Visualization of Process of Wheel Steel High Ingots Simulation

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Abstract. The mathematical model for computation of formation of wheel steel high ingots has been formulated based on the generalized system of equations consisting of the Navier-Stokes equation, the turbulent heat and mass transfer equation and the continuity equation. It is suggested to use a pattern when designing software for simulation of hydrodynamic and thermophysical processes. A software complex with friendly input and output data flows is provided for technologists of metallurgical production.

1. Introduction
Production of round ingots for making wheels or pipes is an important economic task, at the same time their continuous casting is impeded by high probability of crack formation. Therefore, the production is based on ingots casting into moulds.

Simulation of hydrodynamic and heat and mass transfer processes during casting and formation of metallurgical products is related to solution of complex non-linear multidimensional equations for computation of hydrodynamic and heat and mass transfer processes.

Nowadays, simulation systems are used in different industries, in particular in iron and steel industry, more and more often, which can be explained by apparent cost efficiency compared to pilot studies. The following classification features emphasize specific aspects of individual systems of computer-aided simulation [1] (Table 1).

In addition, there are also computational packages of overall profile, which, among other things, allow simulating transfer processes, such as ANSYS and COMSOL Multiphysics.

The expectations that modern integrated packages would easily implement complex models are not always met. Firstly, they are designed for calculation of streams of certain type, and any task different from a standard one requires significant preliminary actions: comparison of solutions received at different packages; evaluation of convergence and stability of the task, etc. It brings to nothing a key advantage of integrated packages – simplicity of mathematical models implementation. Secondly, if a package generates a finite-difference grid (finite elements) independently, then the major criteria is not the physics of streams, but the object geometrics; this could result in the generated grid failing to provide correct values in the area of large velocity gradients. Thirdly, these packages almost do not consider changes of metal state of matter.
Besides, a technologist, for whom the simulation results are eventually intended, shall be provided with a software product with friendly interface and input and output data flows convenient and clear to a production worker.

Therefore, development of application software packages (ASP) with comprehensive tools of computation visualization remains preferable at the moment for simulation of tasks of hydrodynamics and heat and mass transfer in metallurgical processes.

2. Mathematical Model
When designing the ASP, the authors suggest to use a pattern of Model-View-Controller (MVC), which is a scheme of partitioning of data of the application, the user interface and the control logic into three distinct components: a model, a view and a controller, in such a way that modification of each component can be done independently from others [2].

The model provides data and methods of working with them. In our case, the “Model” component in the basis includes libraries of classes and sub-programmes for computation of the given task of simulation of hydrodynamic and heat and mass transfer processes [3–13]. To describe processes of impulse, heat and mass transfer in molten metal, a mathematical model, which consists of equations of flow, continuity, heat and mass transfer, gaseous phase, turbulent kinetic energy \((k)\), its dissipation rate \((\varepsilon)\), and an equation for a solid phase part, is suggested \(\xi\):

\[
\frac{\partial \bar{V}}{\partial t} + (\bar{V}V) = \nabla (\nu \bar{V}V) + g\beta_T (T - T_0) + g\beta_D (C - C_0) - \frac{1}{\rho} \nabla p ; \\
\rho c \left[ \frac{\partial T}{\partial t} + (\bar{V}V)T \right] = \nabla (\lambda \bar{V}T) ; \\
\frac{\partial C}{\partial t} + (\bar{V}V)C = \nabla (D \bar{V}C) ; \\
\nabla \bar{V} = 0 ; \\
\frac{\partial k}{\partial t} + (\bar{V}V)k = \nabla (\nu \bar{V}k) + G - g\beta_T (T - T_0) - g\beta_D (C - C_0) - \varepsilon ;
\]

Table 1. Specific Aspects of Individual Systems of Computer-Aided Simulation.

