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**MATHEMATICAL MODELLING OF THE PURE OXYGEN BLOWING PROCESS
ON SURFACE OF LIQUID BATH IN METALLURGICAL AGGREGATES**

**MATEMATICKÉ MODELOVÁNÍ PROCESU DMÝCHÁNÍ ČISTÉHO KYSLÍKU
NA HLADINU TEKUTÉ LÁZNĚ V HUTNICKÝCH AGREGÁTECH**

Abstract

This contribution describes numerical solution of multiphase flowing in metallurgical aggregate for steelmaking with help of software Fluent 6.1.18. Model of furnace contains liquid steel and gaseous phase 1 (clean oxygen) which is blown on surface of liquid bath through the gaseous phase 2 (air) by means of refine nozzles and additional fuel oxygen burner. Three-phases VOF mathematical model was used for solution. Situation when current technology of oxygen blowing on bath surface (application of two refine nozzles) was completed by another auxiliary burner is described in text. Contribution includes information about velocity field distribution inside of furnace in both investigated variants (variant using two refine nozzles and variant with auxiliary burner) and at the same time information about influence (penetration) of oxygen flow on surface (under surface) of liquid bath under condition of oxygen speed variation in outlet cross-section of auxiliary burner.

Abstrakt

Tento příspěvek popisuje numerické řešení vícefázového proudění v hutnickém agregátu pro výrobu oceli pomocí software Fluent 6.1.18. Model nistěje obsahuje tekutou ocel a plynnou fázi 1 (čistý kyslík), která je dmýchána na hladinu tekuté lázně skrz plynnou fázi 2 (vzduch) pomocí zkujňovacích trysek a přídavného palivo-kyslíkového hořáku. K řešení byl použit třífázový VOF matematický model. V textu je popisována situace kdy byla stávající technologie dmýchání kyslíku na hladinu (použití dvou hlavních zkujňovacích trysek) doplněna o další přídavný hořák. Příspěvek obsahuje informace o rozložení rychlostního pole v nistěji v obou zkoumaných variantách (varianta s použitím dvou hlavních zkujňovacích trysek a varianta s přídavným hořákem) a zároveň informace o vlivu (proniku) proudu kyslíku na hladinu (pod hladinu) tekuté lázně při změně rychlosti kyslíku ve výstupním průřezu přídavného hořáku.

1 INTRODUCTION

In metallurgical industry various types of metallurgical furnaces and vessels (thermal or metallurgical reactors) are used for production and subsequent secondary processing of liquid steels. Different types of reactors are characterized not only by purpose of exploitation, shape and design, but also by constructional lay-out of gaseous media (gaseous phase) supply systems exploited in these reactors. General fact is, that it happens to interaction of gaseous phase (oxygen) with liquid phase (liquid steel). Gaseous phase may be supplied thought the bottom of thermal reactor or by means of nozzle on surface of liquid phase and now and then also thought side wall of reactor. In this contribution effect of the blowing oxygen process on surface of liquid iron (steel) in furnace is described. Pure oxygen is supplied by means of nozzles.

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Conceptual lay-out of the furnace and position of oxygen nozzles and fuel oxygen burner including areas affected by output flows are shown in Fig. 1.1. There are four jets in each nozzle. Depending on smelting technologic process, type and size of furnace it is possible to utilize lay-out with one or more oxygen nozzles. Flowing inside the furnace is characterized as multiphase flow. Multiphase model of the furnace presents agitation of liquid phase (molten steel) by gaseous phase (oxygen), which goes through gaseous phase (air) above surface of bath. In concrete under consideration case existing service conditions of oxygen blowing by means of two nozzles was by reason of smelting intensification extended by additional oxygen fuel burner with the aim of improvement of melt homogenization during smelting

