ARTIFICIAL HEAT SOURCE METHOD IN MODELLING OF CONTINUOUS CASTING PROCESS

Romuald Szopa, Edyta Pawlak

Institute of Mathematics, Czestochowa University of Technology, Poland
edyta.pawlak@im.pcz.pl

Abstract. In the paper the numerical model of continuous casting process is presented. The basic energy equation corresponding to the fixed domain approach is assumed in the form containing the term called artificial heat source. It should be pointed out that a mathematical description of the continuous casting essentially differs from the model of typical foundry technologies, because in the energy equation the additional component being the product of pulling rate vector and temperature gradient appears. It results from the fact that the cast strand shifts through the continuous casting plant. As an example we will consider a rectangular cast slab produced by a vertical plant. The casting shifts in axis z direction and its pulling rate is equal to $\boldsymbol{u}$ (more precisely, the velocity field in domain considered: $\boldsymbol{u} = [0, 0, u]$). In the paper we present the algorithm in which the product $\boldsymbol{u}\cdot\text{grad}\, T$ is treated as the artificial heat source. In the final part of the paper the example of computations is shown.

1. Mathematical formulation of the problems

The vertical rectangular cast strand is shown in Figure 1, while the geometry of the object for which the computations have been realized is shown in Figure 2. It should be pointed out that taking into account a small curvature of radial plant, the equations presented in this chapter can be used also in a such case.

The governing equation describing the thermal processes in casting domain is the parabolic one in which the substantial derivative appears [1]

$$C(T)\left[\partial_t T + u\,\partial_z T\right] = \partial_x\left[\lambda\,\partial_x T\right] + \partial_y\left[\lambda\,\partial_y T\right] + \partial_z\left[\lambda\,\partial_z T\right] \tag{1}$$

where C is the volumetric substitute thermal capacity (STC) [2-4], λ is the thermal conductivity. The STC is a very effective parameter for mathematical modelling of alloys solidification (macro scale) and its introduction leads to the model called fixed domain or one domain method [2-5]

The boundary conditions on lateral surface of cast slab in the form of 3rd type (heat flux continuity) conditions are, as a rule, accepted. The adequate input data concerning the heat transfer coefficients for successive sectors of cooling zones can be found in literature (e.g. [6]). On the upper surface of the casting (free surface of molten metal) the boundary condition of the 1st type (pouring temperature) or the 3rd type can be taken into account. On the conventionally assumed bottom surface limiting casting domain (it is a region of final cooling zone) we can put $q = -\lambda \partial_z T = 0,$ this means the no-flux condition.

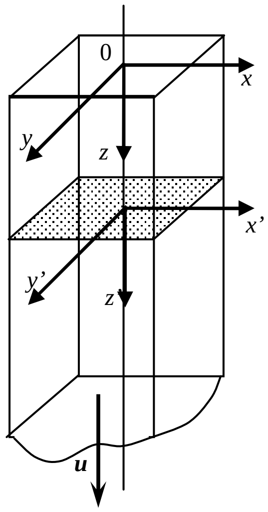

Fig. 1. Rectangular cast slab

The initial condition resolves itself into the assumption, that a certain layer of molten metal directly over the starter bar has a pouring temperature. The starter bar allows to shut the continuous casting mould during the plant starting. It is also possible to assume that the initial temperature in the whole continuous casting domain is equal to the pouring temperature (from a technological view point this is a fiction, of course) but taking into account that solving the problems concerning conticasting technology we seek the border solutions describing the pseudo-steady temperature fields - the above assumption is acceptable.
The equation describing directly the pseudo-steady state results from equation (1)

$$C(T)\, u\, \partial_z T = \partial_x \left[\lambda \partial_x T \right] + \partial_y \left[\lambda \partial_y T \right] + \partial_z \left[\lambda \partial_z T \right] \tag{2}$$

but in this paper we base on equation concerning the transient temperature field.

The real measurements show that conductional component of heat transfer corresponding to the direction of casting displacement z is very small (this component constitutes about 5% of the heat conducted from the axis to the lateral surfaces), it means that the basic energy equation can be simplified to the form

$$C(T)\left[\partial_t T + u\, \partial_z T \right] = \partial_x \left[\lambda \partial_x T \right] + \partial_y \left[\lambda \partial_y T \right] \tag{3}$$

Now we rewrite the equation (1) in coordinate system 'tied' to a certain section of shifting casting, namely $x' = x, y' = y, z' = z - ut$. We assume, as previously, that the heat conduction in z direction can be neglected. It is easy to check up that a new form of energy equation is the following

$$C(T)\,\partial_t T = \partial_{x'}\left[\lambda \partial_{x'} T\right] + \partial_{y'}\left[\lambda \partial_{y'} T\right] \tag{4}$$

