A 3D FRONT TRACKING SLICE MODEL FOR CONTINUOUS CASTING OF ALUMINUM

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Abstract

In the last 20 years the continuous casting has become a modern production technology of metals including steel, aluminum, and copper. Since cooling patterns and the temperature distribution of cast metal significantly influence quality and productivity of final products, metallurgists utilize computer solidification models which allow them for thermal analysis, monitoring and optimization of cast products. Most of models are based on so-called interface capturing methods, e.g. on the enthalpy method which is rather simple and straightforward. The paper presents a solidification model for continuously cast aluminum which is based on another approach. The applied front tracking method offers benefits such as a higher order of accuracy and a possibility to simulate the growth of dendrites. The model allows for 3D simulations and it is based on the slice approach in which a 2D calculation slice moves through the solidifying strand. Results of the slice model are compared to results gained with the use of the enthalpy-based 3D model and a comparison of methods is presented and discussed.

Keywords: Continuous casting, aluminum, front tracking method, slice model, enthalpy method

1. INTRODUCTION

The use of aluminum as a construction material has recently become more and more important. For instance, parts of automotive bodies made of the aluminum have positively contributed to the reduction of weights of cars, and thus to decrease the fuel consumption and CO_2 emissions. Since experimental investigation is usually expensive and time-consuming, computer modelling is frequently utilized. From the metallurgical point of view, the aluminum solidifies at a nearly constant temperature as a pure substance. This behaviour is opposite in comparison to steel which always solidifies in a temperature range as it is at least a binary alloy composed of the iron and carbon. The solidification is accompanied by the release of the latent heat of the phase change. In computer modelling of heat transfer processes with phase changes, the inclusion of the release of the phase change is crucial. The correct incorporation of the latent heat into the numerical formulation of the problem and the fulfilment of the energy balance are especially important in regard to accuracy and reliability of numerical results.

From the modelling point of view, there are two groups of methods applicable for the solution of heat transfer problems with phase changes [1]: interface capturing methods and interface tracking methods. Interface capturing methods are well known and widely applied in a huge variety of problems. The enthalpy method and the effective (sometimes referred to as apparent) heat capacity method are the most well-known interface capturing methods. Such methods are quite simple and easily transferrable into computer programs with no special effort devoted to the phase change. On the other hand, interface capturing methods suffer from lower computational accuracy, especially in the vicinity of the interface separating phases. Due to the simplicity and to the relatively good applicability, a number of applications can also be found in computer models of metal making, especially of steel, see e.g. [2, 3] for solidification models of steel and [4] for simulations of the aluminum. Interface tracking methods form another group of the computational approach to phase change problems. Though they have some benefits in comparison to the interface capturing methods, only a limited number of applications of interface tracking methods can be found in the literature. Main reasons are that the interface tracking methods are more difficult for programming and they usually have higher computational demands. On the other hand, front tracking methods provide higher computational accuracy and allows for direct simulation of dendrite growth. Research papers on the topic of front tracking are aimed at general computational models of solidification and mainly at simulations of dendrite growth (see e.g. [5]) but no paper is directly related to the continuous casting.

The paper presents a 3D front tracking slice model for the continuous casting of the aluminum. The model utilizes the front tracking solution of the temperature distribution and the front location in a cross-section of the cast billet. Such cross-sectional solution is solved in a plane perpendicular to the vector of the casting direction and it is moving in that direction. The 3D solution of the temperature field and identification of the solid and liquid regions is performed with the use of the idea of slice models. Such slice models have attracted an attention of numerous investigators (see e.g. [6, 7]) as slice models are very fast and sufficiently accurate for 3D heat transfer modelling derived from partial 2D solutions. In the paper the front tracking slice model is compared to the traditional enthalpy-based fully 3D model. Results indicate a good agreement between the models with further possibility of the front tracking slice model for its use in microstructure and dendrite growth modelling.

2. BASIC PRINCIPLES OF ENTHALPY METHOD AND FRONT TRACKING METHOD

A brief overview of main principles of the enthalpy method and of the front tracking method is presented in this section. A 3D formulation of the enthalpy method and a 2D front tracking method suitable for the slice model are considered.