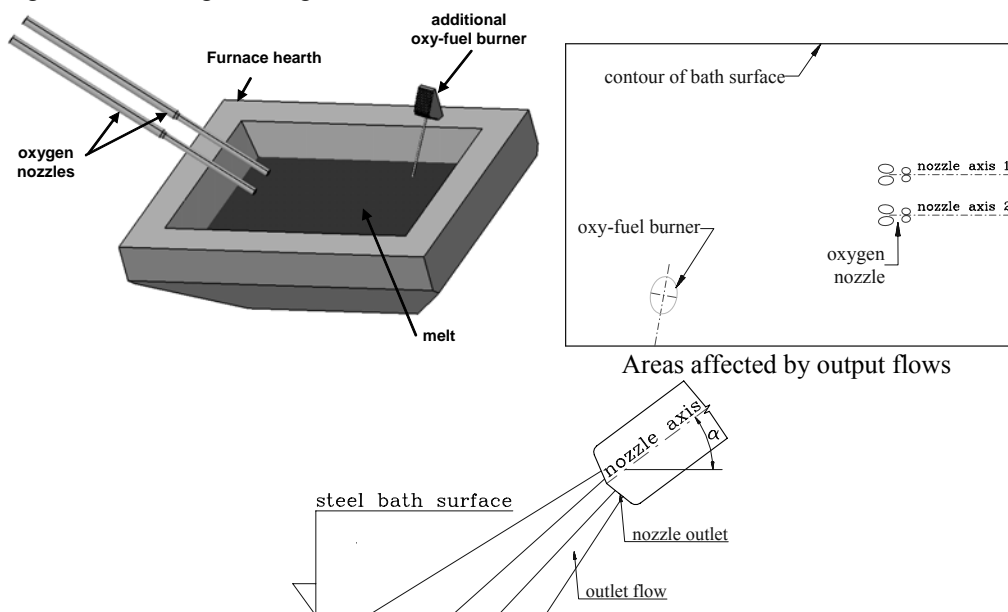


Fig. 1.1 Conceptual lay-out of the furnace and position of oxygen nozzles and oxygen fuel burner

For good simulation of flowing or other phenomenon it is substantial to create corresponding mathematical model. It means to create such model, which incorporate all substantial phenomena and factors (temperature, viscosity, pressure, turbulence, flowing regime, etc.), which influence process on real installation. Some factors it is possible to neglect, because they complicate stability and convergency of solution. That will simplify given model and at the same time it will save results accuracy. On the other hand other factors must be neglected by reason given by software Fluent version 6.1.18 (for example it is not possible to study admixtures flowing and to define chemical reaction in applications to multiphase models). One of the most important factors, that is monitored at process of steelmaking is agitation intensity in molten steel. As a result of intensive agitation of molten steel is more effective process of passing chemical reactions and homogenization of molten steel. For that reason the restriction concerning chemical reactions is acceptable, because more intensive agitation is at the same time certain information about intensity of passing chemical reactions. Heat transfer is neglected. It means that isothermal flowing is studied. Values of physical properties respond to temperature of liquid steel (appr. 1630°C).

2 CHARACTERIZATION OF MULTIPHASE VOLUME OF FLUID (VOF) MATHEMATICAL MODEL

The numerical model (VOF) was considered for flow of three not interpenetrating phases. This model was used for mathematical modeling of flow molten steel inside the furnace. Mathematical model can be described as:

One primary liquid phase is molten steel inside the furnace and two second secondary gaseous phases. The blowing oxygen is one from secondary phases. Oxygen is source of motion the molten steel. Second secondary phase is steady gaseous environment up to surface bath. For this application is substituted by air. The VOF model formulation relies on the fact that two or more fluids (or phases) are not interpenetrating, in reflecting of time steady isothermal flow. It means that in time steady isothermal flow mixture of molten steel, oxygen and air density, dynamic viscosity are not variable. Mathematical model is defined by system of differential equations. Equations are:

The continuity equation for the general phase (liquid) q th has the following form:

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

Then for primary phase – molten steel, the differential equation is not solved, but just express by condition

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

The volume fractions of all phases sum to unity. (N is number of all considering phases in system)

