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COMPUTER STUDY OF IMPURITY MIXING WHEN BLOWING INTO THE MELT THROUGH A TUYERE

КОМП'ЮТЕРНЕ ДОСЛІДЖЕННЯ ПЕРЕМІШУВАННЯ ДОМІШКИ ПІД ЧАС ВДУВАННЯ У РОЗПЛАВ ЧЕРЕЗ ФУРМУ

In the process of steel production, metallurgical enterprises add impurities to the melt. Blowing an impurity through a nozzle is one of the common methods of modifying the chemical composition of a liquid. This process has been studied in many works. The problem lies in the very slow diffusion of the impurity, which means long-term mixing with a constant loss of melt temperature. The speed of mixing is affected by both the number of blowing nozzles and their location. The defined process is analyzed in this work with the help of computer mathematical modeling, which is popular among scientists due to its low cost. Computer implementation allows you to save parameters and results of experiments in a database. Access to functional pages is provided through the web user interface. The website has a researcher registration subsystem and a form for adding calculated fields. As a result of the experiment with an inert gas flow from 40 to 90 l/min and with the number of nozzles from one to three, it was found that the configuration with one nozzle in the center of the radius and two opposite nozzles with a total flow of 90 l/min has the shortest duration of mixing.
***Keywords**: software, computer modeling, melt modification in a ladle, gas-stirring.*

У процесі виробництва сталі металургійні підприємства додають домішки до розплаву. Вдування домішки через фурму є одним з поширених способів модифікації хімічного складу рідини. Цей процес досліджувався у багатьох роботах. Проблема полягає у дуже повільний дифузії домішки, а значить і у тривалому перемішуванні при постійній втраті температури розплаву. На швидкість перемішування впливає як кількість фурм продування так і їх розташування. Означений процес проаналізовано у даній роботі за допомогою комп'ютерного математичного моделювання, яке користується популярністю у науковців завдяки своїй малої вартості. Комп'ютерна реалізація дозволяє зберігати параметри і результати дослідів у базі даних. Доступ до функціональних сторінок забезпечено через веб-інтерфейс користувача.

Проблема перемішування домішок у розплаві полягає в обмеженні по часу, за який необхідно досягти мінімум 95 % осереднення. Одним із методів перемішування розплаву є вдування газу через донні фурми. Витрати газу треба налаштовувати таким чином, щоб шар шлаку не розмивався і сталь залишалася під ним.

Як і лабораторні або промислові досліди чисельне дослідження на математичній моделі передбачає встановлення початкових налаштувань і збереження та обробку результатів *моделювання. Для цього використовуються бази даних та інтерфейс користувача. Проблема одночасного централізованого доступу багатьох користувачів до програмного забезпечення розв'язується за допомогою веб-сайту.*

Мета дослідження полягає у пошуку раціональної витрати інертного газу і в оптимізації розташування фурм продування з метою ресурсозберігаючого перемішування домішки. У якості засобу обрано математичне моделювання масопереносу в розплаву і розробка супроводжуючого програмного забезпечення.

У підсумку проведено чисельні досліди з сумарними витратами інертного газу від 40 до 90 л/хв і з числом фурм від однієї до трьох. Виявлено, що з невеликою перевагою найменшу тривалість перемішування має конфігурація з однією фурмою, яка розташована по центру радіуса, та конфігурація з двома протилежними фурмами і сумарною витратою 90 л/хв.

Рекомендується до впровадження конфігурація з двома протилежними фурмами, яка має прийнятну тривалість перемішування у 92 секунди при витратах газу — 45 л/хв. на кожну фурму.

Відключення фурм на 1 хвилині, коли вся домішка потрапила у розплав, має сенс при високій швидкості розплаву. У даних конфігураціях і при обмеженій сумарній витраті газу достатньо висока швидкість досягається тільки у випадку однієї фурми. При двох або трьох фурмах максимальна швидкість розплаву є малою і перемішування домішки з часом набуває ознаки розсіювання (дифузії). А розсіювання є занадто повільним у всіх означених конфігураціях і не є прийнятним в умовах постійного охолодження розплаву.

***Ключові слова**: програмне забезпечення, комп'ютерне моделювання, модифікації розплаву в ковші, газове перемішування.*

Problem's Formulation

The problem of mixing impurities in the melt is the time limit for which it is necessary to achieve at least 95 % averaging. One method of melt mixing is gas injection through bottom tuyeres. The gas flow rate must be adjusted in such a way that the slag layer is not eroded and the steel remains under it.

