The modelling of Hydraulic and Thermic Phenomena Specific of Casting Alloys

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ABSTRACT

This paper presents the basic phenomena at the casting process of alloys. Are modelled the flowing stage and the transformation from liquid phase into solid phase, in presence of hydraulic, thermic and contraction phenomena of alloy.

For the solving of physic model are used schemes with explicit discretization, based on SOLA-VOF method for flowing, and finite differences for the thermic conductivity. The approach was made in 3-D system.

Based on this general model, we made a particular model for the steel casting in the metallic ingot mold. Also, based on this model we had some conclusions on the possibilities and the conditions of the thermoreactive powder using.

1. INTRODUCTION

The modelling of the casting phenomena problems is very complex through the multitude of physical phenomena which are implied. So, on the international level, the important metallurgical producers appeal to the numeric modelling in order to assure the analysis on the scientific basis of the basic technologies for the metallurgical processing.

In Romania, at Technical University of Cluj-Napoca, exist systematic preoccupation in the approach of the numeric modelling of solidification process, with all implications on the casting technology. [1],[2],[3],[4],[5],[6],[7],[8],[9],[10]

The Conferences :"Modelling of Casting Welding and Advanced Solidification Process" [11],[12] shown some difficulties in the 3-D approach of the problem, the flow with a free surface and the coupling of physics phenomena implied.

This paper proposes the presentation of general model connected by the numeric modelling of the steel solidification into ingot mold, with the notification that this model is a solution granting the highest of performances, containing novelties in the algorithm of alloy free surface motion and including the contraction evolution and shrinkhole forming.

2. METHOD DESCRIPTION

In the achievement of physical-mathematical model we consider that the domains which take part in the solidification process have the following structure : the alloy domain (liquid alloy, alloy during the solidification process, solid alloy); the mold domain; the shrinkhead casting domain; the metallic mold domain; the thermoreactive powder domain; the environment.

The characterisation of these was made using geometric and with the help of the physical characteristics (density, viscosity, specific heat, latent heat of solidification, thermic conductivity, thermic capacity of the thermoreactive powder, the coefficients of the thermic transfer specific of the alloy - environment interfaces, technological elements - environment).

The physics phenomena included in this model consider the alloy flowing like a viscous fluid, the heat transfer and the contraction presents at the solidification with their implications in the shrinkhole forming process.

The alloy flowing under the gravitational and viscous forces action and the pressure gradient is described through the speed field and the pressure field. The evolution of these is given by the Navier-Stokes equations, the continuity equation and by the conditions at the free surface.

Thermic transfer during flowing and solidification is given by Fourier equation (thermic conduction).

This equation is linked with the initial and limit conditions, Cauchy, Dirichlet and Neumann type. The equations are applied to the participant domains.

3. THE ESTABLISHING OF THE NUMERIC ALGORITHM

In the time of mold filling, the position of liquid alloy, the speeds field and the pressures field are determinate by the interactions of viscous forces, of gravitational forces, of moments and the continuity conditions. The connection of these is given by the Navier-Stokes equations, continuity equation and volume function equation :

$$\frac{\partial u}{\partial t}+\frac{\partial u}{\partial x}u+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\nu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right) \quad (1)$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial y}+\nu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right) \quad (2)$$

$$\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial z}+\nu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right) \quad (3)$$

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \quad (4)$$

$$\frac{\partial F}{\partial t}+u\frac{\partial F}{\partial x}+v\frac{\partial F}{\partial y}+w\frac{\partial F}{\partial z}=0 \quad (5)$$

In the Navier-Stokes equations (1)-(3), the signification of the variables is :

$\frac{\partial u}{\partial t}$ - the local variation of speed u;

$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}$ - the advective variation of the speed u;

$\frac{1}{\rho}\frac{\partial p}{\partial x}$ - the pressure gradient in the Ox direction;

$\nu(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2})$ - the viscous acceleration in the Ox direction;

ρ - the density of the alloy;

ν - the dynamic viscousity coefficient;

and similar for the v and w components of the speed.

In the continuity equation (4) is expressing the conditions as the divergence of the speed to be zero.

The terms of the equation (5) represent :

$\frac{\partial F}{\partial t}$ - the local variation of the volume function;

$\frac{\partial F}{\partial x}u+v\frac{\partial F}{\partial y}+w\frac{\partial F}{\partial z}$ - the advective variation of the volume function.

