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Model Tests of the Optimal Location of a New Solution for the Module for Blowing Liquid Steel with an Inert Gas

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Abstract

This article presents the results of research aimed at determining the optimal location in the bottom of a steel ladle for an module for inert gas injection during the argon process. A physical water model of the ladle was used, constructed according to the principles of similarity, at a linear scale of 1:3.4 relative to the industrial device. This model represents a real object with a capacity of 65 Mg of liquid steel. Two variants of the module's position relative to the base point were adopted for the research, designated at a distance of 0.176 m from the horizontal diameter of the ladle bottom and 0.147 m from the vertical diameter. In variant 1, the longer axis of the module was placed parallel to the horizontal diameter of the ladle bottom, and in variant 2, perpendicular. The research was divided into two stages: quantitative and qualitative. A tracer in form of aqueous $KMnO_4$ solution was used for visualization (qualitative studies), while an aqueous NaCl solution was used to determine the mixing curves (quantitative studies). The minimum mixing time value, determined on the basis of the determined mixing curves, was used as a criterion for assessing the effectiveness of the tested modules in various locations.

Keywords: Steel, Ladle furnace, Ladle, Porous plug, Physical modelling

1. Introduction

The development of the metallurgical industry requires the introduction of innovative solutions and modifications to practice [1-4]. The primary goal of this development is to obtain alloys of the highest quality. One of the main directions of the continuous progress of the steel industry is to obtain alloys of excellent metallurgical purity [5-9]. This applies primarily to the steel industry, where steel quality is closely linked to the purity of liquid steel, and high-quality, clean steel is a constant goal of the steel industry's development [10-14].

In the steel industry, secondary refining plays a very important role in improving the purity of liquid steel, and among all the refining technologies, ladle refining is widely used due to its low costs and the fact that the metal reaches the expected composition and properties after carrying out all the necessary refining processes [15,16]. This procedure involves injecting a stream of inert gas, most often argon, into the molten steel through a porous plug installed at the bottom of the ladle [17]. This process aims not only to remove non-metallic inclusions from the molten steel but also to achieve chemical and thermal homogenization [14].

Gas bubbles forming on the surface of the porous plug, rising towards the surface of the liquid steel (gas column), transfer their kinetic energy to the liquid steel, causing circulation and mixing. The resulting bubbles absorb non-metallic inclusion particles and, using buoyancy forces, lift them towards the metal-slag interface [18,19]. Thanks to many years of experience with this procedure, it has become well understood from a hydrodynamic perspective. Its general idea is to generate as many gas bubbles as possible, with the smallest possible size, on the surface of the porous plug. This mechanism of gas column formation ensures the efficient operation of the process [20]. The design of the porous plug has a significant impact on the mechanism of gas column formation [21]. Therefore, the design of porous plugs, improved over the years, has now reached a very high level of advancement in both technological and material terms. For example, commonly used plugs enable the desired hydrodynamic parameters to be achieved depending on the changing requirements for the injected gas flow rate during the process. These plugs, known as hybrid plugs, are equipped with both slots through which the gas is introduced at a higher rate to ensure efficient steel homogenization, and porous materials to enable efficient refining at a lower injected gas flow rate [22,23].

The current level of advancement in the technology of blowing liquid steel with inert gases has been achieved thanks to knowledge derived from industrial practice and numerous scientific studies. One of the fundamental research tools in industrial metallurgical processes is modeling. A commonly used method today is combining physical modeling with numerical simulations. Modeling the process of blowing inert gases through molten steel is being pursued in many directions. The literature contains publications on the results of studies on hydrodynamic phenomena occurring in molten steel as a result of the impact of the injected gas stream. The most frequently discussed issues include the mechanism of gas column formation, the degree of gas dispersion in the volume of liquid steel, the degree of fragmentation and the number of formed gas bubbles, the effect of the gas column on the movement of liquid steel in the ladle, and the effect of the gas column on the metal-slag interface [21,24-26]. Another problem addressed in the literature is the study of the influence of the porous plug design on the process course and the study of the influence of the porous plug position on the ladle bottom on its course [21,26]. An important direction of research is also the determination of industrial process parameters (gas flow rate for effective refining of liquid steel, gas flow rate for effective homogenization of liquid steel, minimum mixing time of liquid steel in the ladle, etc.) [24,27]. Numerical simulations also enable the analysis of changes in the thermal conditions of the system during the process [28].