As well as laboratory or industrial experiments, the numerical study on a mathematical model involves setting the initial settings and storing and processing the simulation results. For this purpose, databases and user interface are used. The problem of simultaneous centralized access of many users to the software is solved using a website.

Analysis of recent research and publications

Recently, a lot of scientific literature has been devoted to the study of melt hydrodynamics and impurity mixing during blowing. For example, in [1], the authors consider the geometry of the gas barrel that arises above the bottom tuyere and compare the radius of the barrel, the concentration and velocity of the gas, as well as the mixing time. The authors proposed a mathematical model of the hydrodynamics of the metal melt, taking into account slag, which can be eroded with the appearance of a steel "eye". The movement of the metal-slag interface was predicted by a separate equation — the slag phase corresponded to one (the volume is completely filled with slag), and the steel phase corresponded to zero (complete absence of slag). It is shown that the slag is liquid enough for its droplets to be captured by the metal melt and immersed in depth. Also, the simulation showed a slight increase in the diameter of the droplets by 1—2 millimeters with an increase in the viscosity of the slag.

The authors of the article [2] investigated six locations of blow tuyeres with different gas flow rates. The mixing time was measured in a laboratory model of a 75-ton ladle–furnace. Water was used as a substitute for steel melt. The authors conducted numerical studies on the mathematical model and found the optimal arrangement of tuyere. Industrial experiments were conducted to measure the content of phosphorus, calcium oxides and iron. The improvement of dephosphorization was found when using the optimal arrangement of tuyeres, which was proposed by the authors as a result of the experiments.

The book [4] presents modern calculation methods used in the computer implementation of mathematical models of hydrodynamics. Iterative methods for linear systems, fast Fourier transform, methods for solving ordinary differential equations, parabolic and hyperbolic equations are considered. The author provided examples of solving problems using Matlab and Python programming languages.

The authors of [5] considered a mathematical model of the motion of the metal melt, taking into account the features of the gas barrel, which is formed on the tuyere and gradually expands, approaching the surface. The main phenomenon that the authors proposed to take into account is the simultaneous connection and separation of gas bubbles during their surfacing. The simulation results correspond to the measurements at the laboratory installation quite accurately, which confirms the adequacy of the mathematical model. The formula for calculating the fluid velocity depending on the melt depth is given.

Formulation of the study purpose

The purpose of the study is to find a rational consumption of inert gas and to optimize the location of the tuyeres for resource-saving mixing of impurities. The mathematical modeling of mass transfer in the melt and the development of accompanying software was chosen as a tool.

Presenting main material

It is believed that before starting the study of impurity mixing in the melt, the supervisor defines the initial conditions and variables within which the search for rational values will be carried out. Using a web interface, the conditions and variables are stored in a database for researchers who will directly conduct the experiments. The results of the experiments are automatically added to the database for further processing and output of graphs of dependencies or other statistical information that may be useful in the formation of recommendations for practical implementation.

The mathematical model of admixture mixing is based on the following assumptions about a multiphase incompressible melt-gas-admixture medium with interpenetrating phases:

1) The steel melt has a cylindrical body.

2) Steel melt is a fluid with solenoidal viscous motion, which has Newtonian properties. The melt has a flat surface.

3) The gas blown through the tuyere is ideal and flows at a constant velocity relative to the melt.

4) The impurity instantly dissolves when it enters the melt and its inertia, as well as its velocity relative to the melt, can be neglected.

Schematically, the melt body with the places of blow tuyeres looks like in Fig. 1 (the cylinder is shown at an angle to indicate the location of the tuyere):

