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DOI: https://doi.org/10.53052/9788366249844.12

MATEMATYCZNE MODELOWANIE EROZJI WYMURÓWKI KADZI PRZEZ TOPNIKI Z MIESZANIEM GAZOWYM

Streszczenie: Krążące kadzie są wykorzystywane przez zakłady metalurgiczne do transportu wytopu między etapami produkcji oraz do mieszania wytopu za pomocą gazu obojętnego. W artykule rozważa się erozję mechaniczną wyłożenia kadzi przez wytop mieszany gazem. Ponadto skupiono się na matematycznym modelowaniu erozji w czterech konfiguracjach świec wydmuchowych. Stwierdzono, że konfiguracja z wyśrodkowanym korkiem ma minimalny wpływ na wyłożenie kadzi, a korek przy ścianie powoduje największą erozję.

Słowa kluczowe: erozja wykładziny kadzi, wytop mieszany gazem, równania Naviera-Stokesa, eksperyment numeryczny

MATHEMATICAL MODELING OF LADLE LINING EROSION BY GAS-STIRRED MELT FLUXES

Summary: Teeming ladles are used by metallurgical plants to transport melt between production stages, and to stir the melt by inert gas. Mechanical erosion of ladle lining by gas-stirred melt is considered. The paper is focused on mathematical modeling of the erosion in four configurations of blowing plugs. It is found that configuration with centered plug has minimal impact on ladle lining and plug at the wall causes the highest erosion.

Keywords: ladle lining erosion, gas-stirred melt, Navier-Stokes equations, numerical experiment

1. Introduction

Metallurgical plants use teeming ladles to transport melt between stages of steel products manufacturing. To maintain the temperature of the melt at different stages of production, the inner side of the ladle is covered with a layer of refractory lining. With each usage, the thickness of the layer decreases, in particular due to mechanical erosion by rapid flows of melt that touch the lining. At different points of contact, the velocity of the melt is different, and therefore the erosion is inhomogeneous. Metallurgists periodically replace the lining, looking for places of greatest erosion, which spends time and material resources.

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It is necessary to investigate the effect of the gas blowing intensity on the depth of erosion (or lining thickness). In this paper it is proposed to predict mentioned influence using mathematical model of melt dynamics. The prediction opens the ways to optimize plug placement and to decrease number of cost lining repairs.

In the papers [1-3] authors study ladle lining degradation during thermal changes. In [1] it is found that preheating to 773K decreases refractory damage. In [2] authors recommend to not exceed 60% of lining erosion, because of very high risk of accident. In the paper [3] it is studied damages of lining done during drying of a ladle. Authors present photos with appeared cracks after 16 cycles of thermomechanical changes (casting). In another paper [4] authors consider thermomechanical loading on brick, including porous medium. Figures show fields of strain and stress during heating and cooling.

There are papers devoted to the laboratory experiments and numerical simulations of the mentioned process. In papers [5-6] there are physical models of the process. Especially, in [6] two geometrical configurations were investigated and it is found, that author`s one is better – lining erosion decreases by 18%.

2. Mathematical model

The process of melt motion in the ladle is idealized using the following approximations:

1) Geometric shape of the melt is cylindrical (Fig. 1–4);
2) Molten steel is replaced by Newtonian viscous gas-liquid continuum. The melt is incompressible and its density is a constant value – fluctuations in density due to the presence of argon are neglected;
3) The presence of argon affects only the acceleration of the vertical component of velocity, according to Boussinesq's assumption. Gas bubbles instantly reach the maximum floatation speed;
4) Waves on the melt surface can be neglected and it is flat;
5) The rate of the lining erosion linearly depends on the melt velocity near it.