Considering the potential for obtaining such advanced knowledge on the process of purifying liquid steel with inert gases and the resulting extremely advanced designs of porous plugs, it can be concluded that further attempts to increase the efficiency of argon treatment by modifying the porous structure of the plug are ineffective and economically unjustified. In this situation, a new approach to the method of introducing gas into liquid steel seems reasonable. The efficiency of the process depends largely on the degree of gas dispersion in the liquid phase. This can be improved by increasing the active surface area of the shape through which the gas is introduced into the bath, and consequently by increasing the volume of the gas column. This assumption became the basis for the design of a slot-type gas-permeable module, which represents an innovative proposal for further improving the efficiency of the argon treatment process [12,28,29].

The article presents the results of tests using a water model of a steel ladle of two variants of installation of the proposed solution - a slot-type gas-permeable module in its bottom.

2. Research problem

The design of the slot-type gas-permeable module has been patented under the number PL 229475 [30] and described in detail in publications [12,28,29]. This design also takes into account the easiest and safest method of mounting the module in the bottom of the ladle. Due to its shape (cuboid), it is easy to install in the bottom of the ladle, and its external dimensions can be adapted to standard refractory elements of the ladle bottom lining. This eliminates the need for additional refractory shapes, as is the case with existing solutions. The proposed module solution offers a significantly larger active surface area than the currently used porous plug. Active surface area refers to the area within which the crevices are located. Comparing the active surface area of the crevice for a traditional plug, it is 0.003847 m², while for the proposed module solution, it is 0.021450 m², with a ladle bottom surface area of 4.735070 m² (see Fig. 1).

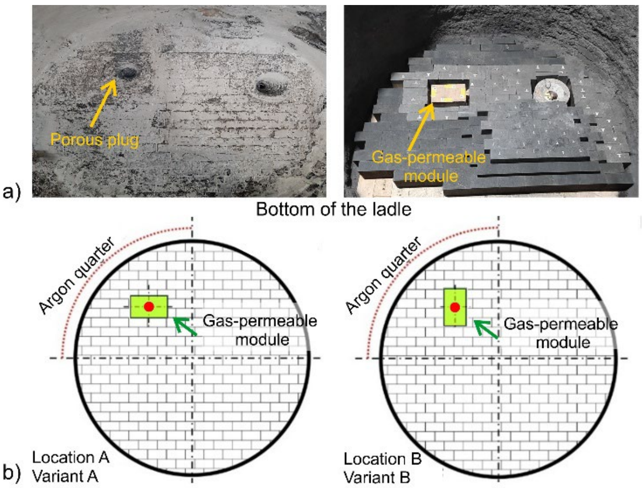

Fig. 1 (a) View of porous plug installed in the steelmaking ladle bottom and module, (b) the location of the module at the bottom of the ladle

The studies presented in [28,29] concluded that the new slot-type gas-permeable module design can be an effective alternative to currently used solutions (traditional porous plugs). However, the location and orientation of the module's longer axis relative to the ladle walls remain problematic. This problem concerns both the efficiency of the modules used and the impact of the forming gas column on the refractory lining of the ladle walls.

Therefore, two variants of the module's location relative to the base point were adopted for testing. In variant A, the longer side of the module was positioned parallel to the horizontal diameter of the ladle's bottom, and in variant B, perpendicular. As a result, the geometric center of the module's active surface is located at 2/3 of the radius from the ladle's axis, similar to the axis of the porous plug currently used. Both module locations in the ladle bottom ensure the simplest possible installation (embedding) in accordance with the arrangement of the refractory layers in the ladle bottom in industrial conditions. The module connections to the existing gas infrastructure of the ladle were also designed to avoid interference with its armor.

