МОДЕЛЮВАННЯ ТА ОПТИМІЗАЦІЯ В ТЕХНОЛОГІЇ КОНСТРУКЦІЙНИХ МАТЕРІАЛІВ

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DOI: 10.31319/2519-8106.2(47)2022.268342
UDC 004.942:669.18

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SOFTWARE FOR A NUMERICAL STUDY OF STAGNANT AREAS OF THE MELT DURING BLOWING

The problem of the existence of melt stagnant regions during inert gas blowing is the risk of its crystallization near the walls of the ladle under conditions of constant temperature decrease. A large number of scientific publications are devoted to solving this problem. One of the possible solutions is to optimize the number and location of melt blowing nozzles in order to minimize the volume of stagnant areas. Mathematical modeling and numerical study of the specified process made it possible to determine the best location of the nozzles and save on the costs of laboratory or industrial experiments. The computer implementation involves recording experiments using a database and a web user interface. Also, this implementation automatically forms graphs of dependent values. After registration, researchers have the opportunity to add the results of experiments in the form of calculated fields. As a result of research, it was found that regardless of the number of lances, a stagnant area is formed at the bottom near the wall of the ladle. There, the melt velocity varies from 1 cm/s to 5 cm/s.

***Keywords**: software, mathematical modeling, molten steel, argon blowing.*

Проблема існування застійних областей розплаву під час продування інертним газом полягає у ризику його кристалізації біля стінок ковша в умовах постійного зменшення температури. Велика кількість наукових публікацій присвячено розв'язанню цієї проблеми. Одним з можливих вирішень є оптимізація кількості і розташування фурм продування розплаву з метою мінімізації об'єму застійних областей. Математичне моделювання і чисельне дослідження означеного процесу дозволило визначити найкраще розташування фурм та зекономити на витратах лабораторних або промислових експериментів. Комп'ютерна реалізація передбачає облік дослідів за допомогою бази даних і веб-інтерфейсу користувача. Також ця реалізація автоматично формує графіки залежних величин. Дослідники після реєстрації мають можливість додавати результати дослідів у вигляді розрахованих полів. У результаті досліджень виявлено, що незалежно від кількості фурм на дні поблизу стінки ковша формується застійна область. Там швидкість розплаву в складає від 1 см/с до 5 см/с.

***Ключові слова**: програмне забезпечення, математичне моделювання, рідка сталь, аргонне продування.*

Problem's Formulation

From the point of view of the subject area "processing of molten steel in a ladle", the problem lies in the existence of stagnant regions of the melt during blowing with inert gas — there is a risk of crystallization near the walls of the ladle under conditions of constant temperature decrease. Using a mathematical model, it is easy to study the movement of the melt in different configurations of blowing nozzles.

The numerical study of stagnant areas of the melt involves determining the initial state of the melt, multipliers and various indicators, as well as recording the results in the form of calculated fields of velocity, pressure, average, minimum velocity values. For this purpose, it is worth creating a database. Numerical experiments can be carried out by many researchers remotely, so it is appropriate to create a website where the results can be collected centrally.

Analysis of recent research and publications

The authors of the paper [1] considered the problem of melt hydrodynamics in the process of filling a ladle in a three-dimensional setting using a cylindrical coordinate system. The work takes into account: air entrainment by the steel flow; gaseous mixing of the melt. The non-solenoid motion of the gas-melting medium is also considered with the assumptions of a small gas volume ratio, a zero ratio of gas and melt densities, and the dependence of the gas phase density only on pressure. In the system of equations of motion of the melt, the barycentric velocity of the gas-melt medium is used.

In the article [2], the single-velocity approach is used to calculate the hydrodynamics of a liquid when filling a cylindrical closed volume, taking into account gas injection, which affects the movement of a gas-liquid medium. The work is characterized by the following assumptions:

1) The medium is incompressible, which simplifies the Navier-Stokes equation;
2) The steel stream enters the melt in the center of the bottom of the ladle.

In work [2] there is no blowing of the liquid with gas. Equations are solved on a checkerboard in natural pressure-velocity variables by the method of splitting physical factors. The authors conducted a series of numerical experiments on filling a cylindrical tank with water, comparing the results with experimental data. The drawings show a good correlation between the mathematical model and the experimental results.