For the numeric solving of the system (1)-(5) is used SOLA-VOF (Solution Algorithm Volume of Fluid) method, based on a scheme with explicit finite differences applied to a crossing grille. The points of the grille used for computing u, v and w components of a speed field are situated at equal distances planes, parallel with the co-ordinate planes, and theirs intersection form a parallelepiped cells network with constant dimensions px,py and pz.

In the knots from the centre of the cells are computed the values of the pressure field, the temperature field and the volume function F (Fig.1). F value is the ratio between the volume of the fluid from the interior of the cell and the volume of the cell. F=1 corresponding to a full cell and F=0 corresponding to an empty cell. For the others cells, function F have the values between 0 and 1.

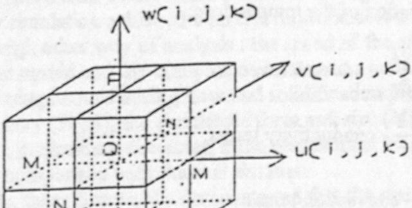


Fig.1. The (i,j,k) cell and the knots of the crossing grille

For the modelling of the thermal transfer exist more variants. A simply variant contains in the equations, only the terms which express the thermic change through conductivity and convection.

This situation is shown in the equations (6)-(8), the 3-D problem of the thermic conductivity become an 1-D equations system with finite differences :

$$\frac{T_{i,j,k}^{n+1/3}-T_{i,j,k}^{n}}{\Delta t}=\frac{a}{3}\,\frac{T_{i+1,j,k}^{n+1/3}-2T_{i,j,k}^{n+1/3}+T_{i-1,j,k}^{n+1/3}}{\Delta x^2} \qquad (6)$$

$$\frac{T_{i,j,k}^{n+2/3}-T_{i,j,k}^{n+1/3}}{\Delta t}=\frac{a}{3}\,\frac{T_{i,j+1,k}^{n+2/3}-2T_{i,j,k}^{n+2/3}+T_{i,j-1,k}^{n+2/3}}{\Delta y^2} \qquad (7)$$

$$\frac{T_{i,j,k}^{n+1}-T_{i,j,k}^{n+2/3}}{\Delta t}=\frac{a}{3}\,\frac{T_{i,j,k+1}^{n+1}-2T_{i,j,k}^{n+1}+T_{i,j,k-1}^{n+1}}{\Delta z^2} \qquad (8)$$

In the general case of the thermic changing in the time of cavity filling, the equations become more complex. Here, are take into account also, the factors which correspond to advective change, very important. In the flowing time, the advective change is the factor which determine the greatest variation of the temperature. In this case, the equation of the thermic transfer become (for continue domain) :

$$\rho c\left(\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}\right)=k\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)+\alpha\left(\frac{\partial T}{\partial x}+\frac{\partial T}{\partial y}+\frac{\partial T}{\partial z}\right) \qquad (9)$$

where :

ρ - the density of the metal;

c - specific heat;

k - conductivity coefficient;

α - the coefficient of the convective changing;

$\frac{\partial T}{\partial t}$ - local variation of the temperature;

$u\frac{\partial T}{\partial x}, v\frac{\partial T}{\partial y}, w\frac{\partial T}{\partial z}$ - advective terms;

$\frac{\partial^2 T}{\partial x^2}, \frac{\partial^2 T}{\partial y^2}, \frac{\partial^2 T}{\partial z^2}$ - conductivity terms;

$\frac{\partial T}{\partial x}, \frac{\partial T}{\partial y}, \frac{\partial T}{\partial z}$ - convection terms.

The discretization form for the equation (9) is [3],[4] :

$$T_{i,j,k}^{n+1} = T_{i,j,k}^{n} - \Delta t[u_{i,j,k}^{n}(T_{i+1,j,k}^{n} - T_{i,j,k}^{n})/\Delta x + v_{i,j,k}^{n}(T_{i+1,j,k}^{n} - T_{i,j,k}^{n})/\Delta y +$$

$$+ w_{i,j,k}^{n}(T_{i,j,k+1}^{n} - T_{i,j,k}^{n})/\Delta z + \frac{k\Delta t}{\rho c}[(T_{i,j+1,k}^{n} - 2T_{i,j,k}^{n} + T_{i,j-1,k}^{n})/\Delta x^2 + (T_{i+1,j,k}^{n} - 2T_{i,j,k}^{n} + T_{i-1,j,k}^{n})/\Delta y^2 +$$

$$(T_{i,j,k+1}^{n} - 2T_{i,j,k}^{n} + T_{i,j,k-1}^{n})/\Delta z^2] + \frac{\alpha\Delta t}{\rho c}[(T_{i,j+1,k}^{n} - T_{i,j,k}^{n})/\Delta x + (T_{i+1,j,k}^{n} - T_{i,j,k}^{n})/\Delta y + (T_{i,j,k+1}^{n} - T_{i,j,k}^{n})/\Delta z]$$

