POLISH ACADEMY OF SCIENCES - COMMITTEE OF MATERIALS SCIENCE
SILESIAN UNIVERSITY OF TECHNOLOGY OF GLIWICE
INSTITUTE OF ENGINEERING MATERIALS AND BIOMATERIALS
ASSOCIATION OF ALUMNI OF SILESIAN UNIVERSITY OF TECHNOLOGY
Conference Proceedings
12th INTERNATIONAL SCIENTIFIC CONFERENCE
ACHIEVEMENTS IN MECHANICAL & MATERIALS ENGINEERING

Modelling of three dimensional liquid steel flow in continuous casting process

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In this work the theory and numerical analysis of fluid flow of liquid steel were presented. The three-dimensional, steady state, Newtonian and incompressible with turbulences model of fluid flow was chosen. The k-ε model of turbulence was used. For computation the system ANSYS, which based on finite elements method, was applied.

1. INTRODUCTION

The simplified scheme of continuous casting process in figure 1 was presented. Because the stream of liquid steel strongly changes (by velocity field) the heat exchange by convection, the numerical analysis of fluid flow both with thermal analysis [1] is very important part in modelling of continuous casting process.

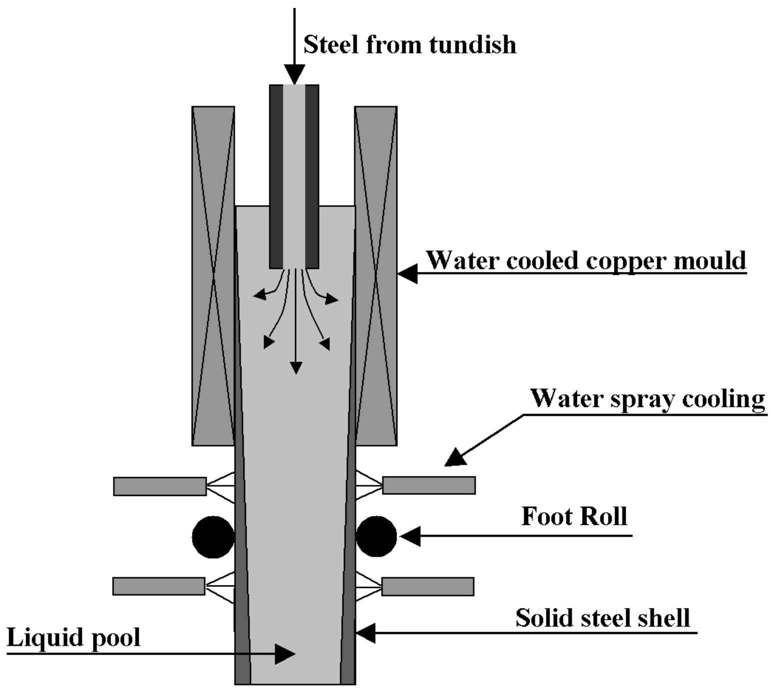

Figure 1. Fragment of continuous caster

2. THEORY

The liquid steel inside the continuous billet can be treatment as incompressible, Newtonian and turbulent fluid. Behaviour of liquid fluid descript following equations [2,3]:

- Continuity equation
- Momentum equations (Navier – Stokes equations)
- Incompressible energy equation
- Turbulence model equations

The k-ε model of turbulence was chosen. This model is very popular for modelling liquid steel behaviour. The continuity equation is descript:

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho v_x)}{\partial x}+\frac{\partial(\rho v_y)}{\partial y}+\frac{\partial(\rho v_z)}{\partial z}=0 \tag{1}$$

where: v_x, v_y, v_z - components of the velocity vector,
ρ - density,
x, y, z - global Cartesian coordinates,
t - time.

The rate of change of density can be replaced by the rate of change of pressure:

$$\frac{\partial \rho}{\partial t}=\frac{\partial \rho}{\partial P}\frac{\partial P}{\partial t} \tag{2}$$

where: P – pressure.