In work [3], the author takes into account the filling of the ladle in the hydrodynamics of the melt, assuming that the steel jet falls in the center of the ladle, and the metal mirror is flat. The author calculated the vertical speed of the melt mirror depending on the speed and radius of the jet, the radius of the metal surface, and also proposed a calculation algorithm. The author provides detailed initial data for the numerical experiment. The figures show a velocity field that infers significant melt movement during pouring, which can be used, for example, to rapidly mix additives.

The authors of the paper [4] propose mathematical models for determining effective modes of steel processing during ladle filling, as well as during siphon filling of the form. Navier-Stokes equations and finite-difference schemes are used to solve the two-dimensional problem of melt hydrodynamics. The figures are given with the velocity field during the filling of a 250 ton bucket.

In [5], a method of splitting by physical factors is presented, which allows solving the Navy-Stokes equation numerically in the physical velocity-pressure variables. In addition, this method is not limited to the two-dimensional formulation of the problem of fluid movement — it also works in the three-dimensional case, which significantly increases the number of processes that can be simulated. In the case of the movement of the melt in the ladle, there are very few configurations that can be reduced to a two-dimensional representation, so the specified method is a priority.

The paper [6] presents a comparison of momentum equations and turbulence models for multiphase melt flow: VOF, Euler-Euler model, Euler-Lagrangian, quasi-single-phase model. Despite the simplicity of the latter model due to the avoidance of calculating each bubble movement, it corresponds well to experiments. The authors present the results of experiments on the installations on the distribution of the diameter of the bubbles in the gas plume, starting near the plug and ending with the upper surface of the liquid. As expected, the bubbles grow larger as they move toward the surface.

Formulation of the study purpose

The article is devoted to the development of software for scientific experiments and the study of stagnant areas of melt in a steel ladle during blowing.

Presenting main material

In the subject area under consideration, scientists conduct numerical experiments of stagnant areas of melt. Before the experiment, the scientist determines the initial values (for example, the gas consumption for feeding through the blowing nozzles) and, after receiving the results, stores them in the database. First, we will describe the mathematical model of the melt movement, and then the software for conducting experiments.

Simplifications will allow modeling the movement of the melt with gas using the conservation law:

1) The body of molten metal has the geometric shape of a cylinder.

2) The melt is an incompressible Newtonian viscous liquid consisting of two interpenetrating phases: the main metal phase, an inert gas. The surface of the melt is flat.

3) An inert gas is considered ideal.

The top view of the bucket with the location of the blowing nozzles is shown in fig. 1.

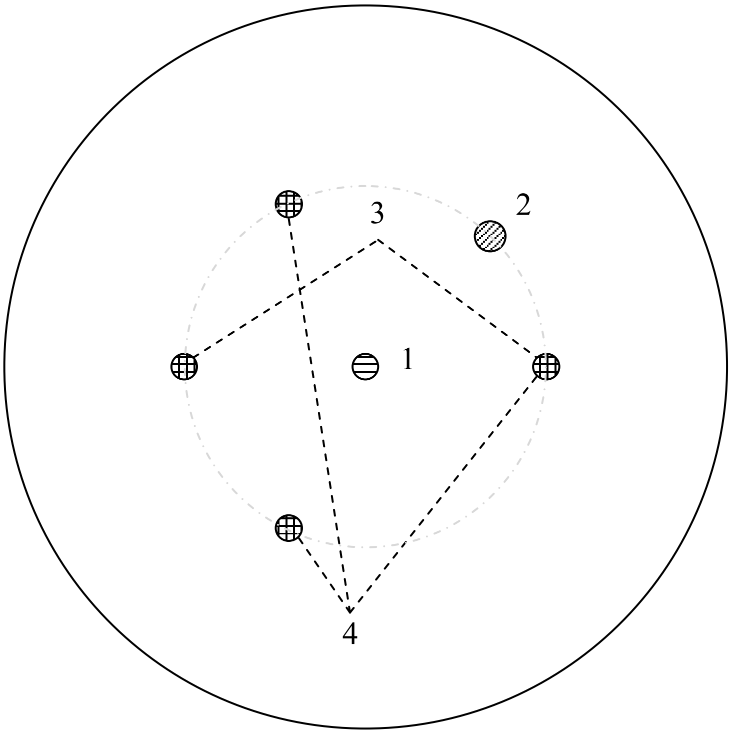


Fig. 1. A top view of the ladle with tuyeres (1/20 scale). Four configurations with one (axial and half-radius), two (opposite) and three tuyeres (equilateral triangle) are shown