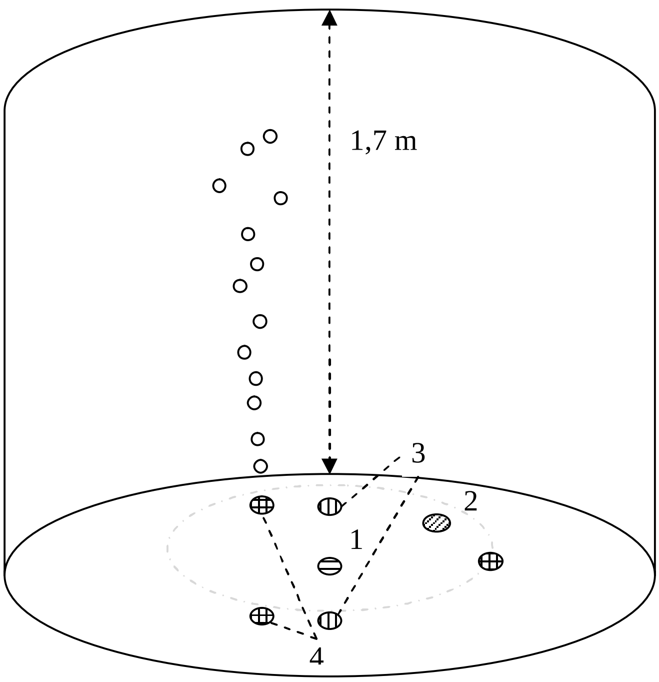

Fig. 1. A cylindrical geometry of the molten steel in the considered ladle (1/20 scale)

Mixing of the impurity in the melt, which is blown by the gas, is predicted by the Navier-Stokes and diffusion-transfer equations, which correspond to the laws of conservation of mass and momentum:

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

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

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

$$S_{\text{б}} = \frac{q}{V}\frac{T_{air}}{T_m} \tag{4}$$

$$\frac{\partial c}{\partial t} + \nabla \cdot (c\vec{\mathbf{v}}) - D_c \nabla^2 c = S_c \tag{5}$$

де D_{v}, D_{a}, D_c — are the effective coefficients of kinematic viscosity, gas diffusion and impurity diffusion correspondingly; g — is the acceleration of free fall (9.81 m/s^2 is assumed); v_f — gas flow rate (0.5 m/s is assumed); S_α, S_c — gas and impurity source (blown through the tuyere); q — gas consumption; T_{air} — gas temperature before entering the melt; T_m — melt temperature (1800 C is accepted).

The velocity equation is supplemented by boundary conditions that correspond to its components — perpendicular and parallel to the surface w of the solid:

$$\left.\frac{\partial \vec{\mathbf{v}}^{\parallel}}{\partial n}\right|_w = 0 \tag{6}$$

$$\left.\vec{\mathbf{v}}^{\perp}\right|_w = 0 \tag{7}$$

where n is the normal to the wall.

The gas transport equation is supplemented by impermeability boundary conditions on solid surfaces. A constant gas release rate is set on the upper surface of the melt.

The equation of impurity transfer is supplemented by the boundary conditions of impermeability on solid and upper surfaces.

The geometric shape of the ladle can be considered cylindrical and the values of unknown quantities can be measured in cylindrical coordinates. There is symmetry only in one case, when the blowing tuyere is located on the bucket axis. In other cases, a three-dimensional formulation of the problem is necessary. The melt space is schematically divided into finite volumes, which corresponds to the method of central differences. The finite volume method is popular in solving these equations due to its visual representation and second order of accuracy. The run method is a standard way to calculate the diffusion terms by an implicit scheme [4], which frees the time step from the additional restriction on the maximum value.

The model of the subject area of numerical study of impurity injection into the melt consists of six entities, two complex and one recalculation class (Fig. 2). Two complex classes define the coordinates of the tuyere, as well as the gas and impurity flow rates. The enumeration class defines the type of field (velocity, pressure, gas, impurity). The manager has an additional possibility to create studies, so there is a generalizing relationship between the entities "Kerivnyk" and "Doslidnyk". Researchers can participate in several studies and a many-to-many relationship is established between the entities "Doslidnyk" and "Doslidzhennya". Each study has minimum and maximum values of technological parameters, within which experiments are conducted, which corresponds to the one-to-many relationship between the entities "Doslidzhennya" and "Doslid". The minimum and maximum values of the parameter can be equal to each other if it is not necessary to change the technological parameter. As a result of the experiment, the scientist receives the values of fields of different types, so there are several one-to-one relationships between the entities "Doslid" and "Pole". The field of values has three dimensions in space and one dimension in time. Such a four-dimensional cube of values can be represented by a hierarchy of axes, in which the time axis has a child spatial axis of angles, which in turn also contains a spatial axis of heights and the same height axis consists of an axis of values along the radius of the cylinder. Thus, the relationship between the entities "Pole" and "Vis" will be "one-to-many". And the entity "Vis" has a one-to-many relationship with itself.