For incompressible fluid the equation (2) can be expressed as:

$$\frac{\partial \rho}{\partial t}=\frac{1}{\beta}\frac{\partial P}{\partial t} \tag{3}$$

where: β – bulk modulus.

The other (Navier – Stokes, energy, turbulence) equations have the form of scalar transport equation [2]:

$$\frac{\partial(\rho C_\Phi \Phi)}{\partial t}+\frac{\partial(\rho v_x C_\Phi \Phi)}{\partial x}+\frac{\partial(\rho v_y C_\Phi \Phi)}{\partial y}+\frac{\partial(\rho v_z C_\Phi \Phi)}{\partial z}=\frac{\partial}{\partial x}\left(\Gamma_\Phi \frac{\partial \Phi}{\partial x}\right)+\frac{\partial}{\partial y}\left(\Gamma_\Phi \frac{\partial \Phi}{\partial y}\right)+ \\ +\frac{\partial}{\partial z}\left(\Gamma_\Phi \frac{\partial \Phi}{\partial z}\right)+S_\Phi \tag{4}$$

where: C_Φ - transient and advection coefficient,
Γ_Φ - diffusion coefficient,
S_Φ - source terms.

Described coefficients and terms are presents in the table 1. The terms, which were not imported for considered analysis, were omitted.

Table 1. Transport equation representation

Φ	Meaning	C_Φ	Γ_Φ	S_Φ
v_x	x – velocity	1	μ_e	$\rho g_x - \frac{\partial P}{\partial x}$
v_y	y – velocity	1	μ_e	$\rho g_y - \frac{\partial P}{\partial y}$
v_z	z – velocity	1	μ_e	$\rho g_z - \frac{\partial P}{\partial z}$

T	temperature	C_p	K	Q_v
k	kinematic energy	1	$\frac{\mu_t}{\sigma_k}$	$\frac{\mu_t \Phi}{\mu} - \rho\varepsilon + \frac{C_4 \beta \mu_t g_i \left(\frac{\partial T}{\partial x_i}\right)}{\sigma_t}$
ε	dissipation rate	1	$\frac{\mu_t}{\sigma_k}$	$\frac{C_1 \mu_t \varepsilon \Phi}{k} - \frac{C_2 \rho \varepsilon^2}{k} + \frac{C_1 C_\mu C_3 \beta k g_i \left(\frac{\partial T}{\partial x_i}\right)}{\sigma_t}$

The table 1 have coefficients not described earlier:

μ - dynamic viscosity,
μ_e - effective viscosity,
g_x, g_y, g_z, - components of acceleration due to gravity
K - thermal conductivity
C_p - specific heat,
Q_v - volumetric heat source,
C_1, C_2, C_μ, σ_k, σ_ε, σ_t, C_3, C_4 - standard k-ε model of turbulence coefficients (table 2).

The used k-ε standard model coefficients in table 2 are presents.

Table 2. Used values of k-ε model coefficient

Coefficient	Value
C_1	1.44
C_2	1.92
C_μ	0.09
σ_k	1.0
σ_ε	1.3
σ_t	1.0
C_3	1.0
C_4	0

Next step to numeric solution is discretization of the equations. The elements matrices are formed, assembled and the resulting system solved for each degree of freedom separately. The discretization process consist of deriving the element matrices to put together the matrix equation [2]:

$$\left(\left[A_e^{transient}\right]+\left[A_e^{advection}\right]+\left[A_e^{diffusion}\right]\right)\left\{\phi_e\right\}=\left\{S_e^{\phi}\right\} \tag{5}$$

For element integration the Galerkin method of weighted residuals is use:

$$\left[A_e^{transient}\right]=\frac{\partial(\rho C_\phi \phi)}{\partial t}\int W^e d(vol) \tag{6}$$

where: W^e - weighting function for the element.