The hydrodynamics of the melt will be determined by the Navier-Stokes equations corresponding to the laws of conservation of mass and momentum:

$$\frac{\partial \vec{\mathbf{v}}}{\partial t} + (\vec{\mathbf{v}} \cdot \nabla)\vec{\mathbf{v}} - D_{\text{v}}\nabla^2\vec{\mathbf{v}} = -\nabla\left(\frac{p}{\rho_0}\right) - \alpha\vec{\mathbf{g}}\,; \tag{1}$$

$$\nabla \cdot \vec{\mathbf{v}} = 0 \tag{2}$$

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

$$S_\alpha = \frac{q}{V}\frac{T_{air}}{T_m}, \tag{4}$$

where D_{v} and D_{a} effective coefficients of kinematic viscosity and gas diffusion; g — acceleration of free fall (accepted as 9,81 m/s^2); v_f — speed of gas ascent (taken as 0,5 m/s); S_α — gas source; q — gas consumption; T_{air} — temperature of the gas before entering the melt; T_m — temperature of the melt (assumed to be 1800° C).

Boundary conditions for the normal and parallel component of velocity on the surface w of a solid body:

$$\left.\frac{\partial \vec{\mathbf{v}}^{\parallel}}{\partial n}\right|_{w} = 0\,; \tag{5}$$

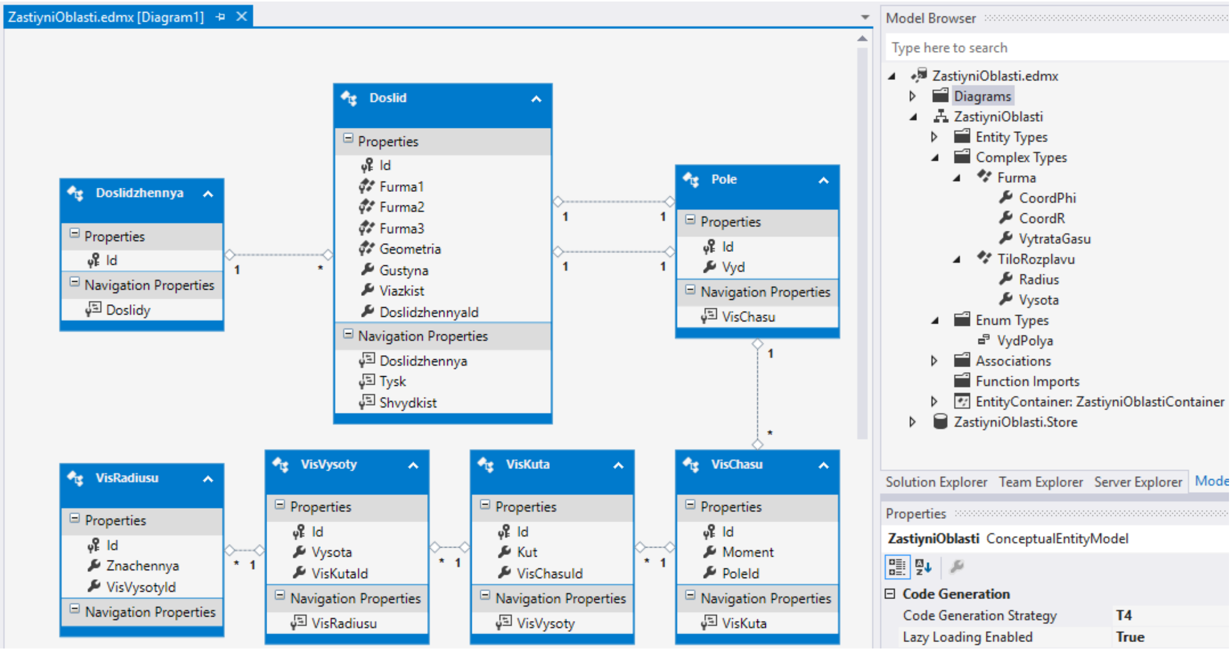
$$\vec{\mathbf{v}}^{\perp}\Big|_{W}=0, \tag{6}$$

where n — normal to the wall.

Boundary conditions for the gas field are: impermeability on solid surfaces and a constant rate of gas exit on the upper surface of the melt. The equations are solved using checkerboard discretization. The cylindrical coordinate system corresponds almost 100 % to the geometry of the melt body. Spatial derivatives are replaced by central differences and the pressure field is determined from the fluid continuity equation. It is recommended to calculate the diffusion term implicitly, which will avoid a strong limitation on the time step in the case of using an explicit scheme.