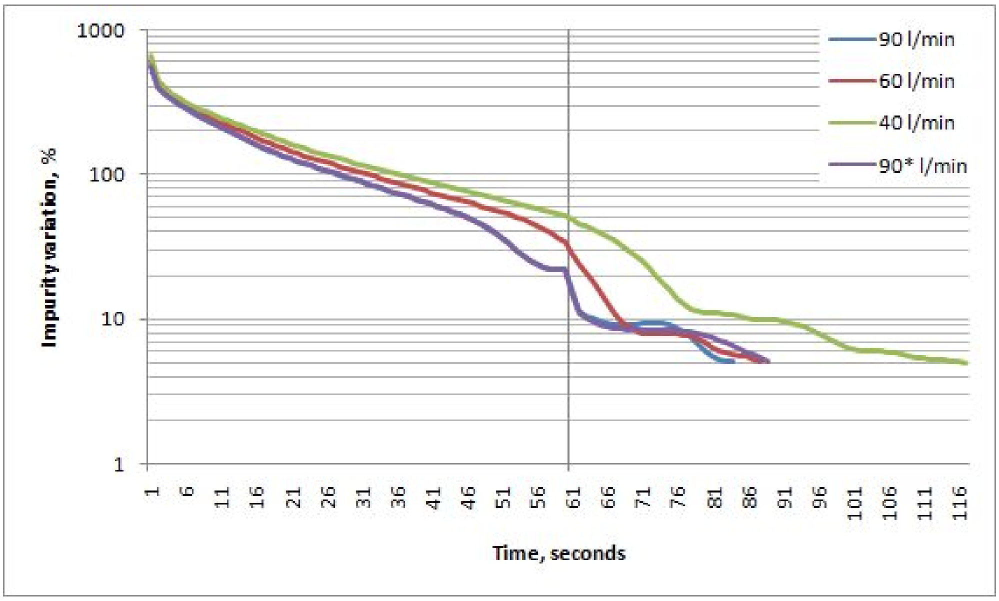

Fig. 2. Configuration with axial tuyere (the line with asterisk corresponds to the experimental case, when blowing is turned off at the 60 second)

It is proposed to implement the model using a free lightweight version of the database management system MS SQL Server, which is part of the programming environment Visual Studio for Web. The latter provides an opportunity to use the technology and library of ready-made components ASP.NET, specially designed for the framework construction of websites. One of the features of this technology is the structuring of the project code into classes of models, views and controllers, which supports easy readability of the code, testing and scaling:

– The model classes of real world objects are the subject area entities and are implemented using the Entity Framework library and annotations.

– The screen forms used by researchers are implemented in HTML5 with built-in Razor constructs for easy display of data and research results on the screen.

– Controller classes are programmed in the advanced high-level language C# and respond to Internet browser requests by connecting to the database and providing entity instances to screen forms.

Thus, to start the experiments, the computer implementation of the mathematical model of the unsteady process of impurity injection into the melt and the model of the subject area of this process requires only initial values and conditions. They are presented in the following tabl. 1, 2.

Table 1. Melt parameters for numerical experiment of impurity injection through tuyere

Melt	
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 tuyeres for numerical experiment of admixture mixing

Blowing tuyeres	
Diameter of tuyeres	0,1 m
1st setting	1 axial tuyere
2nd setting	1 tuyere at half radius
3rd setting	2 opposite tuyeres at half radius
4th setting	3 tuyeres at an angle of 120^o between them at half radius
Total gas consumption (sum of all tuyeres)	40/60/90 l/min
Total mass of impurity	30 kg
Diffusion coefficient of impurity in the melt	$34x10^{-9}$ m/s^2

Additionally, an experiment was conducted with the blowing off at the 60th second and the degree of mixing of the impurity was determined to assess the preservation of inert gas.

Fig. 2—5 show the results of the experiments in the form of the dependence of the coefficient of variation of the impurity concentration on time. The vertical axis has a logarithmic scaling due to the significant difference in values at the beginning of the experiment and at the end.

The configuration with axial tuyere (Fig. 2) mixes the impurity in about 85 seconds. The effect of different gas flow rates on mixing is almost not noticeable, except for the flow rate of 40 liters per minute of purging — mixing is slower by about 25 %. Experimental shutdown does not give significant differences in mixing speed.

