MELT MOVEMENT IN THE HEARTH FURNACE FOR CHOSEN VARIANT OF GAS BLOWING

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Abstract

The agitation of melt in the hearth furnaces is complicated. It depends on introduced system of technological gases blowing, the shape of working profile of the hearth and a degree of hearth lining wear in the course of furnace campaign. In many cases it is insufficient. The results of experimental study on physical models of hearth furnaces with the considered variants of the blowing system are influenced by incomplete similarity of used physical quantities - dissimilarity in invariants of density and viscosity of melt with the model and the real hearth furnace. That is why it was concerned with the mathematical modelling of agitation effects of selected blowing variant on the movement of melt in the furnace hearth. The results of mathematical modelling of melt movement in the considered variants of blowing may serve not only for the selection of most suitable configuration of blowing system or blowing variant for the given furnace and conditions, but also, among others, to the prediction of erosion effects of flowing melt on the refractory lining of furnace hearth depending upon the gradient of velocity of melt flow in the vicinity of walls of furnace lining.

Keywords: Steel, hearth furnace, mathematical simulation, blowing of technological gases, melt agitation

1. INTRODUCTION

Possibilities and conditions for the experimental study of agitation of the melt of metal and slag in the hearth furnaces are considerably limited and the results of physical modelling of this issue are influenced by the incomplete similarity between the model and the real furnace. That is why we were concerned with the building of a mathematical model of transfer of mass and momentum of blown technological gases into the bath in the 3D system.

As the first step of numerical solving we excluded the effects of chemical reactions between melt components and blown technological gas (gases). The greatest emphasis was put on the study of effects of discharge stream from the nozzle (**Figure 1**).

Findings about insufficient bath agitation led already in the past to research into and also development in new optimal systems and regimes of technological gases blowing directed not only on the design of refining nozzles (for instance refining nozzles and post-combustion nozzles), but also on the design of system for bath homogenization by blowing an inert gas, the search for an optimal shape of hearth and the design of the whole furnace for the given technological and operational conditions [1], [2].

2. THE DETERMINATION OF BOUNDARY CONDITIONS OF NUMERICAL SOLVING FOR THE FLOW OF MELT IN THE HEARTH FURNACE

It was necessary, in the course of determination of determinative quantities of blown gas discharge from the main nozzle, to use at the considered distances from the nozzle mouth the numerical analysis of distribution of these determinative quantities in the discharge cross-sections as a basis. From this, the interval of their real integral values in the given cross-section of discharge stream from the nozzle then followed. Velocity of blowing gas at the nozzle mouth was 500 $m.s^{-1}$ [3]. After that, these values were assigned to the set of boundary conditions of numerical solving.

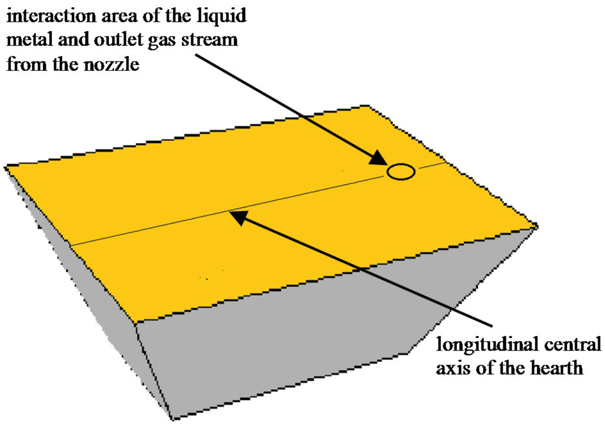

Figure 1 3D model of the experimental hearth

3. THE CHARACTERIZATION OF MULTIPHASE VOF MATHEMATICAL MODEL

For the mathematical modelling of molten steel flow in the hearth furnace, a numerical model was used after the analysis and the subsequent synthesis of all complicated phenomena taking place in the bath at oxygen blowing and with regard to the present level of knowledge in the area of mathematical modelling. It enables the modelling of flow of three considered immiscible phases, namely:

a single primary liquid phase, which is the liquid steel (melt metal) in the hearth of the furnace, and two secondary gas phases. One of them is technological gas blown into the bath, which is a source of its movement; the other secondary phase is a calm gaseous atmosphere above the level of the bath. In the considered solving, that is replaced by air. The used multiphase VOF model enables, as already mentioned, the mathematical modelling of two and multiphase flow of immiscible phases at taking into account their time-steady isothermal flow. In principle, this means that in the time-steady isothermal flow of mixture of molten steel, oxygen and air, the density and dynamic viscosity of them are invariable. The mathematical model is based on the solving of a system of differential equations, namely:

The law of conservation of mass expressed for the common phase (fluid) q in the form

$$\frac{\partial \alpha_q}{\partial t} + \vec{v} \cdot \nabla \alpha_q = 0 \qquad (1)$$

Then for the primary phase - liquid steel it is only expressed by the following condition

$$\sum_{q=1}^{N} \alpha_q = 1 \qquad (2)$$

from which it follows that the sum of volume fractions of phases is equal to one. (N is the number of all considered phases in the given space).

The law of conservation of momentum is defined by the following differential equation

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \cdot \left[\eta \left(\nabla \vec{v} + \nabla \vec{v}^{T}\right)\right] + \rho \vec{g} + F \qquad (3)$$

where

α_q	the volume fraction of phase q	(1)
v	the velocity of phase flow (fluid)	($m.s^{-1}$)
ρ	the density of considered phase	($kg.m^{-3}$)

η	the dynamic viscosity of phase	($kg.m^{-1}.s^{-1}$)
F	the external force influencing the motion of phase	(N)
p	the value of static pressure of considered phase	(Pa)
N	the total number of phases	(1)

Further, the functional dependence of distribution of velocity fields on the volume fractions of individual phases of the mixture represented by the density ρ and the dynamic viscosity η of them is evident from the expression of law of motion. With reference to this, the following relations apply to the determination of mean values of density ρ and dynamic viscosity η of mixture of N phases:

$$\rho = \sum_{q=1}^{N} \alpha_q \rho_q \tag{4}$$

$$\eta = \sum_{q=1}^{N} \alpha_q \eta_q \tag{5}$$

Numerical values of these quantities ρ and η are presented in the following table (**Table 1**) [4].

Table 1 Physical properties of phases

Phase	**Substance (Medium)**	**Density ρ ($kg.m^3$)**	**Dynamic viscosity η (Pa.s)**
Liquid phase	Liquid steel	7000	0.0042
Gaseous phase	Air	1.225	1.7894e-05
Gaseous phase	Blown gas	1.2999	1.919e-05

By using the cited multiphase VOF model at the given boundary conditions for solving the task and the chosen variant of gas blowing, patterns of flow and velocity fields of phases studied were obtained. Results of the calculation of flow and vector fields given in the following chapter are presented by longitudinal sections running through the axis of furnace.

4. CHOSEN CALCULATION RESULTS

The range of melt flow velocity is evident from the relevant colour spectrum of flow field and the velocity scale at the given numerical representation in the sectional plane. During the evaluation of results of mathematical modelling of melt flow, we categorized the velocities of flow field by magnitude into two groups, namely the fields with the maximum values of velocity of flow of mixture of phases v_{max} and the fields with the maximum velocity of 0.1 $m.s^{-1}$ and smaller values of it.

For the more detailed evaluation of flow fields, the patterns of velocity structure in the longitudinal sections (**Figure 2** to **Figure 4**) were calculated. From these representations, the geometry of reaction zone, where velocities of gas phase - blowing gas entering into the bath into a so-called primary area of reaction zone reach the maximum flow velocity of $6.3\ .10^1$ $m.s^{-1}$ can be analysed. In addition, we can evaluate the velocity field in the surface layer of moving melt in the direction of acting blowing nozzles. Besides, we are able to evaluate numerically, from the calculated plane patterns of velocity fields, the zone of melt spattering and the structure of flow field below the point of action of blowing nozzles, where the melt flow divides into two areas, i.e. the area of turbulent fields in front of the nozzles and that along the lateral wall of the hearth. As can be seen in the longitudinal section, the bath flow is laminar; the velocities of flow around the hearth walls and bottom are low and in lower layers of the melt decrease from the velocity of $5.5.10^0$ $m.s^{-1}$ to the value of $1.57.10^{-5}$ $m.s^{-1}$ near the bottom.