The locations of the slot-type gas-permeable module analyzed in the study are shown in Figure 1. The red dot in Figure 1b indicates the location of the currently used porous plug. Figure 1a shows the porous plug installed in the steelmaking ladle bottom and the proposed solution – the gas-permeable module (location A).

This research is part of an ongoing project aimed at developing a new technology for deep refining of steel in the process of secondary metallurgy and tundish casting, enabling an increase in the degree of steel purity - project no. 1.1/POIR/08/2018, the beneficiary of which is Cognor SA Ferrostal Łabędy Gliwice.

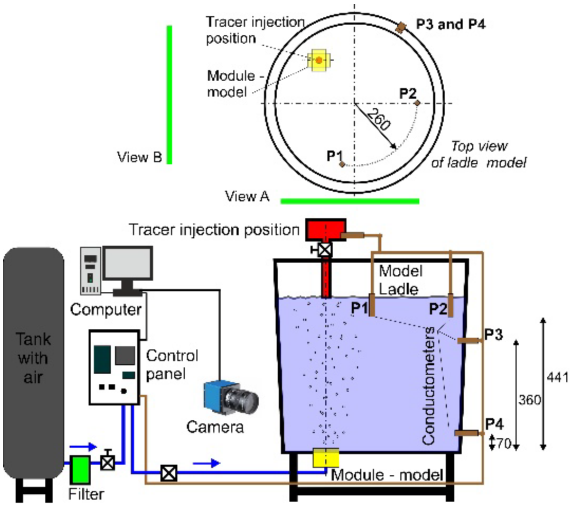

Fig. 2. Schematic diagram of water model experimental equipment, P1-P4 – location of four conductivity meters

3. Experimental method

3.1. Experimental equipment

The experiments were conducted on a test stand equipped with a physical water model ladle with the ability to purge the model liquid with inert gases (see Figure 2). The gas used in the model tests was air.

The control and measurement equipment installed on the test stand enables smooth regulation (Sewenstar D07 series and AR642/S1) and recording of air flow at the inlet to the module model as well as monitoring and recording of changes in the conductivity of the model liquid (MultiCon CMC-99 Lite).

Four GCT20K conductivity meters were installed in the water model ladle at selected points in the model space (see Figure 2 – P1-P4) to measure the conductivity of the model fluid. The measurement points were designated to minimize the negative impact of the sensors on the experiment while maintaining the ability to obtain objective measurement results. Signals from the conductivity meters are recorded in the MultiCon data logger. They are then exported to a computer, where they are processed to plot mixing curves and determine the minimum mixing time.

A proprietary solution was used to introduce the tracer into the model, ensuring repeatable and precise dosing of the designated tracer volume. The tracer volume introduced at a time in each experiment was 0.00015 m^3 (0.15 dm^3). To maintain the similarity of the ladle model's operation to the actual object, the tracer insertion point was placed along the axis of the model module. This location corresponds to the industrial conditions for introducing alloying elements into a metal bath.

In the conducted studies, the tracer was an aqueous $KMnO_4$ solution (qualitative studies) or an aqueous NaCl solution (quantitative studies).

Cameras were used primarily for visualization studies – visual recording of the dynamic flow field after the addition of a colored tracer ($KMnO_4$).

3.2. Object of the research study

The research object is a ladle with a capacity of 65 Mg of liquid steel, which is part of the ladle furnace equipment at the Steelworks of Ferrostal Łabędy in Gliwice. Due to the specific dimensions of the industrial ladle, a linear reduction scale of S_L = 1:3.4 was adopted in the design of the physical ladle model. The ladle model is made of PMMA (poly(methyl methacrylate)). A mounting located at the bottom of the ladle allows for easy installation of the prototype model or the porous plug model in various module positions. The most important dimensions of the industrial ladle and its water model are presented in Table 1 and Figure 3.