Software and information support for numerical experiments consists of a database and a web user interface for filling the database and analyzing the results. The database management system chosen is the lightweight version of MS SQL Server, which comes with the Visual Studio for Web programming environment. ASP.NET MVC is chosen as the website programming technology. It organizes the code into three categories for ease of testing, readability and scalability of the project:

- models of objects (which, in particular, correspond to the essence of the subject area) are presented in fig. 2;
- HTML5 pages with advanced features (loops, conditions, etc.);
- controllers that receive data from the database, process it and display it on HTML pages in response to a browser request.



Code Generation Strategy T4
Lazy Loading Enabled True

Fig. 2. Entity-Relationship diagram for the database. Two complex types (“Furma”, “TiloRozplavu”) and one enumeration (“VydPolya”) are defined additionally to support table “Doslid”

The space occupied by the melt is conditionally divided into cells in which average values are calculated. Foreign cells help to set the boundary conditions. The initial values for the numerical experiment are given in the tabl. 1, 2.

In an additional experiment, the shutoff of the blow down at the 60th second was tested to determine how long the melt could maintain a velocity greater than 0.05 m/s.

Table 1. Melt parameters for the numerical experiment

Melting of steel	
Radius	0,956 m (22 cells)
Height	1,7 m (18 cells)
Angular coordinate	2π (36 cells)
Density	7000 kg/m^3
Temperature	1800 K

Table 2. Parameters of blowing lances for the numerical experiment

Blowing machines	
Total gas consumption	40/60/90 l/min
Diameter of lances	0,1 m
1st setting	1 axial lance
2nd setting	1 tuyeres on half the radius
3rd setting	2 opposite lancets on half the radius
4th setting	3 lancets at an angle of 120° between them at half the radius

In fig. 3—4 shows a vertical cross-section of the developed (about 70 seconds) melt velocity field in 4 configurations of blowing nozzles. Arrows indicate the direction of the velocity vector: it consists of vertical and radial components of the vector. Each arrow has a rectangular background, the color of which determines the length of the vector with a gradient starting from brown (low speed — from 0 to 0.08 m/s) to white (more than 0.5 m/s). The highest velocity is in the middle of the gas barrel above the nozzles.

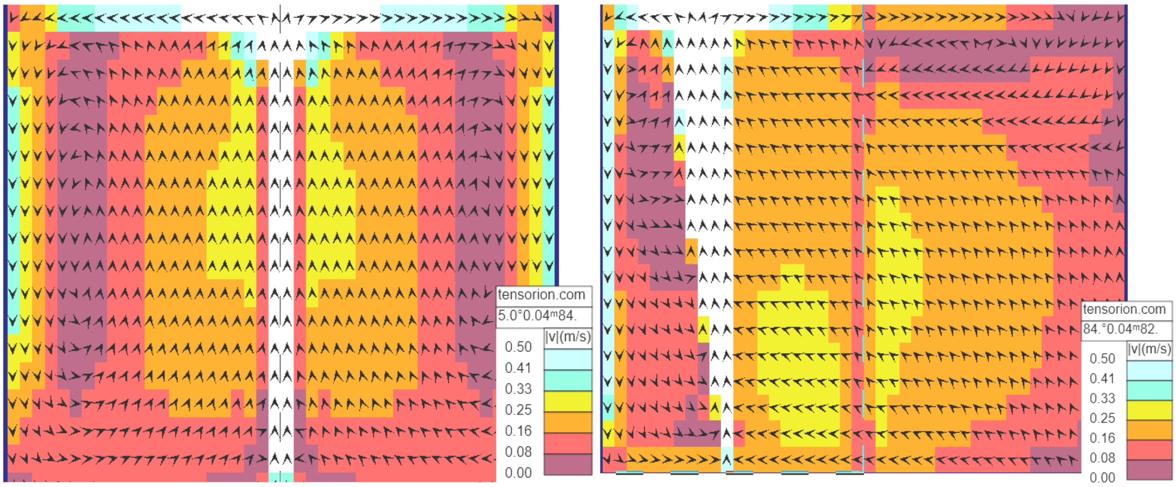


Fig. 3. Developed velocity profiles for single tuyere configurations (left — axial tuyere, to right — half-radius one) using 90 l/min gas consumption