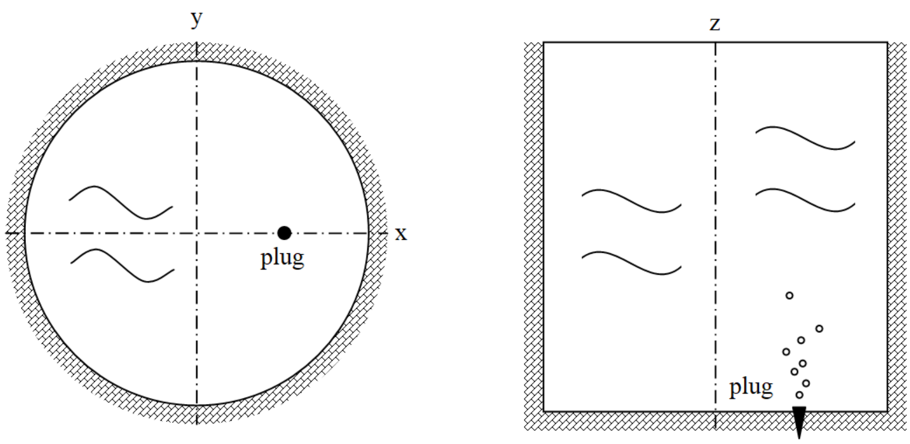

Figure 1. Configuration with blowing plug at the center of the ladle radius

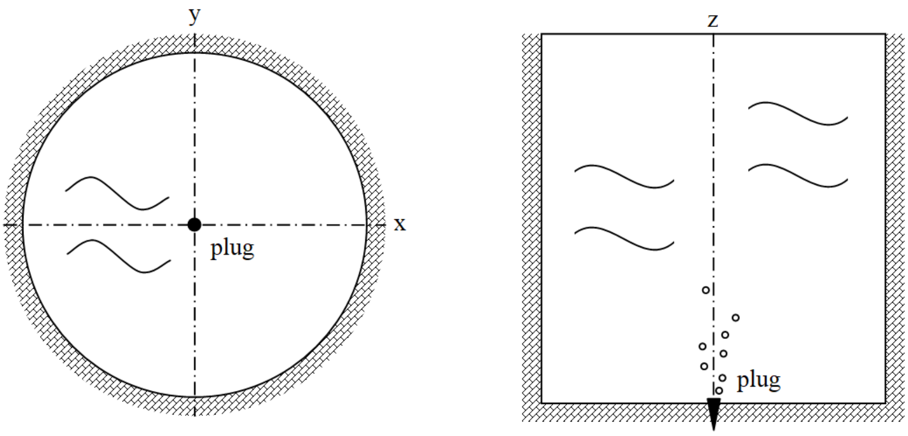

Figure 2. Configuration with blowing plug at the center of ladle bottom

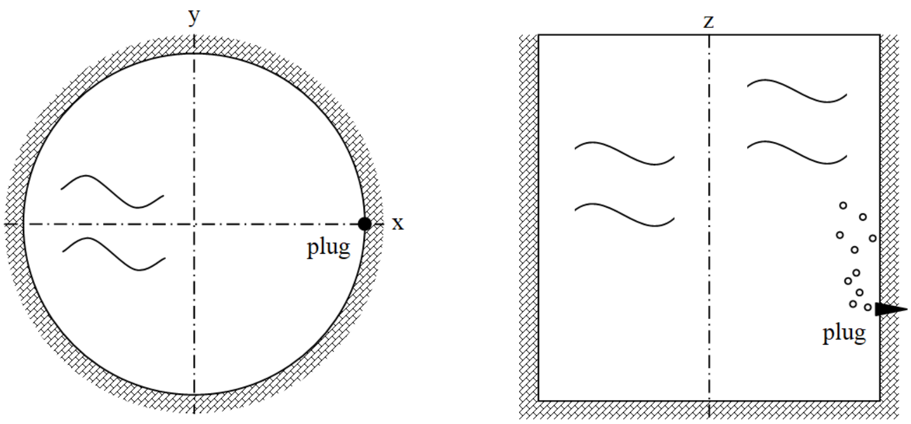

Figure 3. Configuration with plug at the ladle wall at 1/3 of the melt depth

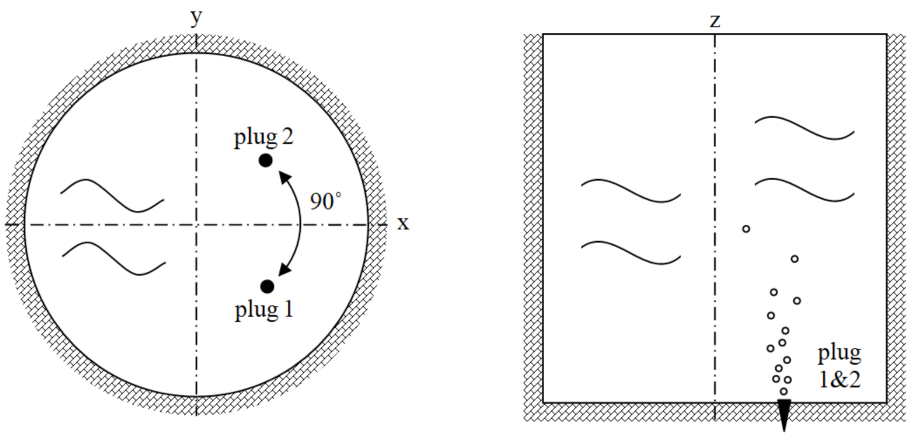

Figure 4. Configuration with two radius-centered blowing plugs

The continuum moves according to the laws of conservation of momentum and mass. Dynamics of the continuum is determined by the Navier-Stokes equations with the condition of solenoidal motion:

$$\frac{\partial \vec{v}}{\partial t}+\left(\frac{1}{2}\nabla\vec{v}^2-\vec{v}\times\nabla\times\vec{v}\right)=-\nabla P+\upsilon_e\Delta\vec{v}-\alpha\vec{g}, \quad (1)$$

$$\nabla\cdot\vec{v}=0, \quad (2)$$

where: υ_e – effective kinematic viscosity;
α – argon fraction in the melt;
P – kinematic pressure.

The gas field moves according to convection-diffusion equation:

$$\frac{\partial \alpha}{\partial t}+\nabla\cdot\left[\alpha\left(\vec{v}+\vec{v}_f\right)\right]=D_\alpha\nabla^2\alpha+S_\alpha, \quad (3)$$

$$S_\alpha=\frac{q}{V}\frac{300}{T_m}, \quad (4)$$

where: v_f – constant gas floatation speed;
D_α – effective argon diffusivity;
q – gas consumption;
V – volume near plug, where bubbles appear;
T_m – temperature of steel.

The field of erosion amount is determined by the melt velocity along the surface of the walls and bottom of the ladle:

$$\frac{\partial s}{\partial t}=k_s\left|\vec{v}^{\parallel}\right|, \quad (5)$$

where: s – depth of lining erosion;
k_s – erosion coefficient.

Boundary conditions include impermeability and slip conditions on the melt surfaces and the axis of the ladle:

$$\left.\vec{v}\cdot\vec{n}\right|_S=0, \qquad \left.\nabla\alpha\cdot\vec{n}\right|_S=0, \quad (6)$$

$$\left.\nabla\left(\vec{v}\times\vec{n}\right)\cdot\vec{n}\right|_S=0, \quad (7)$$

where: n – normal to the surface S.

There is symmetry at the plane y=0, thus only a half of the computational domain requires a numerical solution.

2. Results

The central difference scheme is used to solve equations presented above. Time integration is done by explicit Euler scheme. Numerical experiments use geometrical parameters of a real ladle (Table 1). In the case of two plugs, gas consumption is 30 liters per minute to keep a total consumption the same as in other configurations.

Table 1. Experiment parameters

Object	Parameter	Value
Melt body	Radius	1 m
	Height	1,7 m
Plug	Gas consumption	60 l/min
	Duration	9 min
Computational domain	Volumes along *radius*	14
	Volumes along *angle*	36
	Volumes along *height*	20

The Figure 5 shows difference in average damage of ladle among configurations of blowing plug. On the figure: “1/2 R” means that plug is placed at the half of radius: “Center” means central placement at the ladle bottom; “2 plugs” means configuration with two blowing tuyures; “Wall” means plug placed at the ladle wall. As expected, a plug at the wall causes the highest damage to lining.

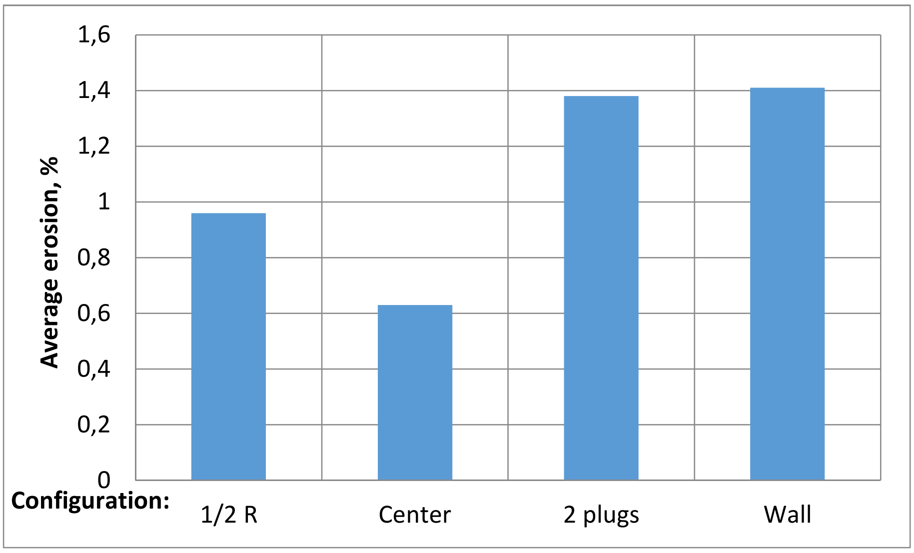

Figure 5. Average erosion of ladle lining depending on proposed configurations after 9 minutes of gas-stirring

The Figure 6 presents maximal local erosion caused to lining by moving fluxes. As expected, it is around a plug, where the gas concentration is maximal. The bubbles accelerate molten steel, speed of which reaches the highest values.