Table 1.
Parameters of the water model and industrial geometry

Parameter	Industrial object	Water model
Upper diameter [m]	2.616	0.769
Lower diameter [m]	2.456	0.722
Ladle height [m]	2.322	0.683
Liquid steel/water level [m]	1.840	0.541
Position of the porous plug A	0.500	0.147
Position of the porous plug B	0.600	0.176

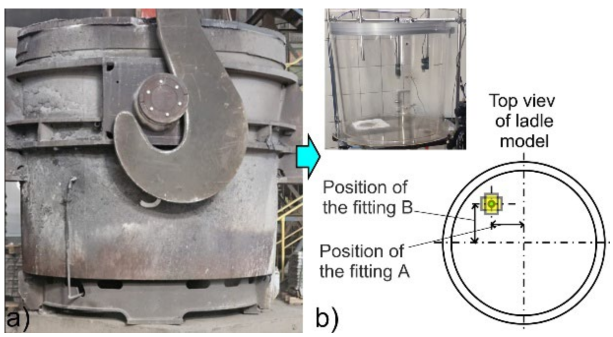

Fig. 3. View of the: (a) industrial ladle (b) water model

To sum up, it should be emphasized that the location of the module (position of the fitting A and B) in the bottom of the ladle (see Fig. 2) results from the previously described premises and is justified by the adaptation to the existing conditions in the steelworks.

The module model for physical testing was created by Łukasiewicz Research Network - Institute of Ceramics and Building Materials, in accordance with patent no. PL 229475. This model was made on the same scale as the ladle model, which is 1:3.4. Due to the design of the water ladle model, the air supply connection is located on the side wall (in the industrial module, it is located at the bottom). The model module is characterized by eight 0.00005 m (50 μm) wide slots (which in industrial conditions corresponds to 0.00017 m (170 μm)). A view of the module model with the most important markings is shown in Figure 4.

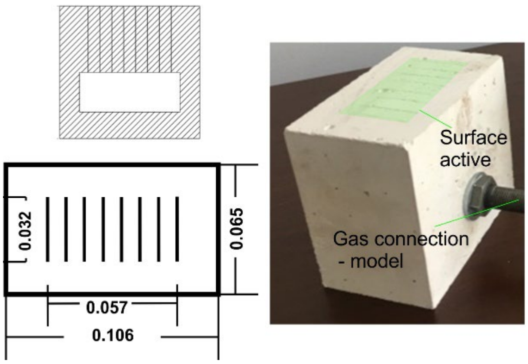

Fig. 4. View of the slot-type module

3.3. Dynamic Similarity

To ensure the similarity of the dynamic model to the actual device, the principle of consistency of the characteristic criterion values in both systems was used [31,32]. The Froude number, commonly used for this type of solutions, was adopted as the main characteristic criterion. In the process of blowing argon through a module (porous plug) placed at the bottom of the ladle, the motion of gas bubbles in the liquid is analyzed [28]. The system under consideration thus takes the form of a two-phase system. The classical form of the Froude number refers to single-phase systems. In the case of multiphase flows (liquid – gas), the similarity of the properties of the individual phases must be taken into account. The classical form of the Froude similarity criterion then requires modification. The modified Froude criterion (Fr_N) is then presented by the relationship [21,31]:

$$Fr_N = \frac{\rho_g \cdot V^2}{\rho_l \cdot g \cdot L} \quad (1)$$

where: ρ_g - gas density, ρ_l - liquid density, g - acceleration due to gravity, L - characteristic dimension, V - gas injection velocity.

The kinetic similarity of the gas flow rate in the ladle model was determined using the scale method [33,34]. The following relationship was used to convert the gas flow rates in real conditions to the model ones:

$$Q_m = \left(\frac{C_m}{C_p}\right)^{-1/2} \cdot S_L^{5/2} \cdot Q_p \quad (2)$$

where: Q_m - fluid flow rate in the model, C_m - mass constant of the model fluid, C_p – mass constant of the industrial fluid, S_L – linear scale, Q_p - fluid flow rate in industry.