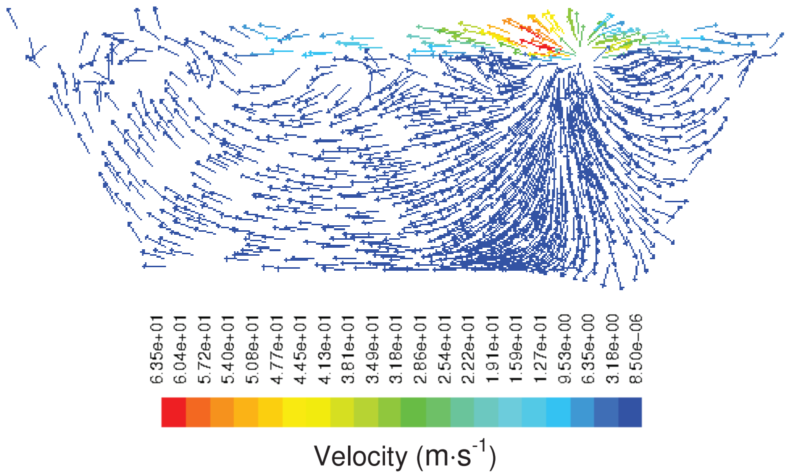

Figure 2 Velocity field in cross section taken perpendicular to the surface of the melt in the longitudinal central axis of the hearth

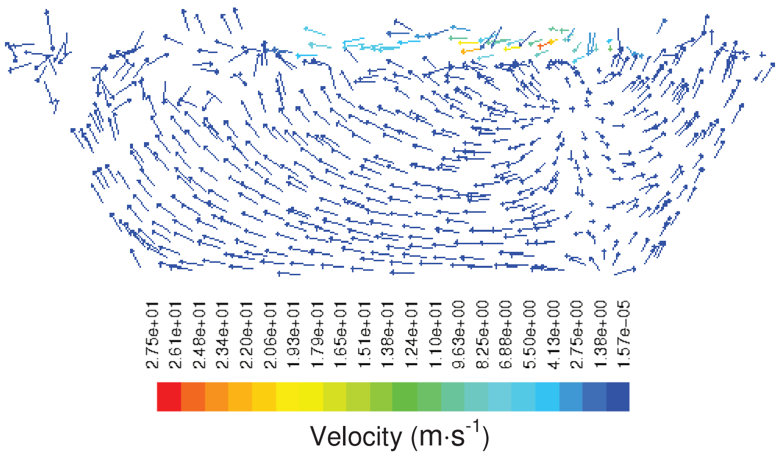

Figure 3 Velocity field in the sectional view taken at a distance of 1.1 m to the right of the longitudinal central axis

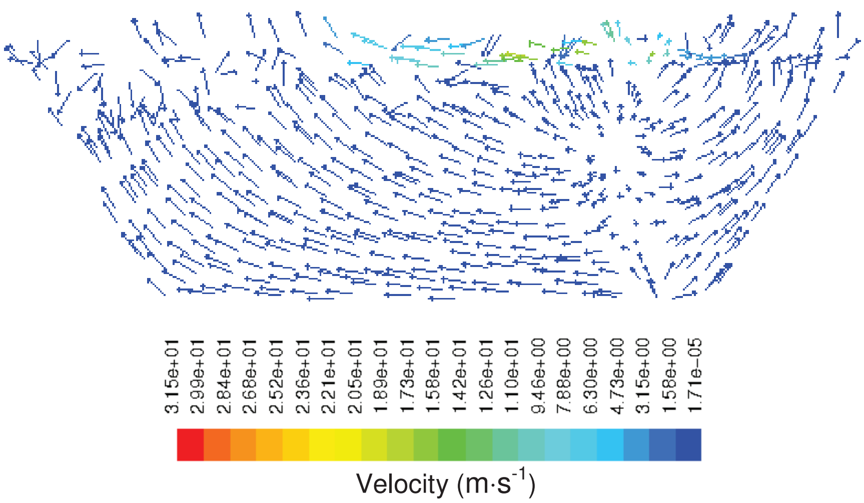

Figure 4 Velocity field in the sectional view taken at a distance of 1.1 m to the left of the longitudinal central axis

In the figures of velocity fields it can be seen that acting discharge streams induce a complicated flow structure with a transition of vertical turbulent fields to the longitudinal and the reverse flow.