2.1. Enthalpy method - interface capturing approach

The well-known enthalpy method [8] belongs to the interface capturing category of numerical methods for the solution of heat transfer problems. A main feature of interface capturing methods is that the latent heat of the phase change is incorporated into the governing heat transfer equation via the source term. The second important characteristic of interface capturing methods is that such methods only solves for the temperature distribution. The identification of phases and the location of the phase interface, so-called front, are determined only from the knowledge of the temperature distribution according to the phase temperature. This also explains lower accuracy of these methods, especially near the phase interface. The enthalpy formulation of the 3D heat transfer equation (see [8] for a more detailed explanation) is

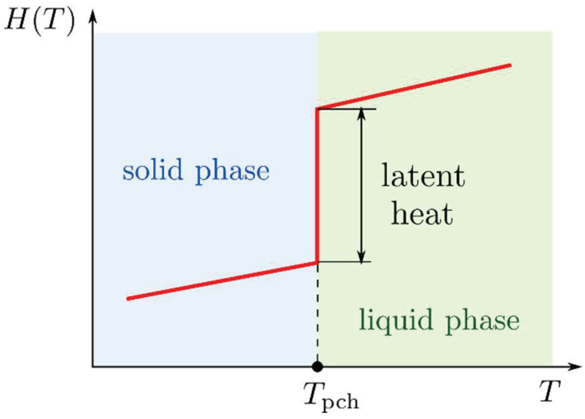

Figure 1 Enthalpy-temperature dependence for an isothermal phase change

$$\frac{\partial H}{\partial t}=\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+v_z\frac{\partial H}{\partial z} \tag{1}$$

where T (K) is the temperature, t (s) is time, k (W/m·K) is the thermal conductivity, x, y, and z (m) are spatial coordinates and v_z (m/s) is the casting speed. The quantity H (J/m^3) is the volume enthalpy defined as

$$H(T)=\int_{T_{ref}}^{T}\left(\rho c_p-L_f\frac{\partial f_S}{\partial\psi}\right)\mathrm{d}\psi \tag{2}$$

where T_{ref} [K] is a reference temperature, ρ (kg/m^3) is the density, c_p (J/kg·K) is the heat capacity at the constant pressure, L_f (J/kg) is the amount of the latent heat and f_s (-) is the solid fraction. The solution of Eq. (1) consists of two consecutive steps: first, the equation is solved for the unknown enthalpy which is determined from the temperature distribution. Second, the enthalpy is then converted into the temperature from the known relation between the enthalpy and the temperature. In case of the pure aluminum considered in the paper, the solidification takes place at the constant temperature of 660 °C rather than in a temperature range as in case of steel. Due to this reason the enthalpy-temperature curve has a shape consisting of nearly linear functions in dependence to the variation of the density and of the heat capacity on the temperature. An example of such curve for a material undergoing the phase change at a constant temperature is shown in **Figure 1**. The determination of the phase interface location completes the calculation procedure. The solid phase is in computational nodes with the temperature below the phase change temperature and the liquid phase is in computational nodes having the temperature above the phase change temperature. The interface is usually determined by means of interpolation between nodal temperatures.

2.2. Front tracking method - interface tracking approach

Front tracking algorithms can be applied in a variety of computational problems from heat transfer and solidification problems, multi-phase fluid flow problems to detailed simulations of solidification and growth of crystals. Numerical methods based on the interface (front) tracking approach differ significantly from interface capturing methods. Front tracking algorithms are not so known as the enthalpy method, effective heat capacity method, or the temperature recovery method from the interface capturing category. One of reasons is that front tracking algorithms are considerably more difficult for programming as well as they have higher computational demands. On the other hand, the interface tracking offers a higher accuracy, direct modelling of the phase interface and other possibilities such as microstructure modelling as already mentioned in the introduction. In comparison to interface capturing methods, the tracking of the phase interface is the main objective of front tracking algorithms and the temperature distribution is solved in the second step from the location of the interface.

