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Numerical analysis of the thermal and fluid flow phenomena of the fluidity test

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Abstract

In the paper, two mathematical and numerical models of the metals alloy solidification in the cylindrical channel of fluidity test, which take into account the process of filling the mould cavity with molten metal, has been proposed. Velocity and pressure fields were obtained by solving the momentum equations and the continuity equation, while the thermal fields were obtained by solving the heat conduction equation containing the convection term. Next, the numerical analysis of the solidification process of metals alloy in the cylindrical mould channel has been made. In the models one takes into account interdependence of the thermal and dynamical phenomena. Coupling of the heat transfer and fluid flow phenomena has been taken into consideration by the changes of the fluidity function and thermophysical parameters of alloy with respect to the temperature. The influence of the velocity or the pressure and the temperature of metal pouring on the solid phase growth kinetics were estimated. The problem has been solved by the finite element method.

Keywords: Solidification; Molten metal flow; Fluidity test; Mathematical and numerical modeling

1. Introduction

Much research has been devoted toward process development for the production of high quality casting goods at low costs. The pouring of molten metal into the mould: this is one of the critical steps in foundry technology, since the behaviour of the liquid and its subsequent solidification and cooling determine whether the cast shape will be properly formed, internally sound and free from defects. The castability is basic technological property that can have an advantageous influence on obtained sound casting [1]. Much work has been carried out to assess the fluidity of casting alloys by various methods of the fluidity test. Currently, the fluidity of the alloys is often measured by using the spiral fluidity test [2,3], the vacuum fluidity test [4] and the fluidity test which consist in the pouring of molten metal into the cylindrical channel in the real vertical mould [5,6]. In these works the results of investigation of the influence pouring temperature on the intensity flow of liquid metal in the fluidity test have been presented. Additionally it has been determined time and speed flow of metal in determined points of these fluidity tests. These are basic information requirements that are expected from the fluidity test at the present time [6,7]. Another approach, although satisfies above requirements, it seems to be the numerical simulation of the molten metal flow process in the vertical channel of the fluidity test. The mathematical model takes into consideration interdependence of the thermal and dynamical phenomena. This is a complex and difficult problem to solve numerically [1,5,8-10]. The analysis of these phenomena is often limited only to their proceedings during the filling process of the slender inlet channel [11-13] or the cylindrical mould of fluidity test [14]. Just as for the case of the cavities, geometric considerations allow further simplification of the governing equations. Making assumptions relating to both the material and the geometry of the region, the general equations for continuity and momentum have been reduced to single equation for pressure. This approach leads as to accelerate significantly of the numerical calculations [11-13].

In the present study, two mathematical and numerical models of the metals alloy solidification process in the cylindrical channels of the fluidity test during its filling, has been proposed. Mathematical models take into consideration interdependence of thermal and dynamical phenomena. Coupling of the thermal and fluid flow phenomena has been taken into consideration by the changes of the fluidity function and the thermophysical parameters of alloy with respect to the temperature. The influence of pouring parameters and rate of heat transfer on molten metal flow and its stopping moment were estimated. The whole task, was solved using the finite element method [5,8-12,15].

2. Mathematical model of heat transfer during the molten metal motions

The proposed model for the numerical simulation of solidification gives consideration to the motions of metal liquid phase during the mould cavity filing process. It is based on solving the following system of differential equations in a cylindrical axisymmetry coordinate system [5,8,11,13]:

$$\frac{\lambda}{r}\frac{\partial T}{\partial r}+\frac{\partial}{\partial r}\left(\lambda\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right)-C_{ef}\left(\frac{\partial T}{\partial t}+v_r\frac{\partial T}{\partial r}+v_z\frac{\partial T}{\partial z}\right)=0 \quad (1)$$

$$\mu\left(\frac{\partial^2 v_r}{\partial r^2}+\frac{1}{r}\frac{\partial v_r}{\partial r}+\frac{\partial^2 v_r}{\partial z^2}-\frac{v_r}{r^2}\right)-\frac{\partial p}{\partial r}+\rho g_r=\rho\frac{dv_r}{dt}, \quad (2)$$