$$\left[A_e^{advection}\right]=\frac{\partial(\rho C_\phi v_s \phi)}{\partial s}\int W^e d(vol) \tag{7}$$

$$\left[A_e^{diffusion}\right]=\int\left(W_x^e \Gamma_\phi W_x^e + W_y^e \Gamma_\phi W_y^e + W_z^e \Gamma_\phi W_z^e\right)d(vol) \tag{8}$$

where:

$$W_x^e \phi = \frac{\partial \phi}{\partial x};\ W_y^e \phi = \frac{\partial \phi}{\partial y};\ W_z^e \phi = \frac{\partial \phi}{\partial z} \tag{9,10,11}$$

$$W_x^e = \frac{\partial W_e}{\partial x};\ W_y^e = \frac{\partial W_e}{\partial y};\ W_z^e = \frac{\partial W_e}{\partial z} \tag{12,13,14}$$

$$S_e^\phi = \int W^e S_\phi d(vol) \tag{15}$$

3. NUMERICAL SIMULATION

For numerical simulation the parameters of continuous caster from metallurgical plant "Zawiercie" in Poland were used. The dimensions of liquid core were taken from earlier analysis [4,1]. The process and material parameters were presented in table 3. The outlet of the pouring tube was located 82 mm under meniscus. The diameter of pouring tube was 65 mm and diameter of outlet – 30 mm. Whole liquid core for considered case have about 11m. In this work simulation for only 1.5 m fragment of liquid core was presented. The velocities for external nodes were set to zero.

For numerical solution of equation 5 the ANSYS finite elements method system was used. The model contained 538 009 tetrahedral elements with 98 277 nodes. The figure 2 presents the fragment of meshed model (meniscus region). The gravity acceleration was set to 9.81 m/s^2. The analysis was steady state.

Table 3. Materials properties and casting conditions

density	7080 kg/m^3
specific heat	806 J/kgK
thermal conductivity	30 W/mK
dynamic viscosity	0.006 kg/ms
mould dimensions	0.165 x 0.165 x 0.78 m
casting speed	0.0266 m/s (1.6 m/min)
inlet velocity	1 m/s
poured temperature	1814 K (1541ºC)
liquidus temperature	1784 K (1511ºC)

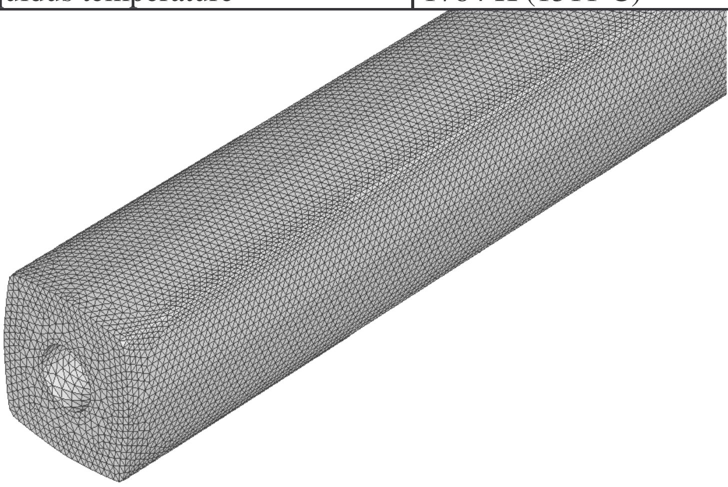

Figure 2. Fragment of meshed model (meniscus region)