| Name                | Application Functionality Level | Methods for Solving Mathematical Physics Equations | Orientation Towards Simulation |
|---------------------|--------------------------------|---------------------------------------------------|-------------------------------|
|                     | Special | General | Medium | High | Finite Differences (FD) | Finite Elements (FE) | Finite Volumes (FV) | Of Individual Physical Processes | Of Casting Technology Options in General |
| WinCast (FRG)       | +       | +       | +      | +    | +                      |                       |                       |                               |                                |
| MAGMASoft (FRG)     | +       | +       | +      | +    | +                      |                       |                       |                               |                                |
| ProCast (USA, Switzerland) | +       | +       | +      | +    | +                      |                       |                       |                               |                                |
| Poligon (Russia)    | +       | +       | +      | +    | +                      |                       |                       |                               |                                |
| LVMFlow (Russia)    | +       | +       | +      | +    | +                      |                       |                       |                               |                                |
| FLOW-3D (USA)       | +       | +       | +      | +    | +                      |                       |                       |                               |                                |
\[ \frac{\partial \xi}{\partial t} + (\vec{V} \nabla) \xi = \nabla (\nu \theta \nabla \xi) + C_1 \nu G - \frac{\nu}{k} \frac{\partial}{\partial t} \left( T - T_0 \right) - \frac{\nu^2}{\kappa} \gamma \sqrt{\frac{\nu}{\kappa}} \] 

\[ \xi(y) = 1 \left( 1 + \frac{c}{W} (T_1 - T_s) \right) \left( 1 - \left( \frac{T_1 - T_0}{T_1 - T_s} \right)^{2\beta} \right) + \frac{c}{W} (T_1 - T_s), \] 

where \( \vec{V} \) is melting speed, \( \nu_\theta = \nu + \nu \) is effective viscosity, \( \nu \) is kinematic viscosity, \( \nu_t = k^2 / \kappa \) is turbulent viscosity; \( g \) is acceleration of gravity; \( \beta_T, \beta_D \) are heat and diffusion factors of volume expansion; \( T, T_0 \) is temperature current and initial; \( C \) is impurity concentration (carbon); \( C_0 \) is initial impurity concentration in the melt; \( \rho \) is melt density; \( \nu \) is pressure; \( c \) is coefficient of specific heat; \( \lambda_\text{ef} = \lambda + \lambda_t \) is effective thermal conductivity, \( \lambda \) is molecular thermal conductivity and \( \lambda_t = \nu_t / 0.9 \) is turbulent thermal conductivity; \( D_\text{ef} = (1 - \xi) D + \xi D_s \) is effective diffusion coefficient, \( D \) is in liquid phases and \( D_s \) is in solid phases; \( G \) is a dissipative term; \( k \) is turbulent energy, \( \varepsilon \) is turbulent energy dissipation rate; \( C_1, \sigma_t \) is empirical turbulence coefficients [4]; \( W \) is latent heat of crystallization; \( T_1, T_s \) is temperature liquids and solidus.

The mathematical model is based on principles of macro-continual mechanics of the multiphase media and the theory of the mushy zone [4, 5]. The model addresses turbulence, gas capture by molten metal (during mould filling), and thermal and mixed convection. The system of equations (1) to (7) is supplemented by boundary conditions. It is important to note that the represented model of turbulence is not always justified [4]. It can be considerably simplified to an algebraic one for some types of stream.

### 3. Mathematical Model Implementation

The “Controller” component provides interaction between a user and the system, it controls and transmits data from the user to the system and vice versa, it uses the Model and the View for implementation of the required action [3].

The “View” component is a central theme of this paper. The View is responsible for receiving necessary data from the Model and their display to the user. The View can influence the condition of the Model, reporting it to the Model.

The scheme of the graphical user interface is shown on Figure 1.

**Figure 1.** Graphical Interface.
The user can receive information in the following ways:
- By visualization of the area where computation is going on
- By curves of temperature, a share of the solid phase, a speed component, etc. at some horizontal or vertical slice
- By text view of computation arrays of temperature, a share of the solid phase, etc.
- Using values of selected data, such as shrinkage cavity.

Any window with information can be printed out. The time of computation, the per cent completion and prompt messages are displayed in the status line during operation.