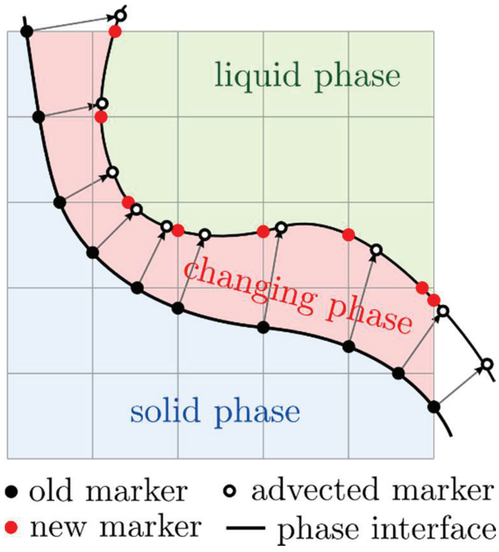

Figure 2 Schematic of the front tracking approach

The front tracking algorithm on a fixed computational grid is considered in the paper and it is based on algorithms presented in [9, 10]. The phase interface - the front - is simulated by means of markers which lie on gridlines of the computational grid, see **Figure 2**. The computational procedure has three main parts [10]: advection of the markers and the determination of their new locations on gridlines, identification of velocity vectors in locations of the markers, and the solution of the temperature distribution by means of the heat transfer equation. The latent heat of the phase change is taken into account via the Stefan condition which is applied at the phase interface [9]

$$k_s \frac{\partial T_s}{\partial n} - k_l \frac{\partial T_l}{\partial n} = \rho L_f v_n \tag{3}$$

where the subscript *s* denotes the solid phase, the subscript *l* denotes the liquid phase, *n* is the normal direction (vector) and v_n (m/s) is the normal velocity of the interface. The Stefan condition is thus applied to each marker and its normal velocity is determined from Eq. (3). The 2D temperature distribution is finally computed from the ordinary heat transfer equation

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

which is solved separately for the solid and liquid parts taking into the markers laying on the front and having the phase change temperature.

3. 3D SLICE MODEL FOR SIMULATIONS OF CONTINUOUS CASTING OF ALUMINUM

In the paper, the continuous casting of aluminum shown in **Figure 3** is considered. The principle is similar to well-known radial continuous casting of steel but the process completely occurs in the horizontal direction. Liquid aluminum flows from the tundish to the water-cooled mould where the solid shell is formed at the surface of the slab. Behind the mould the shell grows up and the heat withdrawal continues by means of forced convection via water or air nozzles and by means of natural convection to the ambient. As for the modelling, the 2D model based was employed in the 3D slice model. Slice models have successfully been applied by various investigators; see e.g. [6, 7]. Their users reported that slice models are much faster that fully 3D models. The schematic of the slice model is shown in **Figure 4**. The 3D temperature distribution is derived from the 2D temperature distribution in the axial cross-sections (slices) of the billet. Though such approach ignores all interaction in the casting direction, it is well reported [6, 7] that such assumption leads to small inaccuracy since interactions perpendicular to the casting direction are much more significant. The computation starts with the slice in the mould where the casting temperature is known. Then the slice fictively "travels" through the billet with the casting velocity which causes the change of the boundary conditions of the slice according to the actual location *z*. The 2D slice model is therefore repeatedly solved as a transient problem having time-dependent boundary conditions. While the slice arrives to the end of the billet, the calculation of the 3D temperature distribution is completed and it can be reconstructed as the temperature history of the 2D slice.