The configuration with the tuyere in the middle of the bucket radius (Fig. 3) has results similar to the first configuration — the deviation from the duration of 86 seconds is insignificant and is not more than 5 seconds. Turning off the 90 litre blowing at 60 seconds extends the mixing duration by about 10 seconds and it becomes 92 seconds — just between the 40 litre and 60 litre continuous gas flow rates.

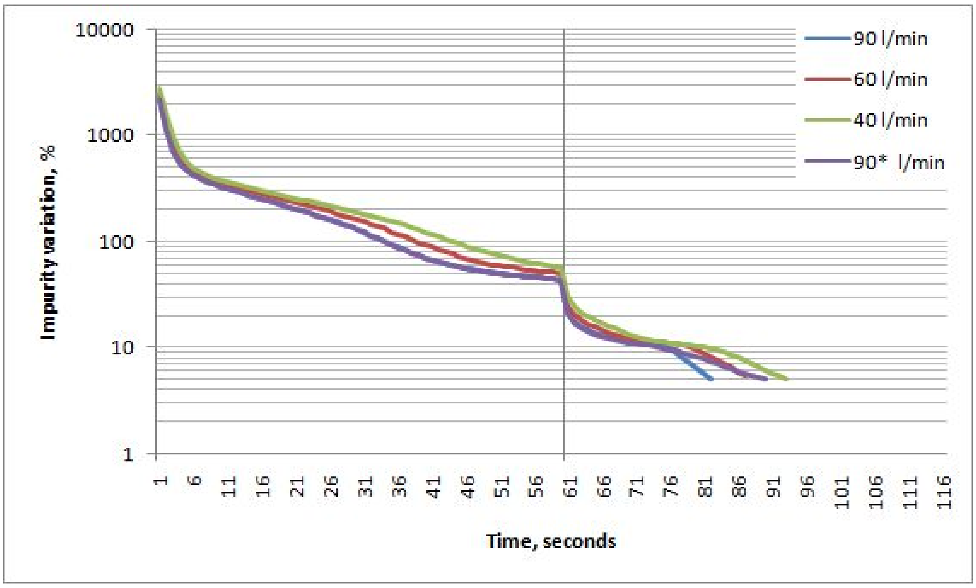

Fig. 3. Configuration with half-radius tuyere (the line with asterisk corresponds to the experimental case, when blowing is turned off at the 60 second)

Two opposite lances (Fig. 4) mix the admixture slower than one lance by about 15 seconds. And different gas flow rates affect the mixing with a difference of 10 seconds. Switching off the tuyere after 60 seconds slightly worsens the averaging — only by 3 %.

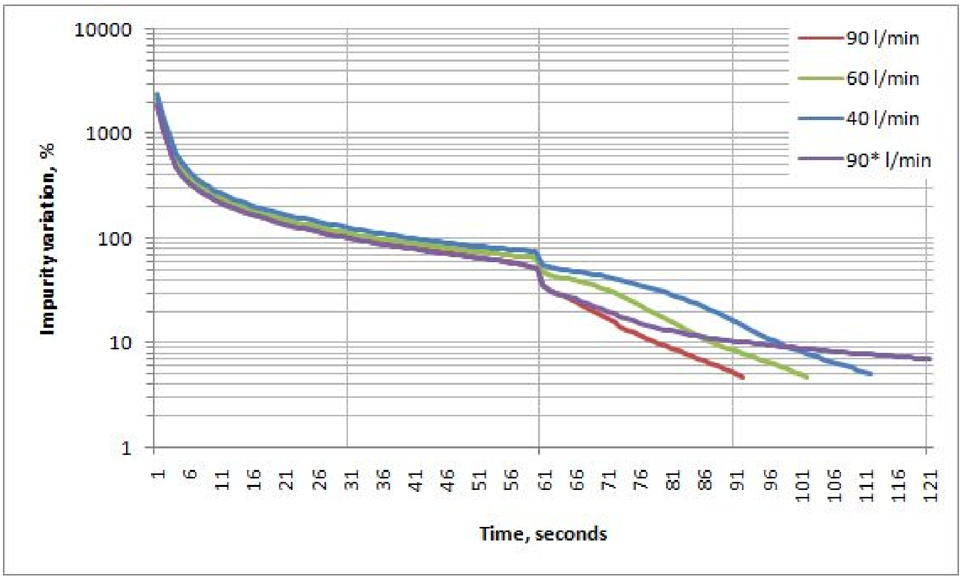

Fig. 4. Configuration with two opposite tuyeres (the asterisk means blowing is turned off at the 60 second)