The central section is a scheme of the two-dimensional area of computation. Generally, the task of simulation of metallurgical processes in moulds could be reduced to the two-dimensional axi-symmetrical model. The scheme of the computation area visualizes this model by colouring into different shades depending on the value of the selected field. Work with the fields of temperature, horizontal and vertical projections of the speed and a share of the solid phase is provided by default. But one can add any other fields representing two-dimensional arrays, for example, an array of local thermal stresses, etc. Interpretation of the computation area scheme is shown on Figure 2.

![Figure 2. Scheme of Computation Area.](image)

The area 1 (Figure 2) represents the coloured scheme of some continuous value distribution, for example, temperature. A certain colour stands for each specific range of this value. Besides, different vector characteristics can be applied to this area, in particular, speed vectors. 18 options of value ranges and colours related to them are provided. A user can view and change these parameters through a set of panels 6 (Figure 2). Each program user can adjust the scheme view based on own preferences.

Switching of output fields is done by a set of selective buttons 3 (Figure 2).

If a mathematical model designer provides a special marking array, where the area geometry is described, contours of internal and external boundaries of a mould, a filler, etc. are laid on to the coloured area.
In addition, functions, which allow laying different isolines (functions of current, vortex structure, isotherms, etc.) on the area, and arrows indicating the speed vector direction are also developed. These functions are called by buttons 4 (Figure 2). The button 5 (Figure 2) calls the setting dialogue box.

Also the information is output from the current (under the mouse pointer) cell of the computation grid to the area 7 (Figure 7).

The graphic component for charting is a container of objects—graphs organized as a list element. One chart is a sample of Graphics class designed for description of the diagram. Features of this class are such characteristics as colour, line type, line thickness, etc. Data for a chart can be received as static points and as function-type variables. For the dynamic-type data, only the initial initialization is required. Later when a window is refreshed, the chart automatically gets updated, because it works with the function address and not with constant values passed to it. The other component characteristics are the coordinate grid (the amount of its cells, the line thickness, the colour, etc.), and the legend (the caption text and font settings). Besides, the evaluator of the mouse movement event is determined so that it could display the value of the coordinate grid under the cursor as an additional message, which is shown on the condition panel during performance of the program.

We discuss the use of visualization during simulation of high ingots (up to 3 m) of wheel steel. The Figure 3 demonstrates the screen of the running program. A metallurgical production technologist, who is a user of the software complex, can both evaluate at glance the processes occurring during simulation, and conduct a more detailed analysis.

![Figure 3. Screen of Running Application.](image)

4. Mathematical Model Sufficiency
Experimental measurements of the liquid pool depth along the ingot axis during solidification (after completion of casting), the study of the shrinkage cavity depth in 8 ingots of KP-3 (Rus. “КП-2”) steel, measurement of temperature of steel and iron moulds surfaces during casting and solidification of wheel steel ingots were conducted at OJSC “INTERPIPE NTRP” in order to evaluate the precision of the calculation results.

The shrinkage cavity depth at the head part of wheel steel ingots was determined on head parts randomly selected after cutting and breakage from 12 ingots of four heats (three from each heat).

The time of hot top filling of the wheel ingot according to the Technological Instruction NTZ-M-02-2005-1 (Rus. “ИТЗ-М-02-2005-1”) para. 7.4.7 was 2 to 3 min (the speed of 70 to 120 mm/min). The level of hot top filling with metal was lower than the upper edge of inserts approximately by the heat-insulation mixture layer thickness of 50 mm. The results demonstrate that the shrinkage cavity
depth from the crown edge to the bottom of the open shrinkage cavity is 20 to 160 mm at the height of 130 to 190 mm from the crown edge to the ingot body.

In the numerical experiment, the shrinkage cavity depth was calculated under the condition of hot top filling with metal to the upper edge of the heat-insulation insert (mould butt end). In practice, it should be borne in mind that the metal pouring level is 40 to 50 mm lower than the upper edge of the slag mixture layer going to the hot top. During crystallization, metal level in the inserts goes down approximately by 50 mm, forming the level of the crown edge of the solid ingot top part [14].