To determine the tracer mixing time in the model liquid, mixing curves were used – an example curve is shown in Fig. 5. The minimum tracer mixing time was used as a criterion for assessing the effectiveness of the liquid steel homogenization process. The analysis assumed that the minimum mixing time value was the longest mixing time obtained from all measurement points.

Based on the analysis of industrial production conditions conducted at the ladle furnace station, two inert gas (argon) flow rates of 200 and 250 $dm^3 \cdot min^{-1}$ were adopted for model tests. These are the most commonly used values. After recalculation according to equation (2), the air flow rates in the water model were determined to be 3.7 and 4.7 $dm^3 \cdot min^{-1}$, respectively.

3.4. Experimental characterization

Laboratory experiments included qualitative and quantitative studies. Their objectives were to determine gas dispersion in the bath volume and the mechanism of gas bubble cone formation (so-called gas column), to determine the proportion of dead zones in the bath volume during inert gas purging, and to plot mixing curves—determining the minimum time for complete bath mixing—a parameter characterizing the process's effectiveness.

Qualitative studies were conducted using visualization. Their progress was recorded in two planes using video cameras. This camera arrangement enabled multi-plane observation of the model fluid circulation within the volume of the steel ladle model. The recorded material was then computer-processed and interpreted. Based on the obtained data, an analysis of the model fluid mixing was performed, along with an assessment of the mechanism of gas bubble cone (gas column) formation and the degree of gas dispersion in the model fluid.

The second stage was a quantitative analysis. The tests were conducted to determine the effectiveness of the model liquid homogenization process under the influence of injected air. Mixing time was assessed based on the determined mixing curves.

The experiments utilized the principle of the system's response to impulse extortion. Extortion was achieved by injecting a specific portion of the tracer (aqueous NaCl solution) at a designated point in the system. The system's response, in the form of changes in the electrical conductivity of the model fluid, representing changes in its concentration, was continuously recorded. Conductometers installed at selected points in the model's working space were used to measure changes in the conductivity of the model fluid. Conductivity values measured at half-second intervals are equivalent to changes in the tracer concentration in water.

The dimensionless tracer concentration for the curve was calculated based on the expression [35,36]:

$$c_b = \frac{c_t - c_0}{c_\infty - c_0} \quad (3)$$

where: c_t, c_0, c_∞ – tracer concentration at time t, at the beginning and at the end of the process, respectively.

Mixing is assumed to be achieved when the degree of bath homogenization reaches 95%, which corresponds to the dimensionless concentration ∈ ⟨0.95;1.05⟩. The ranges described in parentheses indicate the dimensionless range of tracer concentrations [36]. A value of 1 indicates a state of perfect tracer mixing. When the curve is stable within a certain range, for example ±5% as the dotted line shown in Figure 5, it is considered that the system has been completely mixed, and the time is defined as the mixing time from a chemical or metallurgical reaction engineering perspective. The determination of mixing time is schematically shown in Figure 5.

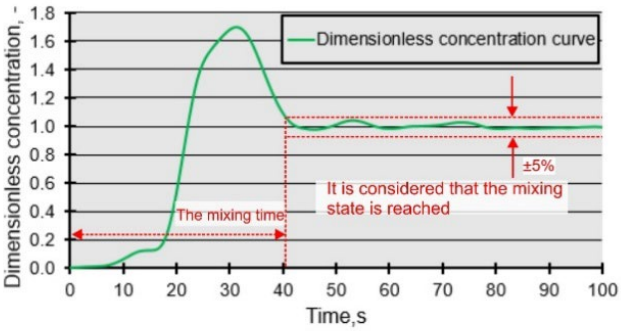

Fig. 5. Schematic diagram of the dimensionless concentration curve (the dotted lines are fluctuation range and mixing time)

4. Results and discussion

The main goal of the visualization modeling studies was to determine the effect of the module's installation method at the bottom of the ladle model on the mechanism of gas column formation and, consequently, on the movement of the model liquid induced by the injected gas stream. Particular attention was paid to the potential negative impact of the gas column on the ladle walls.

4.1. Qualitative research

Figure 6 presents sample test results illustrating the degree of dispersion of gas bubbles in the model liquid and the mechanism of formation of a cone of gas bubbles (so-called gas column).

