.6 m
casting speed - v_c	0.02 m/s (1.2 m/min)
heat transfer coefficient - h	1163 W/m^{2}K
poured temperature - T_{pour}	1803°K (1530°C)
liquidus temperature - T_{sol}	1778°K (1505°)
solidus temperature - T_{liq}	1763°K (1490°)
ambient temperature - T_{amb}	303°K (30°)

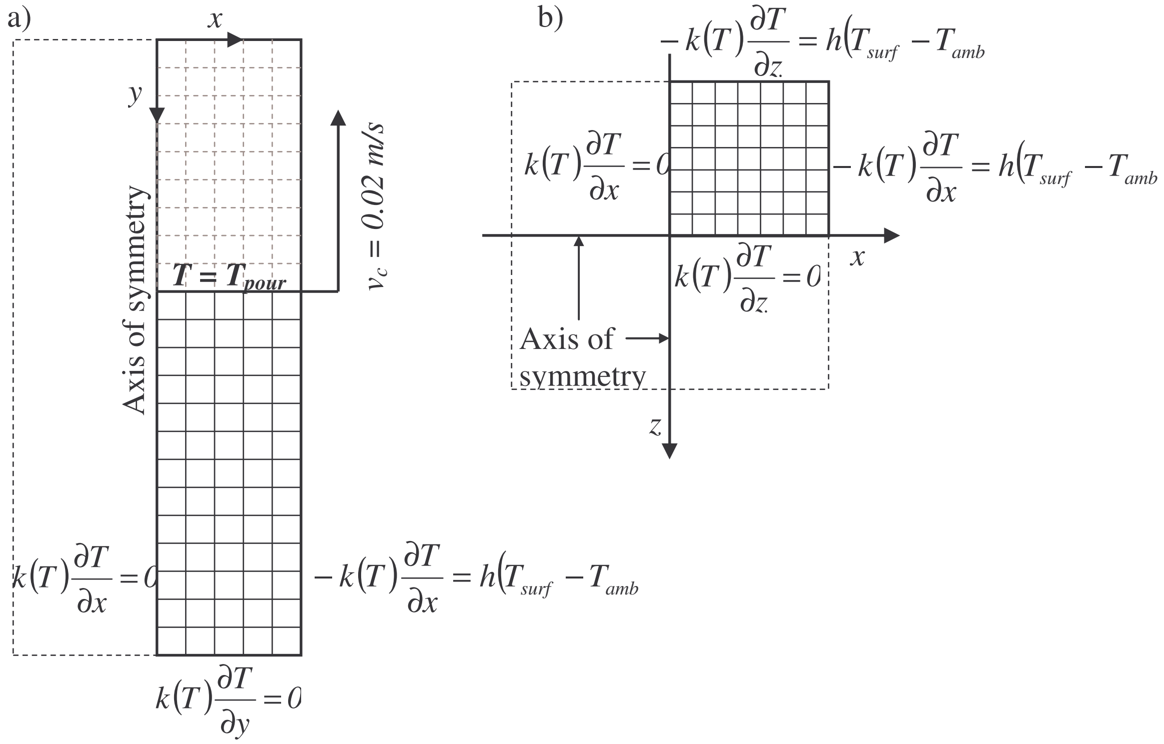

Figure 3. Boundary conditions for rectangular billet (mould zone), a) longitudinal section, b) cross section

3. RESULTS AND CONCLUSIONS

The computed temperature distributions, on surface and inside of billet, in figure 4 are showed. The region of lowest temperatures is located in the corner. On the surface, the region of highest temperatures is located in the side of billet. The solid, liquid and semi-solid zones in figure 4c are presented. The computed shell thickness was compared with Savage-Pritchard and Chipman-Fondersmith equations [1] and is presented in figure 5.

Usefulness of three - dimensional analysis with enthalpy convention for analysis mould zone, during continuous casting process was presented. The numerical results with data from literature was compared. In enthalpy formulation only two non-linear material parameters, thermal conductivity and enthalpy, for computation were needed.

