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MATHEMATICAL MODELING OF SLAG DYNAMICS ON THE SURFACE OF METALIC MELT DURING INERT GAS BLOWING

The article is devoted to a mathematical prediction of slag layer movement on the top of gas-stirred molten steel in a ladle. Motion of the steel affects the thickness of the slag layer and areas emptied from slag can appear. The mathematical model uses Saint-Venant equations for the slag dynamics and Navier-Stokes equations for motion of the steel with coefficient of friction between melts. Presented figures with numerical experiment results on the computer realization show the slag "eye" above corresponding tuyere. The proposed model gives a more realistic result than the one with a single number that represents an average thickness of the whole slag layer.

Keywords: numerical experiment, 3D-hydrodynamics, slag layer, gas-stirred molten steel.

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МАТЕМАТИЧНЕ МОДЕЛЮВАННЯ ДИНАМІКИ ШЛАКУ НА ПОВЕРХНІ МЕТАЛЕВОГО РОЗПЛАВУ ПІД ЧАС ПРОДУВАННЯ ІНЕРТНИМ ГАЗОМ

Статтю присвячено математичному прогнозуванню руху шару шлаку на поверхні металевого розплаву в ковші. Рух сталі впливає на товщину шару шлаку з появою областей відкритого металу. Математична модель використовує рівняння Сен-Венана для динаміки шлаку і Нав'є-Стокса для руху сталі з коефіцієнтом тертя між розплавами. Представлені малюнки, з результатами чисельного експерименту на комп'ютерній реалізації, показують газові «плями» в шлаку зверху відповідної пробки продування. Запропонована модель дає більш реалістичний результат, ніж використання одного числа для середньої товщини всього шлакового шару.

Ключові слова: чисельний експеримент, 3D-гідродинаміка, шар шлаку, розплав сталі з газовим продуванням.

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МАТЕМАТИЧЕСКОЕ МОДЕЛИРОВАНИЕ ДИНАМИКИ ШЛАКА НА ПОВЕРХНОСТИ МЕТАЛЛИЧЕСКОГО РАСПЛАВА ВО ВРЕМЯ ПРОДУВАНИЯ ИНЕРТНЫМ ГАЗОМ

Статья посвящена математическому прогнозированию движения слоя шлака на поверхности металлического расплава в ковше. Движение стали влияет на толщину слоя шлака с появлением областей открытого металла. Математическая модель использует уравнения Сен-Венана для динамики шлака и Навье-Стокса для движения стали с коэффициентом трения между расплавами. Представленные рисунки, с результатами численного эксперимента на компьютерной реализации, показывают газовые «пятна» в шлаке сверху соответствующей продувочной пробки. Предложенная модель дает более реалистичный результат, чем использование одного числа для средней толщины всего шлакового слоя.

Ключевые слова: численный эксперимент, 3D-гидродинамика, слой шлака, продуваемый газом расплав стали.

Problem definition

Treatment of molten steel in a ladle is a widespread technology in metallurgy. The mathematical modeling of physical processes can be used to find rational parameters of mentioned technology. Also it is cheaper than experiments in the laboratory or at the factory.

Gas stirring of a melt with a slag on it in a ladle leads to the appearing of the areas empty from slag. Such area is named "eye". In addition the motion of molten metal causes the movement of above slag too. So the thickness of slag is not constant across the surface and can change over time. Often mathematical models neglect that and include the value of the slag thickness only, which can lead to the problems in model adequacy. For example if an additive granule fell into an "eye" (or molten metal) it would melt in other way than if it fell into the slag because of different thermo-physic properties of the both (including different speed of motion). The slag melt has a higher viscosity, lower thermal conductivity as well as lower density than molten steel. That leads to different overall time of granule melting and mixing in the melt. It would be good to reduce this time. In a practice many ladles have two blowing plugs in their bottom and few "eyes" can appear at the slag layer, so it is needed to take this fact into account.