The momentum balance is defined by following differential equation

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

In equation are

| | | |
|------------|---|---|
| α_q | volume fraction of phase q | [-], |
| v | velocity of flow phase (fluid) | [m.s ⁻¹], |
| ρ | density of considering phase | [kg.m ⁻³], |
| η | dynamic viscosity of phase | [kg.m ⁻¹ .s ⁻¹], |
| F | external force impact on the move of phase | [N], |
| p | value of static pressure in considering phase | [Pa], |
| N | total number of phases | [-], |

Numerical solution of momentum balance is provided tracking of volume fraction each phase in the system.

Then from momentum balance is expressed the evident function dependence of distribution the velocity fields on the volume fraction individually phases of mixture. The dependence is presented by densities (ρ) and dynamic viscosities (η). The volume-fraction-averaged density (ρ) and volume-fraction-averaged dynamic viscosities (η) of mixture from N-phase system are defined by following relations:

$$\rho = \sum_{q=1}^N \alpha_q \rho_q \quad , \quad \eta = \sum_{q=1}^N \alpha_q \eta_q \quad (4)$$

The distribution of velocity fields of monitoring quantities are shared by considering phases of mixture and quantities represent volume-fraction-averaged of. Therefore those physical quantities are defined in the individual cells. Thus the variables and properties in any given cell are either purely representative of one of the phases, or representative of a mixture of the phases, depending upon the

volume fraction values. In other words, if the qth fluid's volume fraction in the cell is denoted as α_q , then the following three conditions are possible:

$\alpha_q = 0$ (volume fraction of phase q in cell is empty, cell is full by next phases)

$\alpha_q = 1$ (volume fraction of phase q in cell is full)

$0 < \alpha_q < 1$ (the cell contains the interface between the qth fluid and one or more other fluids)

Figures of investigation velocity fields were obtained by using multiphase VOF model in correct boundary conditions for chosen variants of oxygen blowing.

3 APPLICATION OF VOF MODEL ON THE MODEL OF GAS STIRRED LIQUID BATH IN FURNACE

Input dates for defining multiphase model were released from Department of Production Machines and Design, concretely for characterization constructional of the furnace, boundary conditions (primarily for oxygen blowing). As gaseous medium is used pure oxygen, which is came by refine nozzles on the surface liquid bath; see Fig. 1.1 for distance 200mm from surface. Outlet profile of refine nozzles are showed from Fig. 3.1 and Fig. 3.2. Four outlet profiles are for one nozzle (two nozzles are using in working state). Characterization of constructional furnace in working state with two refine nozzles is showed in Fig. 3.1. At the next case was changed technology of oxygen blowing and technology was extended by using of next additional fuel oxygen burner. Position of outlet profile is showed in Fig. 3.2. Angle of incidence stream of oxygen from additional fuel oxygen burner is 45° to surface.

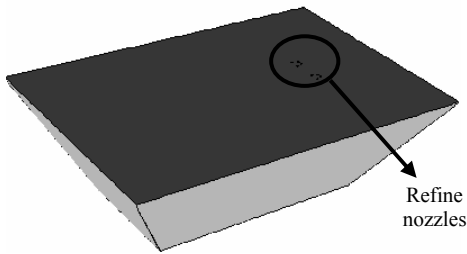


Fig. 3.1 Working state of furnace

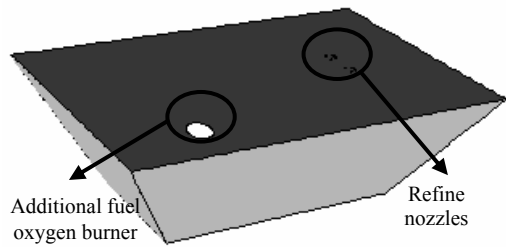


Fig. 3.2 Position of additional fuel oxygen burner in the furnace

3.1 Physical properties of individual phases and boundary conditions

Physical properties of phases are introduced in

Tab. 3.1 Physical properties of phases

| | | Density ρ_q [kg/m^3] | Dynamic viscosity μ_q [$kg/m \cdot s^{-1}$] |
|--------------|--------------|-------------------------------|---|
| Liquid phase | Liquid steel | 7000 | 0.0042 |
| Gaseous | Air | 1.225 | 1.7894e-05 |
| Gaseous | Oxygen | 1.2999 | 1.919e-05 |