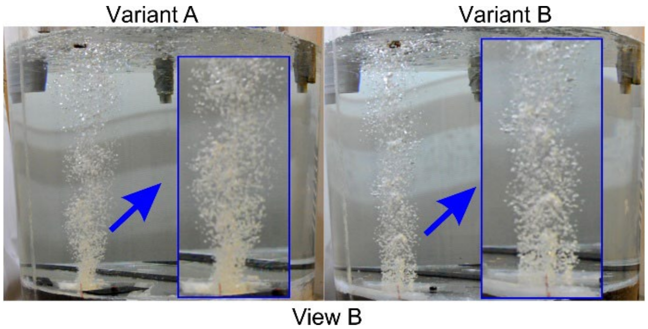

Fig. 6. The mechanism of the behavior of gas bubbles in the model liquid for experimental variants

During the tests, for both module installation variants at the bottom of the model ladle, significant fragmentation of gas bubbles on its active surface was observed. The resulting gas column is characterized by high compactness and stability (see Figure 6). There was no tendency for it to swirl or excessive bubble growth as it flowed toward the bath surface. There was also no risk of bubbles coalescing into larger conglomerates. A much more advantageous method of forming a gas column (for both variants of module location) was also observed, characterized by a larger volume at a lower gas flow rate compared to the previously used blowing technology using a porous plug [12,28]. The studies also showed that despite the strong fragmentation of the bubbles, the compactness of the gas column provides sufficient energy to effectively influence the movement of the liquid phase (see Figure 6). On this basis, it can be concluded that the size of the active surface area of the porous plug/module influences the effectiveness of the process of injecting inert gases into the liquid steel at the ladle furnace station.

This fact allows us to predict the correct course of the argon blowing process, which in turn increases the refining efficiency of the ladle equipped with the module (with increased active surface area compared to porous plug). In both module location variants (despite the larger active surface area), no direct interaction of gas bubbles with the walls of the ladle model was observed. The gas column formed at a safe distance from them. This allows to conclude that there is no risk of washing out the ladle's refractory lining or secondary contamination of the liquid steel under industrial conditions.

The mechanism of the gas column's influence on the motion of the simulant was analyzed using recorded footage obtained from two cameras. The cameras were positioned at a 45° angle to each other. This allowed for observation of the simulant's motion throughout the entire ladle. Visualization of the simulant's mixing process was achieved by introducing a specific portion of an aqueous $KMnO_4$ solution into the system as a marker. Individual frames were extracted from the footage at specific time intervals using a proprietary method. Examples are presented in Figures 7-8. Figure 7 shows images obtained from camera 1 – view A. Figure°8 shows images from camera 2 – view B.

Analysis of the obtained test results allowed to determine the correct mechanism for the circulation of the model liquid for both variants of the module's location at the bottom of the ladle model. The gas column lifts the liquid stream to the mirror, which then descends at the ladle axis and returns to the mirror on the opposite side. This phenomenon is particularly visible when analyzing the

test results obtained from camera 2, View B. By analyzing the material obtained from both cameras together, it can be concluded that two circulation zones are formed within the ladle volume: one encompassing the area around the gas column, and the other with the liquid flowing in the opposite direction on the opposite side.
In the area of interaction between these currents, the liquid flows near the ladle axis toward the bottom. This mechanism creates a risk of creating restricted mixing zones in the liquid surface area, perpendicular to the plane passing through the center of the ladle and the module. In summary, this phase of research indicates that the mechanism of gas column formation and its properties are correct for both module locations at the bottom of the ladle.