Through the solving this problem can be shown some phenomena, which cannot be obtained through the classic way of analysis (the speed of the alloy flow in the interval between the filling of the mould and the complete transition to a solid phase, the distribution of the alloy temperature during flow and solidification, the percentage of the solid alloy, the shrinkhole form and size) and as a final result, the optimisation of the technological parameters (optimisation of the technological correlation between casting temperature, casting speed and environment temperature, the optimisation of the thermic system, optimisation of filling intervals, considering the form, size and distribution of the shrinkhole).

4. THE STRUCTURE OF THE COMPUTING PROGRAM

Based on this general model, was elaborated a special form for the casting of the steel ingots.

a) Discretization - the ingot mold with the space of the ingot was represented through the cubic cells with 112 mm side situated into a volume with the size 7x7x20mm (980 cells). The physical processes which took place in the interval of the one hour from the beginning of casting was simulated, 4200 time steps being necessary for the analysis.

b) Participant domains - we didn't take into account the influence of shrinkhead casting and thermoreactive powder. The ingot mold material was a gray cast iron with the characteristics : c=600J/kgK; ρ=7100kg/m^3 ; λ=40W/mK. For the material of ingot mold we consider a steel with the follow characteristics in the solid state : c=550J/kgK; T_t=1580C T_1=1530^0 C; Ts=1490^0 C; L=250000J/kg; ρ=7284kg/m^3 ; λ=35W/mK.

c)Technological parameters - the casting time was 9 min; the feeding was made on a single cell; the entrance speed didn't vary in the period of the ingot mold filling.

The preliminary simulation achieved with this model shows some phenomena, which cannot be obtained through other way of analysis : the speed of the alloy flow in the interval between the filling of the mould and the complete transition to a solid phase (Fig.2), the distribution of the alloy temperature during flow and solidification process (Fig.3), the percentage of the solid alloy (Fig.4), the shrinkhole form and size (Fig.5).

The results had a preliminary character, these results must be assessed by the next experiments and by the comparison with the real situation.

On the other side, these first results demonstrated that the assumption : the flowing of liquid alloy from the ingot mold can be negligible is an affirmation less plausible. The explanation consist in the existence of a vertical currents which generate a difference between the temperature in the bottom part of the ingot mold, which is less, and the temperature in the upper part of the mold, even at a little speed of feeding.

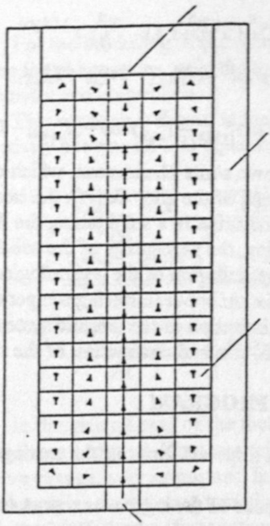
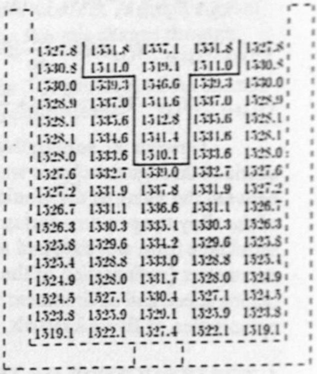
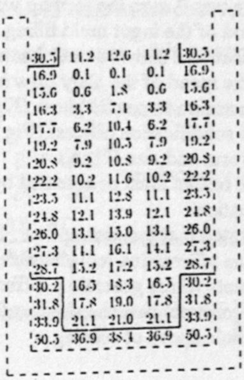