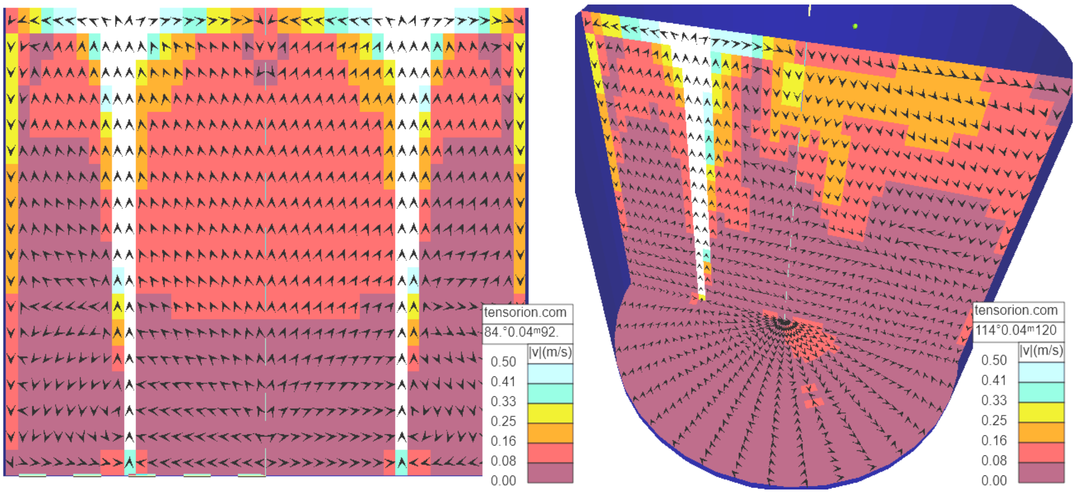


Fig. 4. Developed velocity profiles for two and three tuyeres (left — two opposite ones, right — three ones with 120° between) using 90 l/min gas consumption

In the first configuration of the axial lance, an elliptical vortex is formed with foci in the upper and lower parts of the ladle. At these points, the speed reaches almost zero.

In the second configuration, the gas barrel is located closer to the wall and mixes the melt well on one side, while on the opposite side there are areas of low currents.

In the third configuration, two opposite gas barrels form at least four vortices of different speeds, which positively affects the quality of mixing. At the same time, the lower part of the melt has a markedly lower velocity, which in some places reaches above low values.

In the fourth variant of the location of the blowing nozzles in the shape of a triangle, various vortex structures with medium rotation speeds are observed, especially in the upper part of the melt. But as in the previous configuration, the lower part is much slower, which increases the risk of stagnation.

In all configurations, stagnant regions remain in the corners of the melt body near the wall. But the first two have an average speed higher than the third and fourth. It should be noted that in the presence of a slag layer, the first two configurations are more prone to blurring the slag layer, which should also be avoided.

Conclusions

As shown by the experiments with turning off the lances after 1 minute of blowing, it is possible to save a little on gas consumption, because the kinetic energy of the melt is enough to continue its movement for 11—17 seconds, which can be enough for the final mixing up to 5 % coefficient of variation. It works especially well with a flow rate of 90 l/min.

As a result of the conducted research, it was found that regardless of the number of lances, a stagnant area forms at the bottom near the wall of the bucket. There, the melt velocity varies from 1 cm/s to 5 cm/s.

References

[1] Vykhlevshchuk, V. A., Dubyna O. V., Poliakov V.A. et al (2001). Scientific and technological fundamentals of the production of reinforcing steels of a new generation. Kyiv: Naukova Dumka, p. 53. ISBN 966-00-0704-3.

[2] Ohurtsov, A. P., Samokhvalov, S. E. & Nadryhailo, T. J. (2003). Splitting methods in problems of hydrodynamics, heat and mass transfer. Dnipro: System technologies, p. 156.

[3] Kabakov, D.Yu. (2014) Three-dimensional mathematical model of hydrodynamics and heat transfer in a gas-liquid medium during steel processing in a ladle-furnace (Candidate dissertation). Dniprodzherzhinsk: Dniprodzherzhinskyi state technical university, p. 62.

[4] Vykhlevshchuk, V. A., Ohurtsov A. P., Pavliuchenkov I. A. et al (1997). Mathematical modeling of processes of out-aggregate steel treatment. Kyiv: IECM Ministry of Education and Science of Ukraine.

[5] Belotserkovskyi, O.M., Hushchyn, V.A. & Shchennykov, V.V. (1975). The splitting method in application to the solution of the dynamics of viscosity of incompressible liquid. ***Computational mathematics and mathematical physics***, (1 (15)), 197–207.