The approach above presented is called 'the wandering cross section method' (e.g. [6]). The equation should be solved assuming the initial condition in the form $T(0) = T_p$, while the boundary conditions on the periphery of this section are functions of time. If Δt_1 corresponds to the 'hold time' of the section in the continuous casting mould region, then for $0 \le t \le \Delta t_1$ on the casting periphery the boundary condition for the primary cooling zone is assumed. For the next interval Δt_2 we consider the boundary condition characterizing the heat transfer in the 1st sector of the secondary cooling zone etc. One can see that solving the 2D problem we find the 3D solution, and analogously for 1D task (e.g. x - axis is oriented perpendicularly to a shorter side of section) we obtain the temperature field in $\{x, z\}$ plane, because for a distinguished moment t we can determine the adequate coordinate $z = ut$.
Let us transform the equation (1) to the form

$$C(T)\,\partial_t T = \partial_x\left[\lambda \partial_x T\right] + \partial_y\left[\lambda \partial_y T\right] + \partial_z\left[\lambda \partial_z T\right] + Q \tag{5}$$

where Q is the capacity of artificial internal heat sources defined as follows

$$Q = -C(T)\,u\,\partial_z T \tag{6}$$

In numerical realization the 2D problem has been analyzed (the lateral the cross section shown in Figure 2) and then

$$C(T)\,\partial_t T = \partial_x\left[\lambda \partial_x T\right] + \partial_y\left[\lambda \partial_y T\right] + Q \tag{7}$$

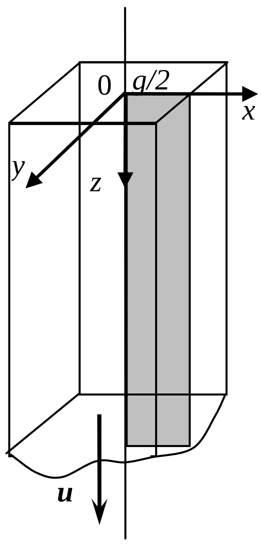

Fig. 2. Section considered

2. Example of numerical simulation

At the stage of numerical computations the control volume method (see: [7]) has been used.

The steel cast slab of dimensions 0.2×0.6 m (a lateral section) has been considered, at the same time the pulling rate was equal to $u = 0.018$ m/s. Heat transfer coefficients [W/ m^2 K] for successive cooling zones have been assumed as follows

$$
\begin{array}{ll}
z \le 0.7: & \alpha_1(z) = 1500 \\
z \in (0.7,\ 2.6]: & \alpha_2(z) = 1200 \\
z \in (2.6,\ 4.5]: & \alpha_3(z) = 950 \\
z \in (4.5,\ 8.2]: & \alpha_4(z) = 550 \\
z \in (8.2,\ 12.2]: & \alpha_5(z) = 430 \\
z \in (12.2,\ 16.3]: & \alpha_6(z) = 250 \\
z > 16.3: & \alpha_7(z) = 225
\end{array}
$$

The cooling water temperature is equal to $T^{\infty} = 20\,^{\circ}$C.

The substitute thermal capacity in the form of piece-wise constant function [5, 8] and for the carbon steel (0.44% C)

$$
C(T) = \begin{cases} 5.904\cdot 10^6\ \mathrm{J/m^3K} & T > 1505\,^{\circ}\mathrm{C} \\ 56.700\cdot 10^6 & 1470 \le T \le 1505 \\ 4.875\cdot 10^6 & T < 1470 \end{cases}
$$

The thermal conductivity of casting domain is assumed to be a constant value $\lambda = 35$ W/mK.

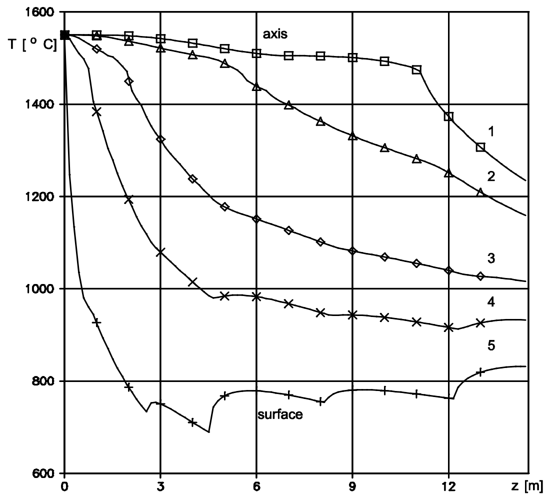

Fig. 3. Temperature history

In Figure 3 the final temperature distribution along the lines x = const (the pseudo-steady state) is shown. Full lines illustrate the solution presented in [1], while the symbols denote the solutions obtained by means of the method presented in the paper. Specified above boundary conditions correspond to technology used in steel plant USINOR (France).

References

[1] Mochnacki B., Suchy J.S., Numerical Methods in Computations of Foundry Processes, PFTA, Cracow 1995

[2] Mochnacki B., Majchrzak E., Methods of inverse problems solution in the thermal theory of foundry processes, in: Research in Polish Metallurgy at the Beginning of XXI Century, Committee of Metallurgy of Polish Academy of Sciences 2006, 239-254.

[3] Szopa R., The parametric sensitivity analysis of solidification process, Archives of Foundry Engineering 2005, 5, 15, 395-404.

[4] Ruddle E.W., The solidification of casting, Institute of Metals, London 1957.

[5] Szopa R., Senmsitivity analysis and inverse problem in the thermal theory of foundry processes, Publ. of the Częst. Univ. of Techn., Częstochowa 2006.

[6] Mochnacki B., Pawlak E., Identification of boundary condition on the contact surface of continuous casting mould, Archives of Foundry Engineering 2007, 7, 4, 202-206.

[7] Domanski Z., Ciesielski M, Mochnacki B., Application of CVM using the Voronoi tessalation in numerical modeling of solidification process, Current Themes in Engineering Science, American Institute of Physics, Melville, New York 2010, 17-27.

[8] Majchrzak E., Mochnacki B., Suchy J.S., Kinetics of casting solidification, an inverse approach, Scientific Research of the Institute of Mathematics and Computer Science 2007, 1(6), 169-178.