Fig.2. The speed of the alloy flow



1527.8	1551.8	1557.1	1551.8	1527.8
1530.8	1511.0	1519.1	1511.0	1530.8
1530.0	1539.3	1546.6	1539.3	1530.0
1528.9	1537.0	1511.6	1537.0	1528.9
1528.1	1535.6	1512.8	1535.6	1528.1
1528.1	1534.6	1541.4	1531.6	1528.1
1528.0	1533.6	1510.1	1533.6	1528.0
1527.6	1532.7	1539.0	1532.7	1527.6
1527.2	1531.9	1537.8	1531.9	1527.2
1526.7	1531.1	1536.6	1531.1	1526.7
1526.3	1530.3	1535.1	1530.3	1526.3
1525.8	1529.6	1534.2	1529.6	1525.8
1525.4	1528.8	1533.0	1528.8	1525.4
1524.9	1528.0	1531.7	1528.0	1524.9
1524.5	1527.1	1530.4	1527.1	1524.5
1523.8	1525.9	1529.1	1525.9	1523.8
1519.1	1522.1	1527.4	1522.1	1519.1

Fig.3. The distribution of the alloy temperature



30.5	11.2	12.6	11.2	30.5
16.9	0.1	0.1	0.1	16.9
15.6	0.6	1.8	0.6	15.6
16.3	3.3	7.1	3.3	16.3
17.7	6.2	10.4	6.2	17.7
19.2	7.9	10.5	7.9	19.2
20.8	9.2	10.8	9.2	20.8
22.2	10.2	11.6	10.2	22.2
23.5	11.1	12.8	11.1	23.5
24.8	12.1	13.9	12.1	24.8
26.0	13.1	15.0	13.1	26.0
27.3	14.1	16.1	14.1	27.3
28.7	15.2	17.2	15.2	28.7
30.2	16.5	18.3	16.5	30.2
31.8	17.8	19.0	17.8	31.8
33.9	21.1	21.0	21.1	33.9
50.5	36.9	38.4	36.9	50.5

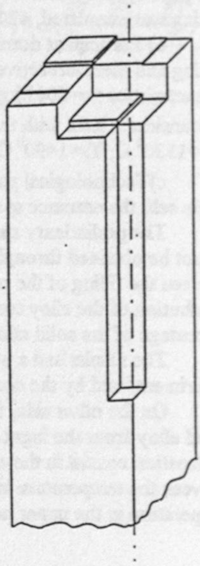


Fig.4. The percentage of the solid alloy

Fig.5. The shrinkhole form and size

5.THE POSSIBILITIES OF ANALYSIS FOR THIS MODEL

This model gives a new tool of analysis and creates multiple possibilities for the interpretation and optimisation of the casting process of the mold ingots, in view of the energetic and materials consumption reducing and the increase of the quality of the parts.

Tab.1 snows the largest number of the parameters which influenced a numeric simulation of the ingot casting (over 50). For to show the influence of one parameter on the simulation process are necessary over 3 simulations with different values of this parameter. Result that the minimum number of simulations for the technology optimisation in over 100.

The model gives the following possibilities of analysis : optimisation of the technological correlation between casting temperature, casting speed and environment temperature; optimisation of the thermic system; optimisation of the filling intervals, considering the form, size and distribution of the shrinkhole; study about the influence of the environment temperature on the quality of the ingot mold; study about the influence of the ingot mold on the quality of the ingot; study about the influence of the thermoreactive powder on the volume and distribution of shrinkhole; study about the undesirable technological processes in the ingot obtaining field.

As an example for the using of numeric simulation at the optimisation of casting technology we was consider the using of the thermoreactive powder.

We consider that the dynamic state, with the alloy in motion is technologically correct (Fig.2); the heating is produced in the upper of the ingot, but, also, in the mass of steel.

The results of the simulation can give the optimal values of the following parameters: the moment of the powder introducing; the duration of the introducing; the quantity of powder; the zone of the free surface of the ingot where must introduced the powder; the optimal state of the steel motion.

Tab.1. Parameters for a numeric simulation

Numeric parameters	Physics parameters	Technological parameters
- time step (2 param.) - maximum divergence(1param.) - spatial step of the network on the 3 coordinate axis (1-3 par.) - speed (1 param.)	- physic properties of the alloy in the solid and liquid phase and the variation with the temperature (over 12 param.) - alloy viscousity and the variation with the temperature (2 param.) - solidus and liquidus temperature (2 param.) - specific heat and thermic conductivity of the ingot mold material (2 param.) - specific heat and thermic conductivity of the shrinkhead material (2 param.) - thermic power of the thermoreactive powder (1param.) - thermic transfer coefficients (3 param.)	- the geometry of the ingot mold (over 3 param.) - the geometry of the shrinkhead (over 3 param.) - quantity of the powder (1 param.) - time of the powder introducing (2 param.) - casting , ingot mold and environment temperature (3 param.) - the zone of powder introducing (over 2 param.)

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