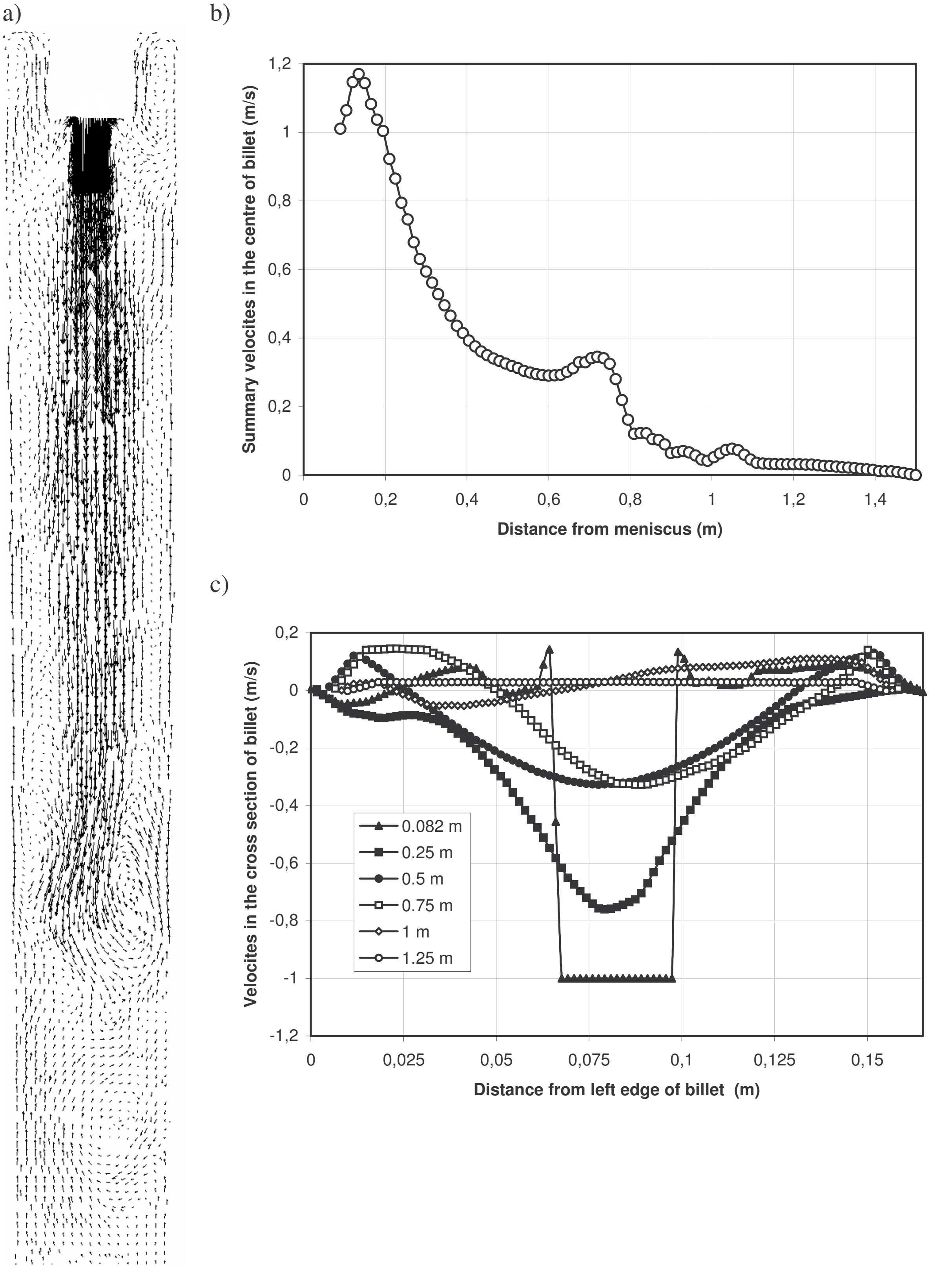

Figure 3. Computed results, a) velocity field in the fragment of longitudinal section, b) summary velocities in the centre of billet, c) profiles of velocity in cross section of billet for various distances from meniscus

The computed field of velocity vectors in figure 3a was showed. The maximum values of velocities in the centre of billet in figure 3b were presented. The profiles of velocity for various distances from meniscus in figure 3c were showed.

The maximum range of the stream of liquid steel can be determined as 1.1 m. Also between meniscus and 1.1 m is located the region of maximum mixing of metal. Therefore the convective effects of transport of heat reach maximum values for this region.

Simulation of whole liquid core (from meniscus to unbending point - about 11m) required high computer power. In case of only simulation region of high mixing, the cost of computation quickly decreasing.

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