3.2 Boundary conditions

After discussions with Department of Production Machines and Design was decided for definition two variants of setting:

- ❑ Variation of current setting (working state) with two refines nozzles. Outlet velocity is $488,7 \text{ m.s}^{-1}$ for all outlet jets.
- ❑ Variation of setting with two refines nozzles and one additional fuel oxygen burner. Outlet velocity is $488,7 \text{ m.s}^{-1}$ for all outlet jets and velocity from outlet profile of burner is (50 m.s^{-1} , 110 m.s^{-1} , 130 m.s^{-1} , 160 m.s^{-1}). This variation is showed in the Fig.3.3. And outlet profile of burner is marked on the figure. Vector of velocity at the inlet impacts in direct of longer axis the ellipse. And vector of velocity impacts to surface of molten up to angle 45° .

3.3 Results of numerical simulation

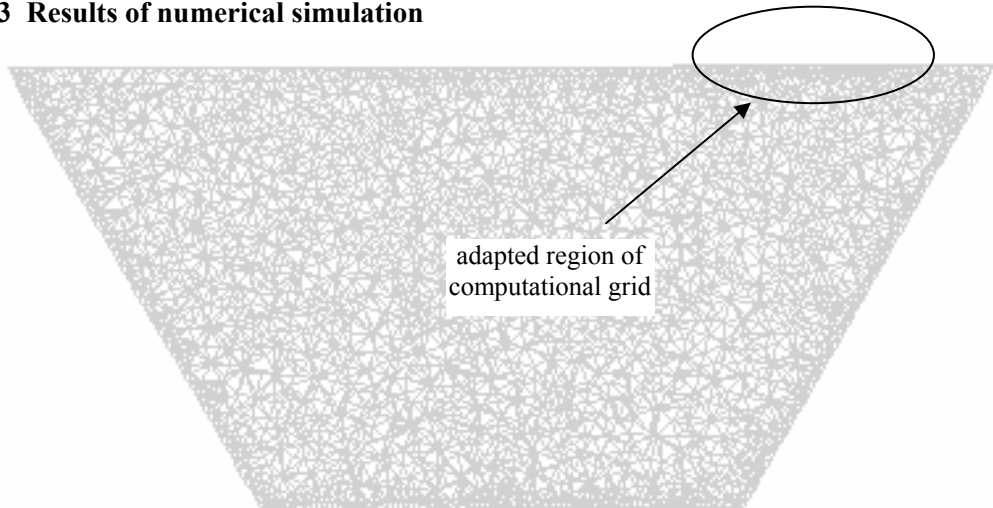


Fig. 3.3 Computational grid in cross-section of region

Software Gambit was used for creation of computational grid. Total number of cells were 449 461. Computational grid is showed in cross-section through computational region of furnace (Fig. 3.3). The grid was adapted for better stability and convergence of solution. It was made in regions where we assume move of secondary phase (gaseous).

Results of mathematical modelling of flow the melt metal in furnace and evaluation

From evaluation and comparison of the structure vectors in individual plane (Fig. 3.4) and in blowing of working state (two refine nozzles) and for variant (using additional fuel oxygen burner) we finish to following conclusions:

1. All figure of vector field, which the were selected for analysis distribution of velocity in flow of mixture correspondently flow of oxygen blowing by burners and nozzles and their constant distance up to bath.
2. Current configuration of system two nozzles is in comparison with considering variant (using additional fuel oxygen burner) characterizing by off-centre position couple of nozzles which are build in symmetric to lengthways axis of furnace. Axis is stooped to surface up to angle 35° . Installation those elements make in molten metal typical structure of velocity fields with three-dimensional into the laminar flow along wall of tandem and back flow into the place of work nozzles and next on the side wall of furnace and to zone behind nozzles.