$$\mu\left(\frac{\partial^2 v_z}{\partial r^2}+\frac{1}{r}\frac{\partial v_z}{\partial r}+\frac{\partial^2 v_z}{\partial z^2}\right)-\frac{\partial p}{\partial z}+\rho g_z=\rho\frac{dv_z}{dt}, \quad (3)$$

$$\frac{1}{r}\frac{\partial}{\partial r}(rv_r)+\frac{\partial v_z}{\partial z}=0, \quad (4)$$

where: $T(\mathbf{x},t)$ - the temperature [K], λ - the thermal conductivity coefficient [W/(mK)], $\rho=\rho(T)$ - the density, t - time [s], p - the pressure [N/m^2], r - the internal radius of the channel [m], $C_{ef}(T)=\rho_{LS}c_{LS}+\frac{\rho_S L}{T_L-T_S}$ - the effective heat capacity of the mushy zone [J/(m^{3}K)], c_{LS} - the specific heat of the mushy zone [J/(kgK)], $\rho_S, \rho_L, \rho_{LS}$ - the density of solid phase, liquid phase, and mushy zone, respectively [kg/m^3], L - the latent heat of solidification [J/kg], $\mathbf{x}(r, z)$ - the coordinates of the vector of the considered node's position [m], $\mathbf{v}(v_r, v_z)$ - the velocity vector of molten metal flow [m/s], $\mu(T)$ - the dynamical viscosity coefficient [Ns/m^2], $\mathbf{g}(g_r, g_z)$ - the vector of the acceleration of gravity [m/s^2].
In the applied model of the solid phase growth, the internal heat sources are not come evident in the equation of heat conductivity, because they are in the effective heat capacity of the mushy zone [5,8-11,14,15].

3. Simplified mathematical model of the molten metal flow and heat transfer

System of differential equations describing the coupling of the thermal and fluid flow phenomena during the filling process of the cylindrical channels of the fluidity test is us follows [11,13]:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\lambda\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right)-C_{ef}\left(\frac{\partial T}{\partial t}+v_r\frac{\partial T}{\partial r}+v_z\frac{\partial T}{\partial z}\right)=0, \quad (5)$$

$$\frac{\partial}{\partial z}\left(r_S S_1\frac{\partial p}{\partial z}\right)=0, \quad (6)$$

where: $S_1=\frac{1}{2r_S}\int_0^{r_S}\frac{r'^3}{\mu}dr'$ - the fluidity function [m^5/(Ns)].

The z-component of velocity (v_z) as follows [11,13]:

$$v_z(r)=\frac{1}{2}\frac{\partial p}{\partial z}\left[\int_0^{r}\frac{r'}{\mu}dr'-\int_0^{r_S}\frac{r'}{\mu}dr'\right] \quad (7)$$

where: r_S - the radius indicating of the melt-solid interface [m].
Equation (6) is a single equation for pressure that combines the momentum and continuity equations. The system of equations (1-4) and (5-7) is completed by the appropriate initial conditions and the boundary conditions gave in work [1,5,15,16]. The above problem was solved by the finite element method in the weighted residuals formulation [5,8-12,15].

4. Example of numerical calculations

The calculations were made for the system casting-mould-ambient. The given dimensions of the essential elements of that system were as follows: d=0.017, d_M=0.067, h=0.135[m], δ=0.15[mm] [5,16]. The numerical calculations were made for Al-4.5% Cu alloy which poured into a cast iron mould. The thermophysical properties were taken from works [5,15] and calculations were made according to relationships shown in works [17]. The linear change of density (ρ) and thermal conductivity (λ) was assumed in $T_L \div T_S$ temperature interval. The variability of the dynamical viscosity coefficient (μ) with respect to temperature was determined according to relationship in [17]. The overheated metal with temperature T_{in}=1003[K] was poured with velocity v_{in} = 0.048[m/s] or the pressure p_{in}=1[N/m^2] into the mould with initial temperature T_M=423[K].