From the section (**Figure 5**) through the flow field 0.5 m below the considered calm melt level we are able to evaluate both the velocity structure of reaction zone and the vector field of the remaining volume of the hearth. In the figure, there are planar outlines or boundary of primary sphere of reaction zone with velocities in the range from $1.03.10^{-2}$ $m.s^{-1}$ to $6.69.10^{-3}$ $m.s^{-1}$, where the gas phase prevails, and also the boundary of secondary sphere of reaction zone, where the flow velocity diminishes up to $3.2.10^{-5}$ $m.s^{-1}$.

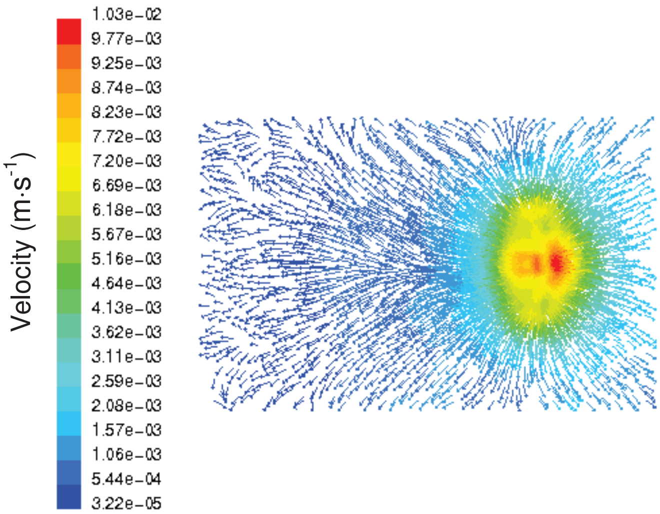

Figure 5 Velocity field in the sectional view taken at a distance of 0.5 m under bath level

As far as the flow velocity structure in the vicinity of lining wall, namely in the plane field at a distance of 30mm from the surface (**Figure 6**), is concerned, a good accordance with the other results of dealing with this blowing variant is evident. The values of flow velocity are very low, and thus it is not possible to achieve the required level of melt agitation induced by discharge jets from the nozzle along the hearth walls.

The mathematical modelling of this reference variant confirmed uniquely previous knowledge and experience generally known, i.e. that with this blowing variant and the existing working profile of the hearth, any increase in the level of agitation and thus homogeneity in the melt during melting cannot be achieved.

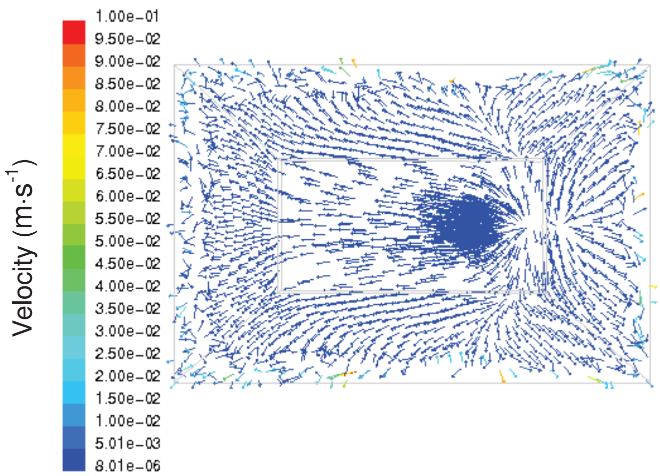

Figure 6 Velocity field in the sectional view taken at a distance of 0.03 m from hearth surface

CONCLUSION

From the comparison of results of physical and mathematical modelling a good accordance is clear. In spite of the fact that the numerical solution presupposes the time-steady isothermal flow of blowing gas from the nozzle and does not consider the influence of chemical reactions between the supplied oxygen and the melt, it provides, in comparison with the physical model, the detailed structure of velocity fields in the melt, from which changes in the flow field induced by the effects of gas blown into the bath at various arrangements of blowing system can be analysed.

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