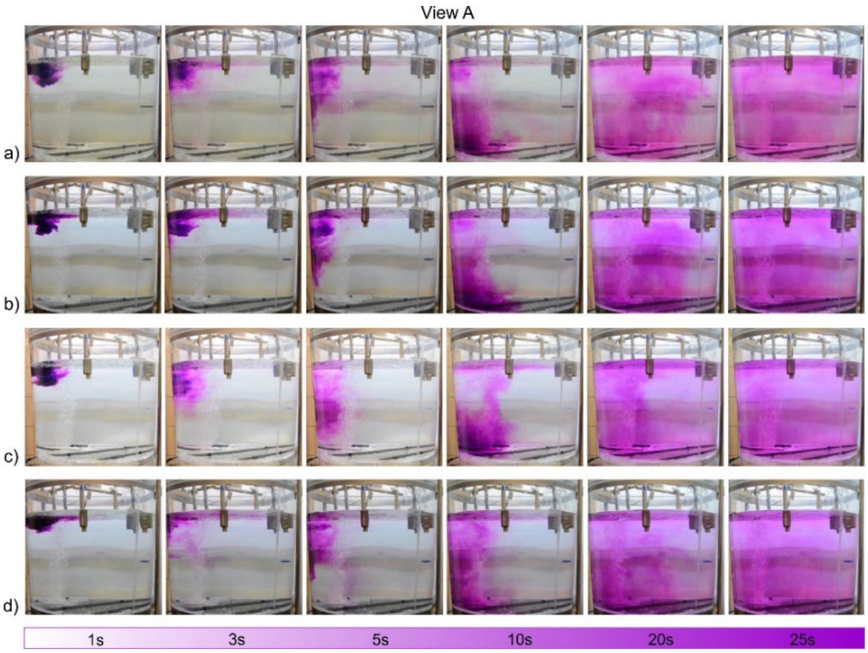

Fig. 7. Visualization of mixing in view A: a) module location A - gas intensity 3.7°dm^3·min^{-1}, b) module location B - gas intensity 3.7°dm^3·min^{-1}, c) module location A - gas intensity 4.7°dm^3·min^{-1}, d) module location B - gas intensity 4.7°dm^3·min^{-1}

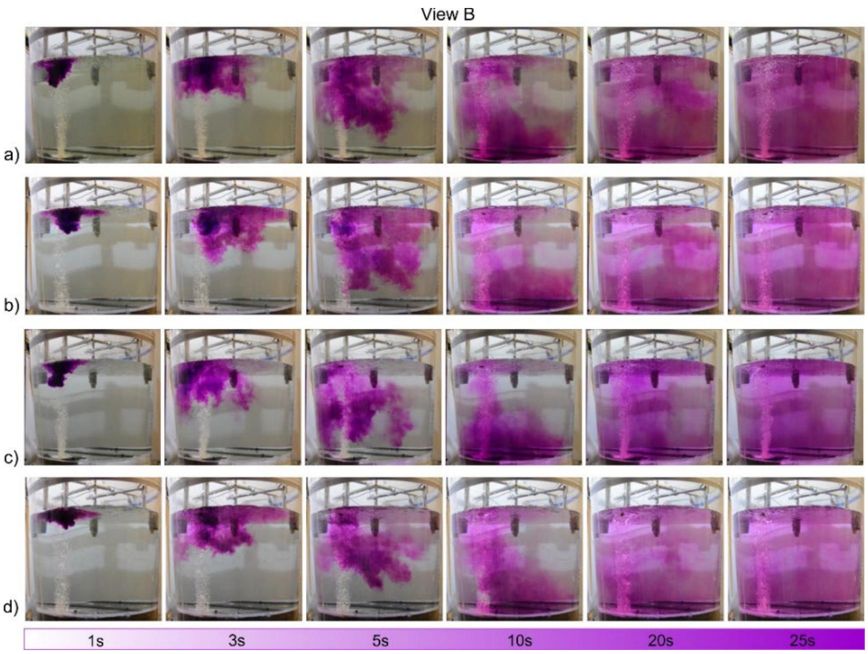

Fig. 8. Visualization of mixing in view B: a) module location A - gas intensity 3.7°dm^3·min^{-1}, b) module location B - gas intensity 3.7°dm^3·min^{-1}, c) module location A - gas intensity 4.7°dm^3·min^{-1}, d) module location B - gas intensity 4.7°dm^3·min^{-1}

4.2. Quantitative research

The main goal of the quantitative modeling studies was to determine the minimum mixing time of the tracer in the model liquid volume for various positions of the model module at the bottom of the ladle.