In reality, the configuration of the steel ladle, which has three tuyeres, is almost never encountered, but from the point of view of research, it is of interest to scientists. Three tuyeres arranged at an angle of 120 degrees can compete with the previous configuration only at a gas flow rate of 90 liters per minute of purging (Fig. 5). At lower flow rates, the averaging slows down by another 20 seconds or about 25 %. Turning off the tuyeres at 60 seconds significantly slows down the mixing and averaging less than 10 % will not occur even at 136 seconds.

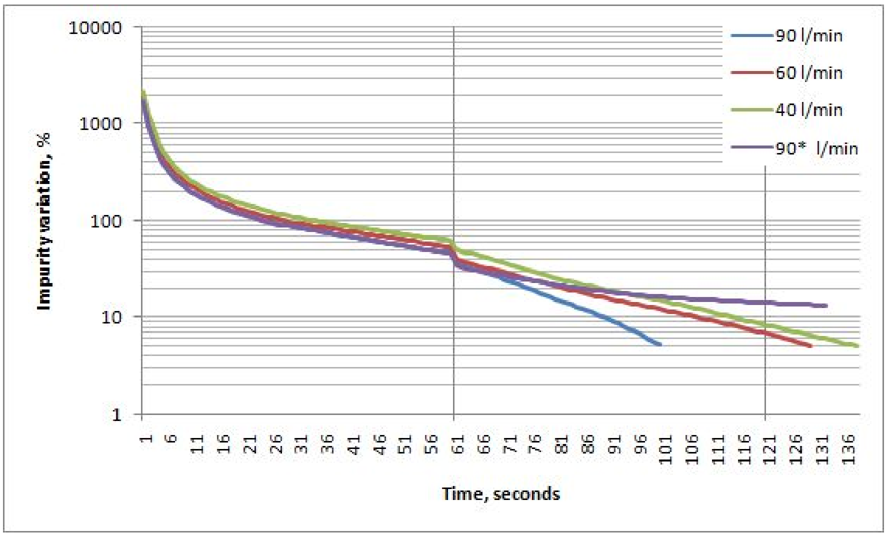

Fig. 5. Configuration with three tuyeres (the line with asterisk means turning tuyeres off at the 60 second)

In all configurations, after stopping the admixture injection at 1 minute, the degree of admixture averaging improves dramatically. This phenomenon is explained by the dispersion of high concentration of impurity near the tuyere, where it is blown into the melt. Within 5 seconds after the first minute, the mixing slows down somewhat.

Single tuyere configurations can lead to slag erosion due to the high melt velocities achieved by the high gas flow rate. In view of this, it was decided to conduct experiments with two and three tuyeres (Fig. 4, 5), but to divide the gas consumption equally for each tuyere.

The three-dimensional screening of the results is popular due to its clarity. Taking this into account, a video of the experiment with the first configuration of tuyere was created and published on the website https://www.tensorion.com/lab/metallurgy/ladle/impurity-mixing. The video shows the circulation of the impurity after it is blown into the melt. It is also obvious that the symmetry of the admixture field relative to the ladle axis is preserved.

Conclusions

As a result, numerical experiments were conducted with total inert gas flow rates from 40 to 90 l/min and with the number of tuyere from one to three. It was found that the configuration with one tuyere, located in the center of the radius, and the configuration with two opposite tuyeres and a total flow rate of 90 l/min have the shortest mixing time with a slight advantage.

It is recommended to implement the configuration with two opposite tuyeres, which has an acceptable mixing time of 92 seconds at a gas flow rate of 45 l/min for each tuyere.

Shutting down the tuyeres at 1 minute, when all the impurity has entered the melt, makes sense at high melt speed. In these configurations and with a limited total gas flow rate, a sufficiently high speed is achieved only in the case of one lance. With two or three tuyeres, the maximum melt velocity is low and the mixing of the impurity eventually acquires signs of dissipation (diffusion). And the dispersion is too slow in all these configurations and is not acceptable in conditions of constant melt cooling.

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