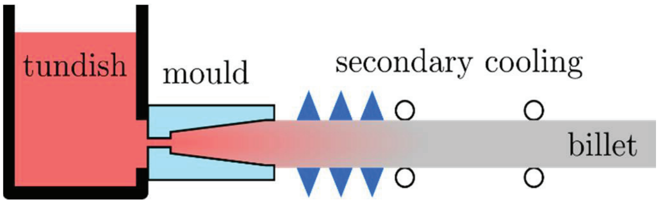

Figure 3 Schematic of horizontal continuous casting

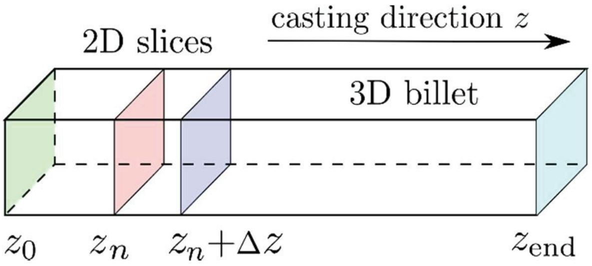

Figure 4 Schematic of slice model principle

4. RESULTS AND DISCUSSION

The implemented "traditional" fully 3D enthalpy-based model and the slice model based on the 2D front tracking method were used for the computation of the continuous casting process of aluminum. In the paper the steady state casting is presented. The aluminum billet with the square cross-section having the dimensions of 120 × 120 mm and the horizontal casting described in the foregoing section were considered. The length of the billet was set to 5 m. The heat withdrawal from the mould having the length of 1 m was characterized by the heat flux of 760 kW/m^2 while the heat withdrawal in the secondary cooling zone was assumed by mild forced convection (usually assured by means of air nozzles) and radiation to the ambient with the combined heat transfer coefficient of 70 W/m^2·K. The casting temperature was set to 710 °C with the solidification temperature of 660 °C. **Figure 5** shows a typical output of the computer models: a 3D distribution of the temperature in the longitudinal cross-section of the billet.

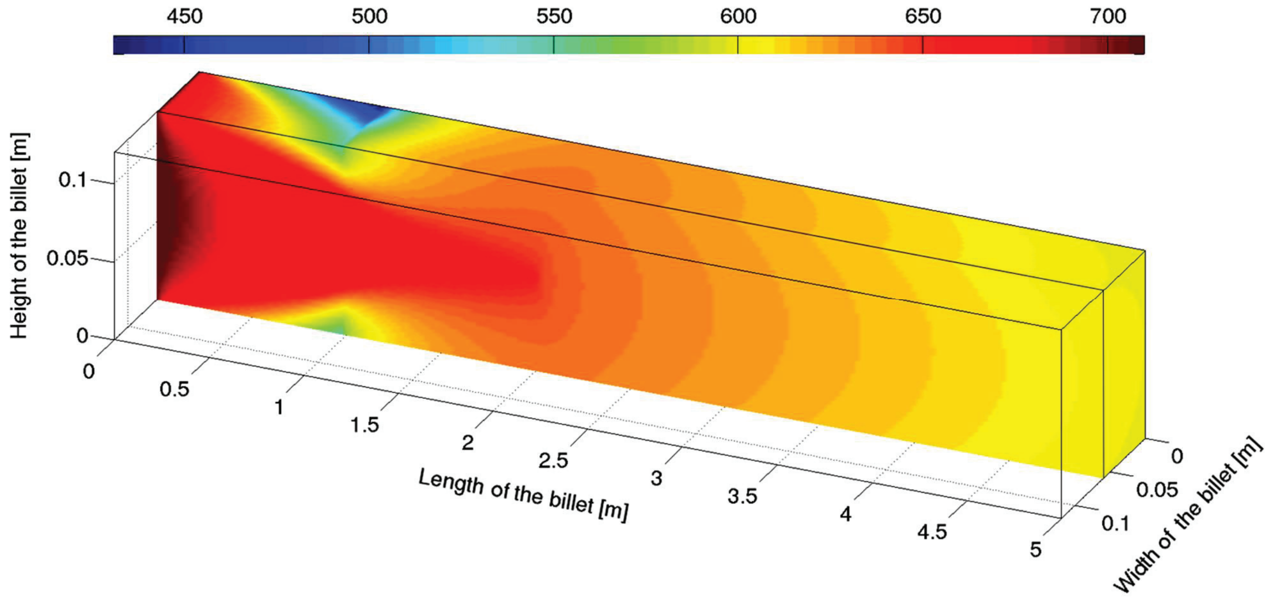

Figure 5 3D temperature distribution of the billet

However, the plot shown in **Figure 5** is rather unsuitable for the comparison as it would be difficult to observe differences between results. **Figure 6** shows more convenient visualization of the results - the phase interface separating the liquid and solid phases in the longitudinal cross-section of the billet. As can be seen in **Figure 6**, both the models provide comparable results. The phase interface computed by the fully 3D enthalpy-based model (blue curve) is coarser as it is computed by means of the interpolation which is a typical approach for interface capturing methods. On the other hand, the slice model results in a smoother phase interface which is due to tracking of the interface, higher accuracy of the method [11] and due to higher resolution as the slice moves through the billet in the casting direction. The difference in the so-called metallurgical length (the distance between the pouring level and the end of liquid phase) is about 10 cm. The difference is mainly caused by higher inaccuracy of the fully 3D enthalpy-based model and also due to the nature of the slice model which ignores interactions in the casting direction.