[6] Liu, Y., Ersson, M., Liu, H., Jonsson, P.G., & Gan, Y. (2019). A review of physical and numerical approaches for the study of gas stirring in ladle metallurgy. ***Metallurgical and materials transactions***, (2(50B)), 555–577. DOI: 10.1007/s11663-018-1446-x.

ПРОГРАМНЕ ЗАБЕЗПЕЧЕННЯ ДЛЯ ЧИСЕЛЬНОГО ДОСЛІДЖЕННЯ ЗАСТІЙНИХ ЗОН РОЗПЛАВУ ПРИ ПРОДУВЦІ

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Реферат

Проблема існування застійних областей розплаву під час продування інертним газом полягає у ризику його кристалізації біля стінок ковша в умовах постійного зменшення температури. Велика кількість наукових публікацій присвячено розв’язанню цієї проблеми. Одним з можливих вирішень є оптимізація кількості і розташування фурм продування розплаву з метою мінімізації об’єму застійних областей. Математичне моделювання і чисельне дослідження означеного процесу дозволило визначити найкраще розташування фурм та зекономити на витратах лабораторних або промислових експериментів. Комп'ютерна реалізація передбачає облік дослідів за допомогою бази даних і веб-інтерфейсу користувача. Також ця реалізація автоматично формує графіки залежних величин. Дослідники після реєстрації мають можливість додавати результати дослідів у вигляді розрахованих полів. У результаті досліджень виявлено, що незалежно від кількості фурм на дні поблизу стінки ковша формується застійна область. Там швидкість розплаву в складає від 1 см/с до 5 см/с.

З точки зору предметної області «обробка розплаву сталі у ковші» проблема полягає у існуванні застійних областей розплаву під час продування інертним газом — є ризик кристалізації біля стінок ковша в умовах постійного зменшення температури. На математичній моделі легко дослідити рух розплаву в різних конфігураціях фурм продування.

Чисельне дослідження застійних областей розплаву передбачає визначення початкового стану розплаву, множників і різних показників, а також фіксацію результатів у вигляді розрахованих полів швидкості, тиску, середніх, мінімальних значень швидкості. З цією метою варто створити базу даних. Чисельні досліди можуть проводитися багатьма дослідниками дистанційно, тому доречно створити веб-сайт, на якому централізовано збирати результати.

Статтю присвячено розробці програмного забезпечення наукових дослідів і вивченню застійних областей розплаву у сталерозливному ковші під час продування.

Як показали досліди з відключенням фурм після 1 хвилини продування можна дещо зекономити на витратах газу, адже кінетичної енергії розплаву вистачить щоб продовжувати свій рух на протязі 11—17 секунд, що може бути достатньо для остаточного перемішування до 5 % коефіцієнту варіації. Особливо гарно це працює з витратою у 90 л/хв.

У результаті проведених досліджень виявлено, що незалежно від кількості фурм на дні поблизу стінки ковша формується застійна область. Там швидкість розплаву в складає від 1 см/с до 5 см/с.

Література

1. Vykhlevshchuk V. A., Dubyna O. V., Poliakov V.A. and others. Scientific and technological fundamentals of the production of reinforcing steels of a new generation. Kyiv: Naukova Dumka, 2001. p. 53. ISBN 966-00-0704-3

2. Ohurtsov A. P., Samokhvalov S. E., Nadryhailo T. J. Splitting methods in problems of hydrodynamics and heat & mass transfer. Dnipro: System technologies, 2003, p. 156.
3. Kabakov D.Yu. Three-dimensional mathematical model of hydrodynamics and heat transfer in a gas-liquid medium during steel processing in a ladle-furnace: thesis of PhD: 01.05.02 / Dniprovskyi State Technical University. Kamianske, 2014. p. 62.
4. Vykhlevshchuk V.A, Ohurtsov A. P., Pavliuchenkov I. A. and others. Mathematical modeling of processes of out-aggregate steel treatment. Kyiv: IECM Ministry of Education and Science of Ukraine, 1997. 151 pages.
5. Belotserkovskyi O.M., Hushchyn V.A., Shchennykov V.V. The splitting method in application to the solution of the dynamics of viscosity of incompressible liquid. *Computational mathematics and mathematical physics*. 1975. Vol.15, No 1. P. 197–207.
6. Liu Y., Ersson M., Liu H., Jonsson P.G., and Gan Y. A review of physical and numerical approaches for the study of gas stirring in ladle metallurgy. *Metallurgical and materials transactions*. 2019. Vol. 50B, No 2. P. 555–577. DOI: 10.1007/s11663-018-1446-x