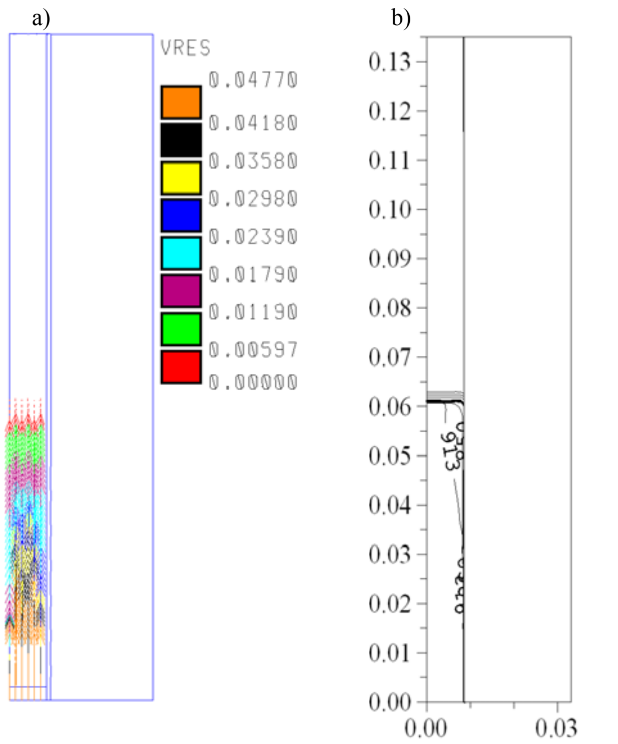

Fig. 1. Velocity vectors (a) and temperature field (b) during the mould cavity filling of the vertical fluidity test (general model)

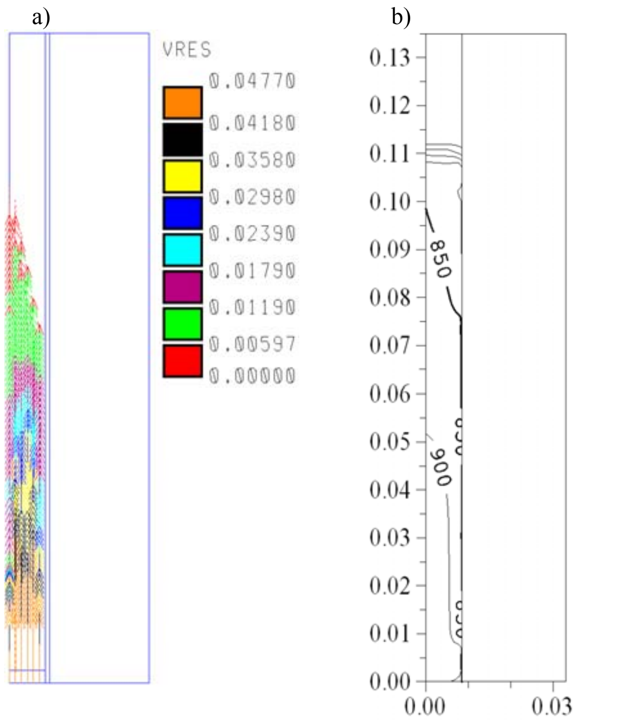

Fig. 2. Velocity vectors (a) and temperature field (b) after stopping of the molten metal flow (general model)