Related publications

In [1] authors used Navier-Stokes equations to predict motion of steel melt in a ladle. They take into account the gas phase and consider a single speed field and a double speed field with different borders of bubbling zone. Their 2d-model showed better results for double speed field.

The work [2] is devoted to 3d simulation of melt hydrodynamics with free surface using a volume of fluid model and bubbles` motion using a discrete particle model in the software ANSYS Fluent. Author took into account turbulence by standard *k-e* model.

The three-phase mathematical model in work [3] uses multiphase VOF model to predict phase distributions and interactions between molten steel, slag and oxygen especially the splashes that occurs at the slag surface during oxygen blowing through bottom tuyeres.

In [4, 5] authors consider flow of interacting three phases "gas-steel-slag" with formation of slag "eye" with detailed description of the process, physical and mathematical modeling. They used Large eddy simulation (LES) for turbulence and hybrid DBM-VOF for motion of free surface and immiscible fluids with gas bubbles.

Some older models described slag with one number – the thickness of the layer – and didn`t take into account that its surface changes over space in reality.

Goal of investigation

The goal is a mathematical description of slag dynamics interacting with molten steel stirred by inert gas from bottom plug and, in addition, numerical experiment with presentation of graphical results.

Presentation of the research material

It is accepted following assumptions of considering process:

1) Molten steel and slag are uncompressible Newtonian viscous fluids.
2) Cylindrical shape of the steel body (Fig. 1).
3) Steel-slag interface is flat.
4) Slag viscosity is much higher than steel viscosity.
5) Slag thickness is much lesser than slag surface radius.
6) Vertical speed of slag can be neglected.

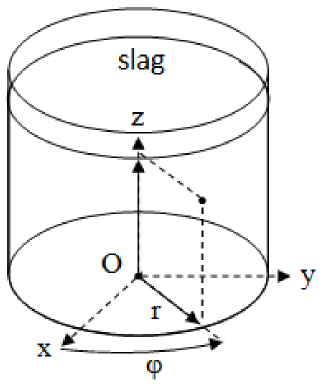

Fig. 1. Cylindrical body of the molten steel and the slag layer

On the basis of these assumptions dynamics of the molten steel is mathematically modeled using Navier-Stokes equations:

$$\frac{\partial \vec{u}}{\partial t} = \upsilon \nabla^2 \vec{u} - (\vec{u} \cdot \nabla)\vec{u} - \nabla P + \vec{W}, \tag{1}$$

$$\nabla \cdot \vec{u} = 0, \tag{2}$$

where u – speed field of the metallic melt;
P – kinematic pressure;
υ – kinematic viscosity;
W – acceleration due buoyant force of gas field:

$$\vec{W} = -\vec{g}(1-\alpha), \tag{3}$$

where α – gas field;
g – gravitational acceleration constant.

The latter expression is based on assumption that amount of gas is much lesser than amount of steel in the same volume and the density changing can be neglected. This idealization is used in the Boussinesq approximation for heat-driven flows in fluids and gases. Movement of gas phase based on melt`s speed field $\vec{u}$ and defined by diffusion-convection equations:

$$\frac{\partial \alpha}{\partial t} = D_{\alpha} \nabla^2 \alpha - \left(\vec{u} + \vec{u}_b\right) \cdot \nabla \alpha + \Phi_{\alpha}, \quad (4)$$

where u_b – buyoance velocity of the gas phase;
D_a – diffusion coefficient of gas phase;
Φ_a – source of gas phase:

$$\Phi_{\alpha} = \frac{q}{V_b} \frac{T + 300}{300}, \quad (5)$$

where q – amount of gas per second entered in molten steel through blowing plug at the bottom of the ladle;
T – an average temperature of the molten steel;
V_b – volume of bubbling zone near tuyere.