Distribution of flow velocity melt and value of velocity we can evaluate in arbitrary place of bath by oxygen blowing and we can evaluate from detailed image plane cross-section. Two cross-sections are evaluated, which are intersecting by selected places of furnace (Fig. 3.4). In those cross-

sections we can evaluate velocity fields in primary reaction region and in marginal region then velocities in under the surface of bath.

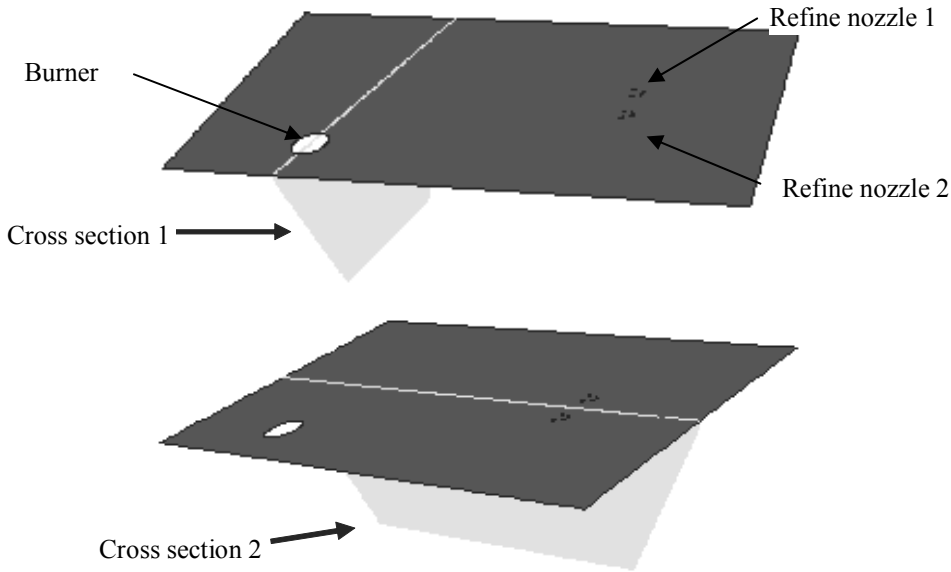


Fig. 3.4 Scheme of the cross-section by burner axis (cross-section 1) and scheme of the cross-section by furnace centre (cross-section 2) for evaluating of velocity field

According to evaluated pictures of melt velocity fields in furnace (Fig. 3.6) it is evident that the melt flow velocity in direction of actuating nozzles and along the furnace step by step drop to low values of about 10^{-5}m.s^{-1} . In principle the fact that the region of low step by step decreasing speeds except of narrow undersurface thickness of fluid-liquid mixture spreads almost on the whole volume of furnace for variant of two-nozzles (working conditions) is valid.

From detail analysis of melt velocity fields in furnace it is evidential, that the melt agitation in the area behind actuating nozzles and first of all in corners and in the surrounding of opposite side wall and also intensity of agitation effect of flowing oxygen from nozzles is very low.

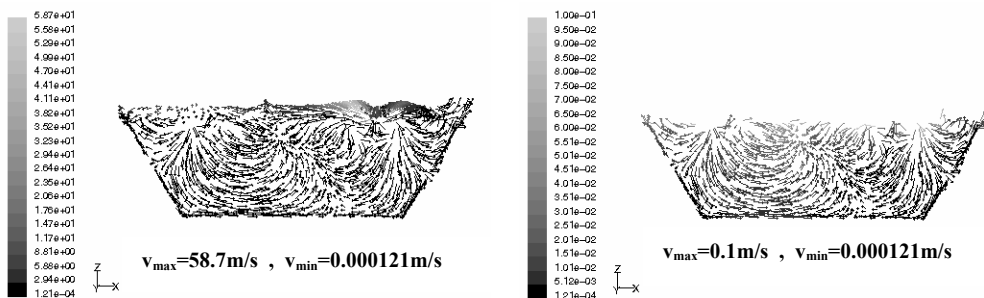


Fig. 3.5 Velocity field in cross-section 2 – outlet gases velocity from additional burner above liquid metal surface – $v=130 \text{m.s}^{-1}$