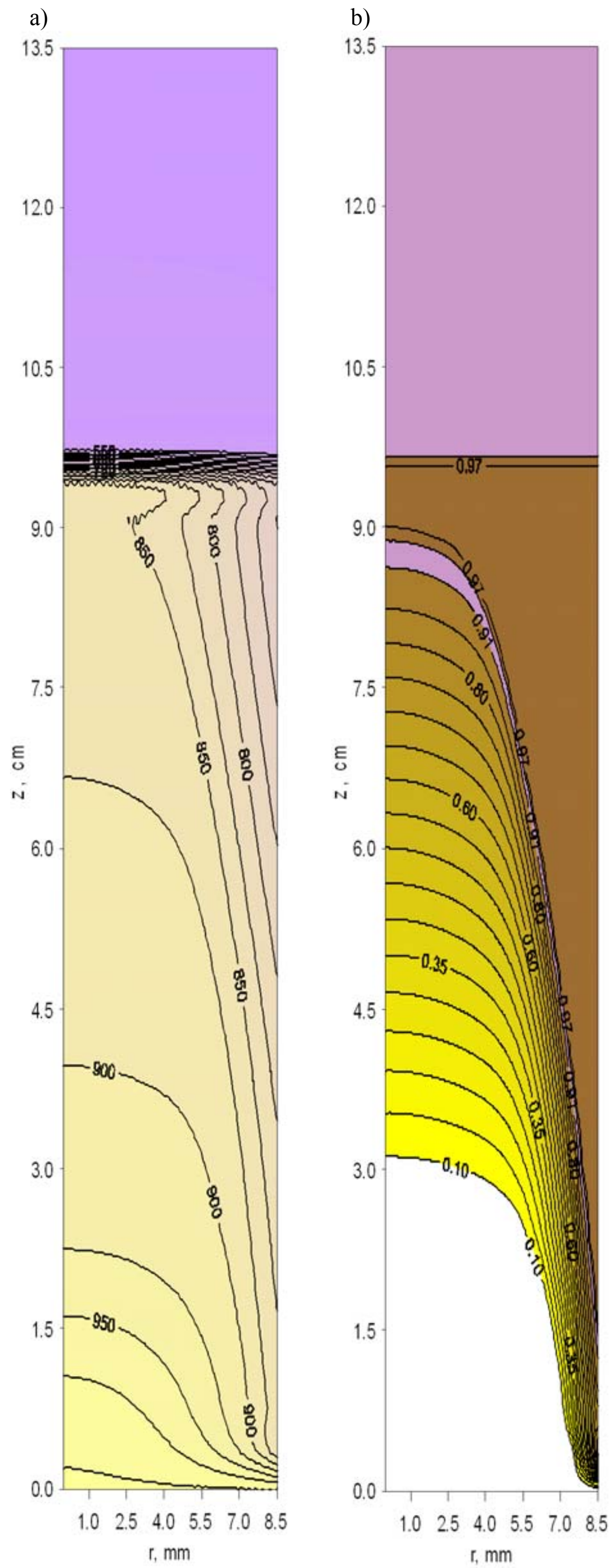

Fig. 3. Temperature field (a) and solid phase fraction (b) after stopping of the molten metal flow (simplified model)

The remaining characteristic temperatures were equal to: T_L =913[K], T_S =850[K] and T_a =300[K]. Thermal and flow phenomena, which proceeded in the mould cavity during filling until total solidification of the casting, were analysed by the general model (Fig.1-2) and the simplified model (Fig3). The influences of liquid metal movement inside the mould on the solidification kinetics of the casting were determined. Examples of calculation results are shown in the form of the temperature, solid phase fraction and velocity fields.

5. Conclusions

This paper has presented the coupled model of solidification for the transient evaluation of fluid flow and heat transfer during casting solidification processes. The changes in the thermophysical parameters, with respect to temperature, were taken into consideration. The problem was solved by the finite element method. Numerical analysis included filling process of the mould cavity with molten metal, fluid flow, convectional motions of molten metal and solidification process. The influence of the velocity or pressure and the temperature of metal pouring on the solid phase growth kinetics and the moment of stopping of the fluid flow, were estimated. It was noticed, that length of the way of alloy flowing in the channel of the fluidity test, depends more from the speed or the pressure of pouring than from the temperature of pouring.

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