And dynamics of the slag defined using Saint-Venant equations [6, 7]:

$$\frac{\partial h}{\partial t} + \nabla \cdot \left(\vec{v}\left(H + h\right)\right) = 0, \quad (6)$$

$$\frac{\partial \vec{v}}{\partial t} + \left(\vec{v} \cdot \nabla\right)\vec{v} + \vec{g}\nabla h = \upsilon \nabla^2 \vec{v} + \vec{f}, \quad (7)$$

$$\vec{f} = \mu\left(\vec{u} - \vec{v}\right), \quad (8)$$

where h – scalar two-dimensional field of thickness deviation from its mean value H;
$\vec{v}$ – two-dimensional velocity field of slag;
$\vec{g}$ – acceleration of gravity;
υ – kinematic viscosity;
$\vec{f}$ – external force of friction, caused by steel movement ($\vec{u}$), with friction coefficient μ .

Equations are complemented by boundary conditions:

1) on the solid surface of the ladle wall and the axis of the ladle there are sliding and impermeability conditions:

$$\vec{n} \cdot \nabla \vec{u}_{||}\Big|_S = 0, \qquad \vec{u}_{\perp}\Big|_S = 0, \quad (9)$$

where $\vec{n}$ – normal vector to the surface S;
$\vec{u}_{||}$ – speed`s component that is parallel to the surface S;
$\vec{u}_{\perp}$ – speed`s component that is normal to the surface S.

2) on the steel-slag interface there are sliding and impermeability conditions too.
For the pressure field boundary conditions is got by projection of impulse equations at the surface:

$$\vec{n} \cdot \nabla P\Big|_S = 0, \quad (10)$$

3) by angle φ there is conjugation:

$$u\big|_{\varphi=0} = u\big|_{\varphi=2\pi} \quad (11)$$

$$P\big|_{\varphi=0} = P\big|_{\varphi=2\pi} \quad (12)$$

4) slope of the ladle wall can be taken into account by setting boundary conditions of solid surface on the corresponding cells near wall after discretization of the above equations.

The boundary conditions for the gas field α have following view:

1) impermeability condition on the solid surface of the ladle wall and axis:

$$\vec{n} \cdot \nabla \alpha\Big|_S = 0, \quad (13)$$

2) on the steel-slag interface there is free buoyant conditioni розплаву – вивільнення газу з розплаву і перешкоджання проникненню домішки:

$$\alpha\Big|_S = 0, \quad (14)$$

The pressure field P is found using equation $\nabla \cdot \vec{u} = 0$ and used in previous models three-step method of physical factors splitting. Dividing time axis t by step τ on the layers with index n, the calculation of speed $\vec{u}^{n+1}$ has the following form:

1) According to the impulse equation the intermediate field of speed is calculated without pressure field and has divergence:

$$\frac{\vec{u}^{*}-\vec{u}^{n}}{\tau}+\left(\vec{u}^{n}\cdot\nabla\right)\vec{u}^{n}=\upsilon\nabla^{2}\vec{u}^{n}-\left(1-\alpha^{n}\right)\vec{g}, \tag{15}$$

2) Then the pressure field is calculated using Poisson's equation:

$$\Delta P^{n+1}=\frac{\nabla\cdot\vec{u}^{*}}{\tau} \tag{16}$$

3) New speed field, which is solenoidal, is defined using the found pressure field and the intermediate field of speed:

$$\frac{\vec{u}^{n+1}-\vec{u}^{*}}{\tau}=-\nabla P^{n+1}, \tag{17}$$

where τ – time step between time layers *n* and *n*+1.

The equations are solved numerically on a staggered grid in cylindrical coordinates using finite volume method. Values of speed field defined at edges of cell and scalar fields at the centers. Speed field of the slag and speed field of the steel have the same count of steps for discretization, which makes the calculation simpler.

Fig. 2 shows the results of numerical experiment for gas stirring using single tuyere at the bottom of the ladle. A small thickness of the slag layer causes appearing of a large area emptied from it. Slag layer has gray color, backside of the ladle wall is blue and its front side is invisible. The molten steel is also transparent. Red volumes have some amount of the gas. Arrows on the cross-section of the speed field show flows of the melt, which follows the gas phase.