The results of the numerical experiment of determination of open shrinkage cavity depth in ingots cast in iron and steel moulds during 10 to 18 minutes at the duration of filling of hot top insert 220 mm high of 120 to 160 seconds demonstrated that the shrinkage cavity depth in the entire study range is between 180 and 240 mm expectedly growing with the increase of the casting speed (Figure 4).

“T” and “S” are iron and steel moulds respectively

Figure 4. Calculation of Shrinkage Cavity Depth at Different Steel Casting Speed.

It should be noted that the shrinkage cavity depth received by numeric simulation is overstated, since the specific behaviour of the heat-insulation mixture, under which ingot casting is performed, when the metal is approaching the top part, is not taken into account.

Solidification of the ingot axial zone was evaluated by immersion of the metal rod into the ingot central part and determination of its immersion depth at different points in time.

The time of solidification of the ingot axial zone in the iron mould, according to simulation results, is about 90 minutes, and it coincides well with the pilot studies when extrapolating the curves.

Thus, the analysis of theoretical and pilot studies of wheel steel 8-billet ingot formation, conducted under conditions of the existing production of OJSC Interpipe NTRP, and the numerical experiment (Figure 5) demonstrated the appropriateness of the mathematical model, of the computational algorithm, and of the satisfactory correlation of the results obtained. The simulation uncertainty is 6%. 
5. Conclusions

Visualization of results of the mathematical simulation of processes in wheel steel high ingots is demonstrated via examples of solution of the generalized system of equations of hydrodynamics and turbulent heat and mass transfer. The sufficiency of the mathematical model and the computational algorithm is proved. The Model-View-Controller pattern is used for designing the software for simulation of hydrodynamic and thermo-physical processes. A software complex with friendly interface and broad capabilities of simulation process visualization is provided for technologists of metallurgical production.

References

[1] Volnov I N 2007 The Systems of Computer-Aided Modeling – Status, Problems, and Prospects 
    *Founder of Russia* 6 14–17

[2] Fowler M, Rice D, Foemmel M, Hieatt E, Mee R and Stafford R 2002 *Patterns of Enterprise 
    Application Architecture* (Addison-Wesley Professional) p 560

[3] Yu A Bazdyreva et al 2017 IOP Conf. Ser.: Mater. Sci. Eng. 192 012032

[4] Leibenson V A, Kondratenko V M, Nedopekin F V, Belousov V V et al 2009 *Solidification of 
    Metals and Metallic Compositions* (Kiev: Naukova Dumka) p. 446

[5] Anishchenko N F, Shablovsky V A, Belousov V V and Bondarenko V I 2006 *Metallurgical and 
    Mining Industry* 3 91–93

[6] Belousov V V, Babanin AY, Beskrovnya M V et al 2013 *Metallurgist* 56 933–37

[7] Shalapko Y I and Dobrzanski L A 2011 *Computer modeling of wheel steel ingots formation. 
    Scientific basics of modern technologies: experience and prospects. Monograph* 
    (Khmelnitsk: Khmelnitsky National University)
[8] Nedopekin F V, Belousov V V and Bondarenko V I 1997 *Artificial Intellect* 1–2 86-90
[9] Nedopekin F V, Belousov V V, Kondratenko V M et al 2005 *Solidification of Metal Compositions: Production and Simulation* (Donetsk: South-East) p 231
[10] Bondarenko V I, Bilousov V V, Nedopekin F V and Shalapko J I 2015 *Archives of Foundry Engineering* 15 13–6.
[11] Belousov V V, Bondarenko V I, Nedopekin F V, Bodryaga V V et al 2017 *Bulletin of Cherepovets State University* 1 20–7
[12] Nedopekin F V, Belousov V V, Bodryaga V V, Bondarenko V I and Stepanov A T 2017 *Bulletin of Cherepovets State University* 1 74-9
[13] Bodryaga V V, Nedopekin F V, Belousov V V and Okuneva T A 2017 *Bulletin of Cherepovets State University* 1 28-32
[14] Bondarenko V I, Komarov V F, Belousov V V, Nedopekin F V et al 2013 *Mathematical support and Computer Technologies for Simulation of Hydrodynamic and Thermophysical Processes in Metallurgy*. Monograph (Donetsk: South-East) p 210