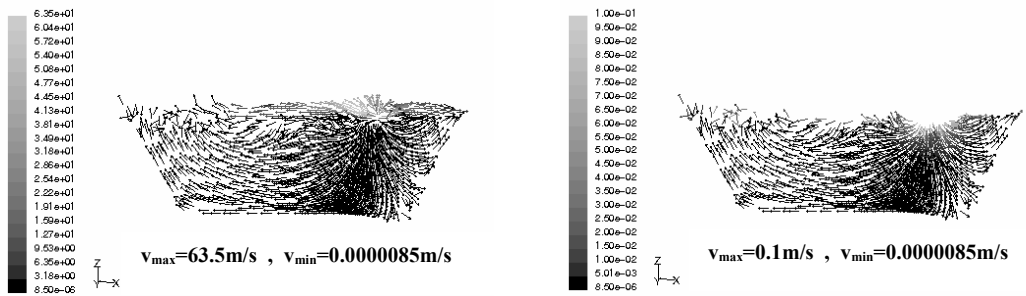


Fig. 3.6 Velocity field in cross-section 2 – two refine nozzles condition

Results of numerical solution coming in question so called realizable variant of combined oxygen blowing with using additional burner prove substantial increasing of agitation (stirring) effect of blown oxygen in melt. Base on results evaluation of that variant it is possible to say, that while blowing by this system it happens to expressive reduction of area with low melt velocity in furnace at the expense of velocity increasing in predominant part of furnace volume.

According of velocity fields pictures (Fig. 3.5) or at combined oxygen supply to the bath by means of nozzle and inbuilt burner the dominant burner effect on increasing of melt agitation (stirring) intensity in furnace is proven. Expressively higher stage of bath stirring is reached in variants when oxygen is blowing by additional burner and its outlet velocity is $v=110\text{m}\cdot\text{s}^{-1}$, $v=130\text{m}\cdot\text{s}^{-1}$ and $v=160\text{m}\cdot\text{s}^{-1}$.

To obtain wider idea about influence of mentioned variants on melt agitation in furnace there are documented pictures expressing distribution of steel mass fraction under condition of changing oxygen outlet velocity from additional burner (Fig. 3.7, Fig. 3.8, Fig. 3.9). It is evident more intense penetration of oxygen flow to the liquid steel depending on increasing oxygen outlet velocity from additional burner. In figure 3.10 there is dependence of penetration depth of outlet flow versus outlet oxygen velocity from additional burner.

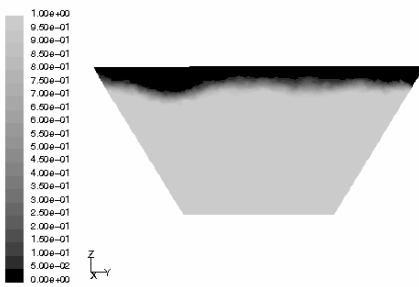


Fig. 3.7 Mass fraction distribution of steel in cross-section 1 for variant of $v=110\text{m}\cdot\text{s}^{-1}$

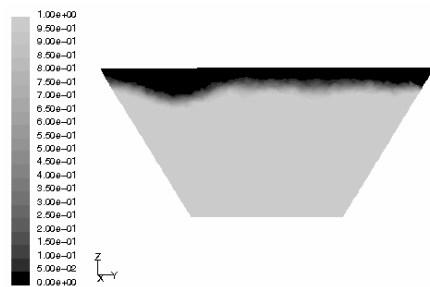


Fig. 3.8 Mass fraction distribution of steel in cross-section 1 for variant of $v=130\text{m}\cdot\text{s}^{-1}$