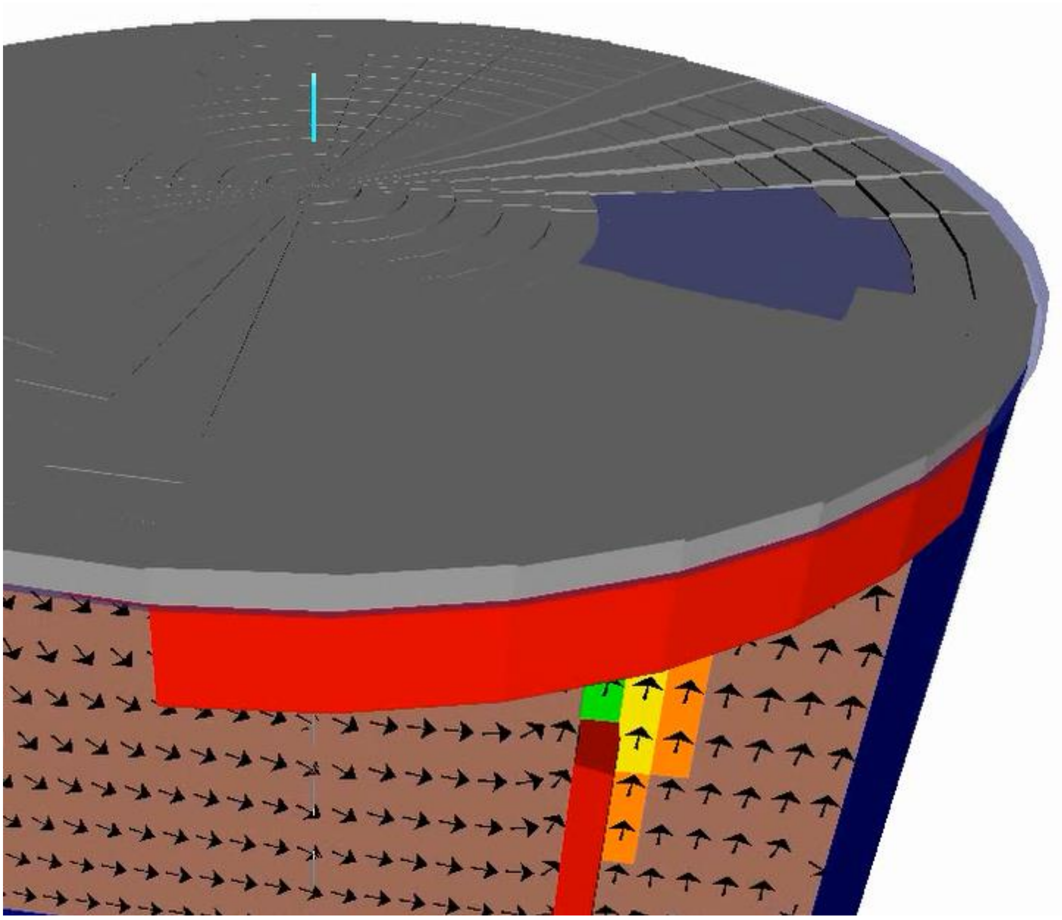

Fig. 2. Slag layer has area, which is "eye", above tuyere during gas stirring

Fig. 3 shows the state of the system with two blowing tuyeres when two areas, emptied from slag, appear. White dashed line on the bottom of the ladle is y-axis. The left "eye" of the slag is smaller than another because corresponding tuyere is smaller – lesser amount of the gas from it reaches the slag layer. Later in this experiment one tuyere is turned off and the left "eye" disappears with the left gas column.