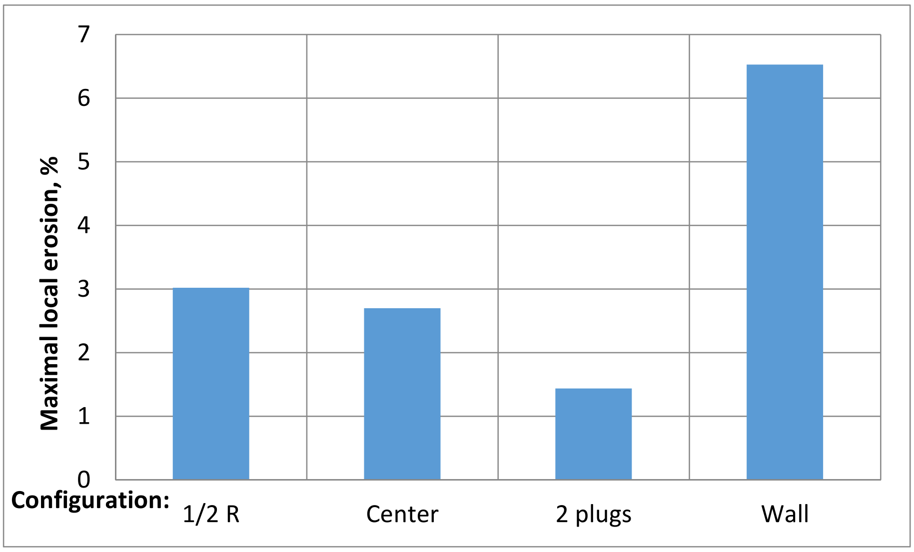

Figure 6. Maximal erosion of ladle lining after 9 minutes of gas-stirring

The Figure 7 presents perspective rendering of ladle (blue) with horizontal and vertical speed profiles (arrows are directions of flow and color corresponds to its speed).

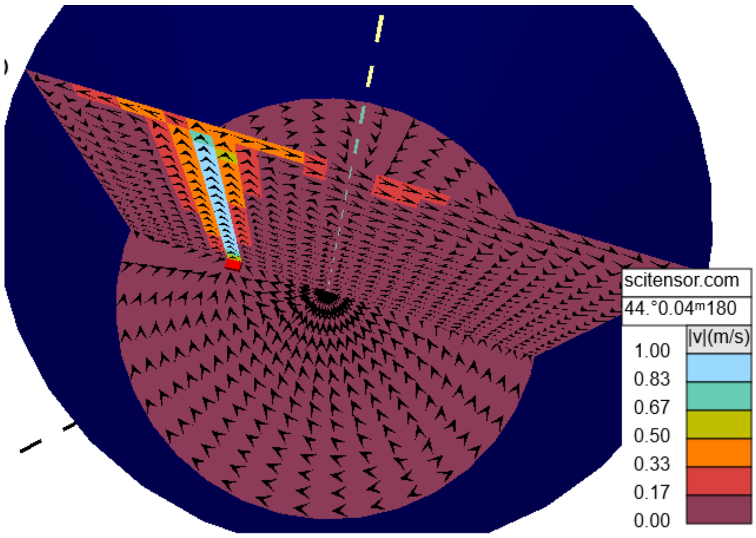

Figure 7. Visualization of mathematical model state after 9 minutes of gas-stirring (configuration with two plugs)

3. Conclusions

The motion of gas-stirring melt in the ladle with four plug placements are investigated using numerical simulation based on proposed 3D mathematical model. The model includes Navier-Stokes equations and convection-diffusion equation. Presented results show minimal average erosion when plug at the center of ladle bottom is used. However, if one needs minimal local erosion, then he use configuration with plugs and gas consumption rate of 30 l/min. Based on the results it is not recommended to use plug at the wall, because of the highest local and average damage of lining – it is from double to quadruple times higher than the other configurations.

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