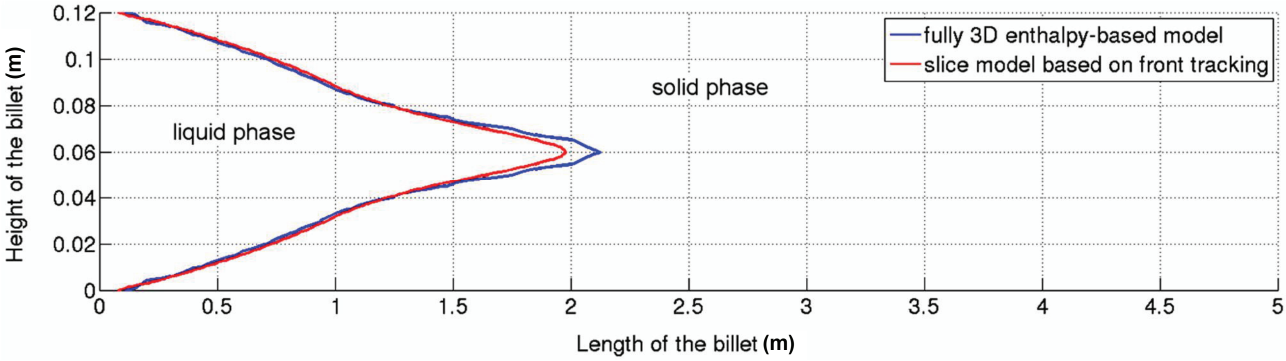

Figure 6 Simulated phase interface in the longitudinal cross-section of the billet

Figure 7 presents phase interface locations in perpendicular cross-sections of the billet at the distance a) 1m, b) 1.5 m, and c) 1.9 m from the pouring level. Similar conclusions as in case of **Figure 6** can be made. As can be seen in **Figure 6-7**, results computed by the models are comparable to each other; experimental results would be needed for a more detailed comparison. However, computational results indicate that the slice model is significantly faster with a higher accuracy of the front tracking [11]. Moreover, the front tracking method applied in the slice model has also further possibilities for detailed simulations of solidification.

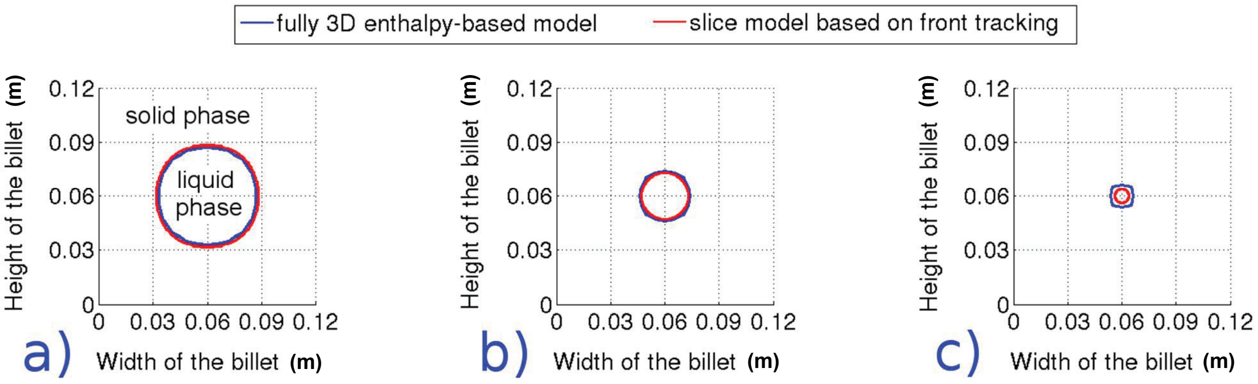

Figure 7 Simulated phase interface in the perpendicular cross-sections of the billet at the distance of a) 1m, b) 1.5 m, and c) 1.9 m from the pouring level in the mould

5. CONCLUSION

Computer models of casting processes are important tools for metal makers and they allow for optimization of metal properties and for the reduction of defects. The paper presents the front tracking slice model for simulations of the continuous casting of aluminum. The results were compared with the “traditional” fully 3D enthalpy-based model with the conclusion that the models provide comparable results. However, the slice model is faster than the fully 3D model and previous results indicate higher accuracy of the front tracking method and its capability for more detailed simulation of the solidification process and of the formation of structure. Such approach is therefore a promising way applicable in computer simulations of metal casting.

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