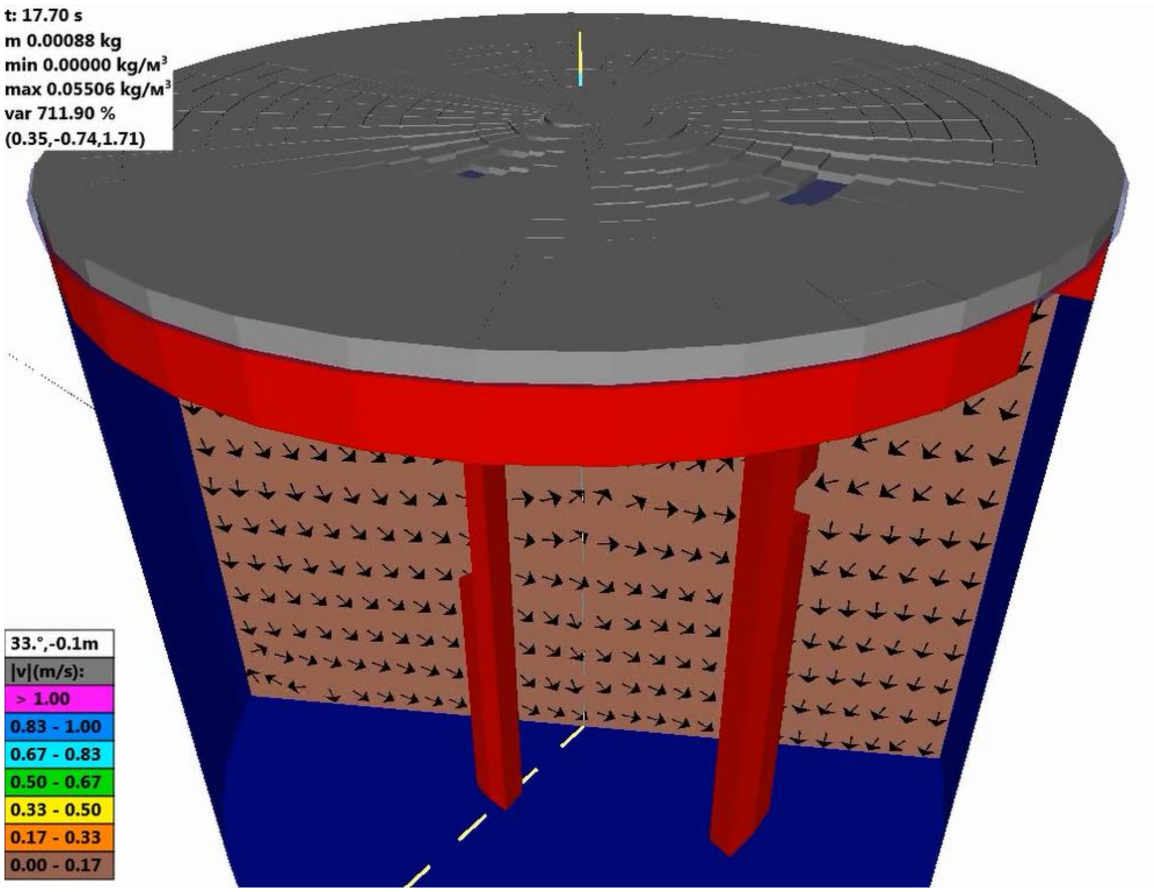

Fig. 3. Two “eyes” appears when two tuyeres work

Results and conclusions

Computer implementation of the numerical scheme for Saint-Venant equation is simpler than one for Navier-Stokes because latter needs for solving Poisson`s equation with pressure field. Also computation time of the latter is much lesser than the former.

One of the disadvantages of the proposed model is inability to track down separate parts of slag, which occasionally can blast off the surface. Such details have been neglected.

The use of the proposed model will give a more realistic picture of the mentioned metallurgical process, since in reality the slag surface is not flat. One of the additional applications of the work can be the insertion of lump material in the form of a granule. The granule can fall into the slag or steel in different places, which can lead to different results of additive digestibility.

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