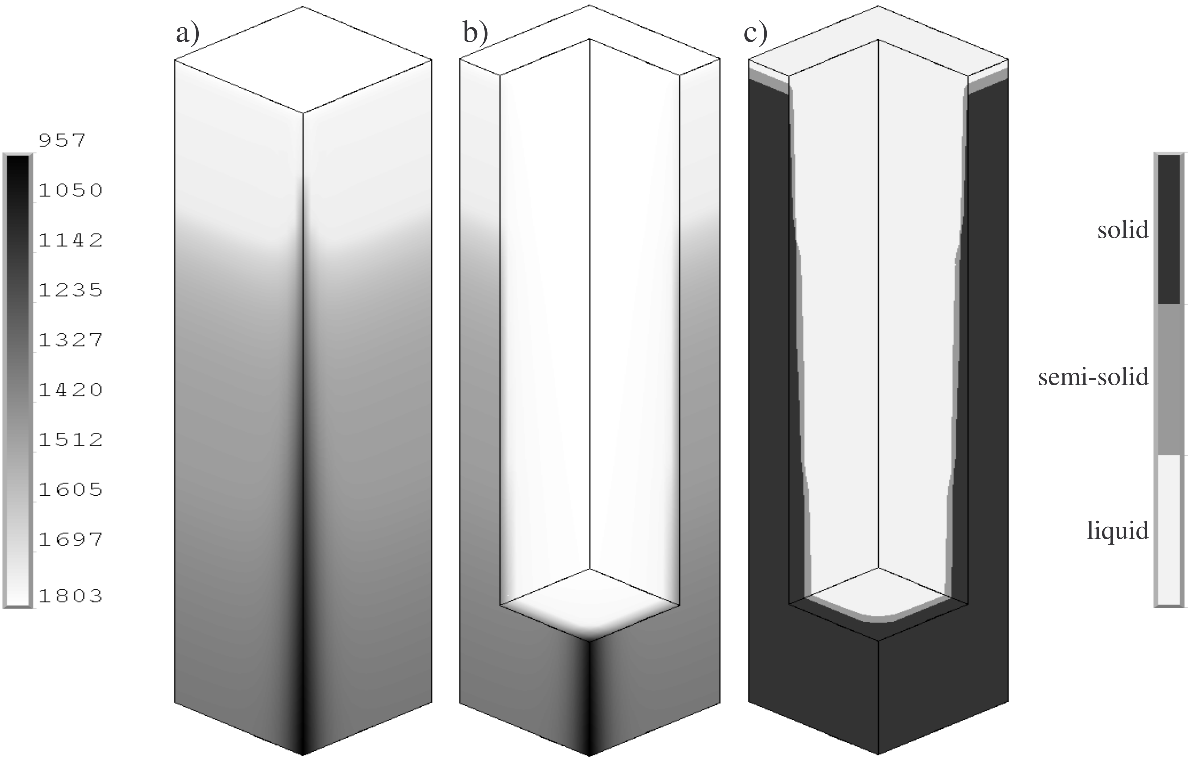

Figure 4. Temperature distribution in (one quarter) continuous casting mould region, a) on surface, b) inside billet, c) liquid, solid and semi - solid zone

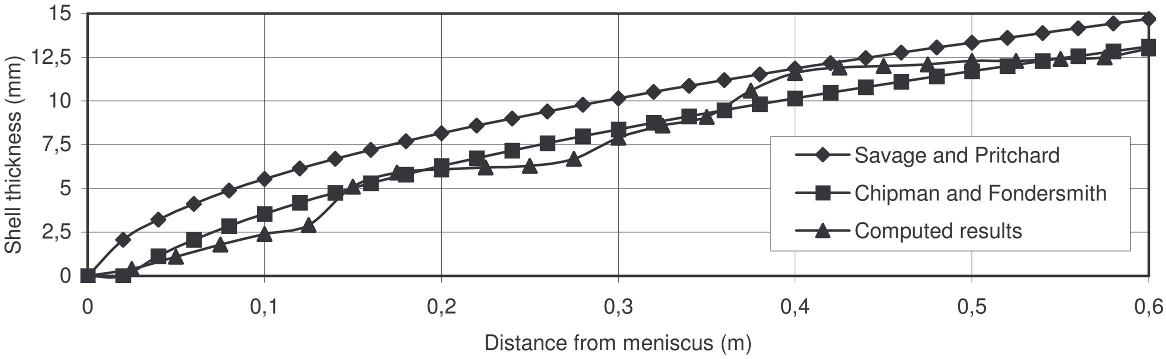

Figure 5. Comparison between computed shell thickness and data from literature

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