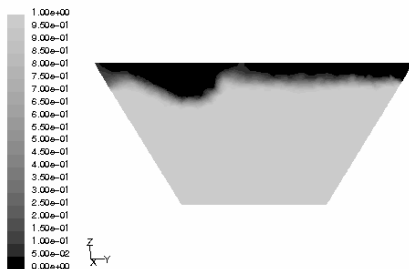


Fig. 3.9 Mass fraction distribution of steel in cross-section 1 for variant of $v=160\text{m}\cdot\text{s}^{-1}$

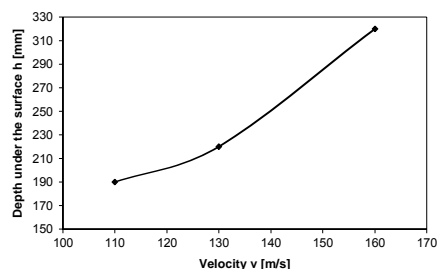


Fig. 3.10 Depth of oxygen intersection under the surface of liquid steel

CONCLUSION

The objective of mathematical simulation of melt movement in furnace was to survey and compare the results of first variant with using two oxygen nozzles and the second designed variant of combined oxygen blowing to the bath with using of additional oxygen fuel burner. Motion intensity changes of liquid bath in dependence on change of outlet velocity from additional oxygen fuel burner were tested numerically. Only hydrodynamic conditions in melt during isothermal oxygen blowing without thinking of chemical effect were tested. Tests results documented that higher spectrum of flow velocity distribution in melt it is possible to achieve in variant with using of additional oxygen fuel burner.

Appropriate realization of combined oxygen blowing system on surveyed shape of furnace is complicated problem. Even if the additional oxygen fuel burner will be used in surveyed shape of furnace there will be areas, in which melt motion will more or less stagnate in furnace. The shape change of furnace would considerably intensify melt motion in furnace. From point of view of bath motion intensity it would be preferable to equip the furnace by oval shape of furnace, that would not resist bath motion as it is in case of existing (square) furnace. In case of continuation of existing technology, it will be necessary take a think over technology rationalization and furnace construction (design) for existing operating conditions.

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REFERENCES

- [1] FLUENT: Fluent 6.1.18 - *User's guide* Fluent Inc. 2003. VŠB-TU Ostrava <URL:http://sp1.vsb.cz/DOC/Fluent_6.1/html/ug/main_pre.htm>.
- [2] Kozubková, M., Drábková, S., Štáva, P.: *Matematické modely nestlačitelného a stlačitelného proudění. Metoda konečných objemů*. [Skriptu]. Ostrava: VŠB-TU, 1999, 106 s.
- [3] Shokin, J., Miloshevich, H., Rychnov, A.: *Modeling of the top blow-down process in oxygen steel-making converters*. Second International Conference on CFD in the Minerals and Process Industrie, CSIRO, Melbourne, Australia, 6-8 December 1999, 59 – 63 p.
- [4] Kovář, L., Mikolajek, J. et al.: *Studium pohybu taveniny v nístěji tandemové pece pro vybrané varianty dmýchání plynů*. Výzkumná zpráva projektu MPO ČR, ev. č. projektu FT-TA/082: Výzkum, vývoj a modernizace výroby oceli na tandemových pecích. FS VŠB-TU Ostrava. 2005. 54s., 8 lit.
- [5] Kovář, L., Mikolajek, J., Bojko, M.: *Studium pohybu taveniny v nístěji tandemové pece pro vybrané varianty dmýchání plynů*. Výzkumná zpráva projektu MPO ČR, ev. č. projektu FT-TA/082: Výzkum, vývoj a modernizace výroby oceli na tandemových pecích, Etapa II. – matematické modelování. FS VŠB-TU Ostrava. 2006.. 2006, 69 s.

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