Figure 9 shows exemplary sample mixing times, determined according to the procedure described above (see Figure 5), obtained for four monitoring points, for position variant A - gas intensity of 4.7 $dm^3 \cdot min^{-1}$.

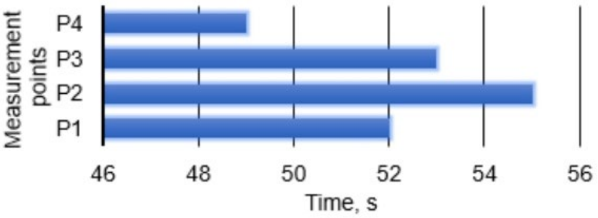

Fig. 9. Exemplary specification for mixing time at individual monitoring points

The mixing time values recorded by individual sensors, presented in Figure 9, confirm the risk of limited mixing zones forming in the area of the model liquid surface at the interface between two circulating currents, observed during the visualization. The sensor located in this zone indicated the longest mixing time. The remaining mixing time values also confirm the circulating movement of the model liquid observed during the visualization, characterized by an upward current near the ladle walls and a downward current in its center. However, it should be emphasized that the data presented in Figure 9 clearly indicate that the correct determination of mixing time depends on the location of the monitoring location (measuring point).

The minimum mixing time marker values for the entire volume of the ladle in all the studied cases, determined based on the analysis of mixing curves, are presented in Table 2. The table was also supplemented with the results of comparative tests carried out using the gas-permeable fitting used so far in the model.

Table 2.
Average values of the minimum mixing time for the analyzed variants

Parameter	Water model	Industrial object	Water model	Industrial object
Flow rate of gas, $dm^3 \cdot min^{-1}$	3.7	200	4.7	250
Minimum mixing time, s	porous plug			
	79	145	63	116
	Location A			
	54	100	55	101
	Location B			
	56	103	57	105

The presented values of minimum tracer mixing time clearly show that these times are very similar for the analysed variants. This allows to assume that the module design is not significantly sensitive to module position or changes in gas flow rate within the tested range.

The minimum mixing time does not change significantly with increasing gas flow rate. It should also be noted that, for the same gas injection conditions, the mixing time for the current technology with a porous plug is significantly longer. The presented data demonstrate a significant increase in the efficiency of tracer mixing in the simulant using the module compared to the previously used porous plug injection technology. In connection with the above, it can be concluded that increasing the active surface and, consequently, modifying the hydrodynamic conditions has a positive effect on the efficiency of homogenization of liquid steel in the ladle. This result supports the conclusion that certain benefits can be achieved by reducing gas consumption in industrial environments.

The presented data (see Table 2) confirmed previous observations. There were no significant differences in the effectiveness of tracer mixing in the model liquid volume due to the module positioning variants at the bottom of the model ladle.

To sum up both research techniques used in the model tests, it is permissible to use both variants of the position of modules A and B in the bottom of the ladle in industrial conditions.

5. Conclusions

Based on the modeling studies, it can be concluded that:

- Increasing the active surface area in the module has a positive effect on increasing the degree of gas dispersion in the metal bath, and thus on improving the refining efficiency and increasing the mixing efficiency.
- In both tested variants, a correct gas column formation mechanism and a highly fragmented bubble structure within the gas column were observed. This factor favors the effective capture of non-metallic inclusions and their removal to the slag phase.
- No significant differences in tracer mixing efficiency were observed between the two tested variants (a 3-4% difference depending on the gas flow rate). For both module positioning variants, there was no risk of the gas column washing over the ladle walls.
- Complementary comparative testing of the module with the previously used technique of injecting gas through a gas-permeable fittings revealed a significant increase in mixing efficiency, ranging from 14 to 29%, depending on the gas injection rate and module location.
- Using the module in industrial conditions can reduce processing time at the ladle furnace by approximately 10%.

Acknowledgements

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