RESEARCH OF POROUS PLUG SLOT-TYPE OF A NEW DESIGN - PHYSICAL AND NUMERICAL MODELING

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Abstract

Argon is the currently used and relatively simple method for refining liquid steel. This is most often done in a ladle furnace. Contemporary porous plugs used for refining liquid steel are characterized by a high degree of design sophistication. Further increasing their efficiency is difficult and inefficient. In response to growing process requirements, an innovative solution was developed in the form of a slotted gas-permeable module. The proposed design is based on a modular structure, representing a new concept in the construction of porous plugs. This solution allows for a significant increase in the active surface area modulus compared to the active surface area of currently used porous plugs.

This article presents the results of numerical simulations and physical modeling of a new design solution for a slot-type gas-permeable module. Initial research - numerical simulations were conducted using a 1:1 scale ladle and a hot metal-argon system. The studies were comparative between the currently used technology (porous plug) and the proposed solution. To verify the numerical modeling results, tests were conducted on a physical water model of ladle in a 1:3.4 scale. Experimental results demonstrated high agreement with data obtained from CFD. The qualitative criteria for assessing the functionality of the tested solution included visualization results in the form of the gas column formation mechanism, the degree of gas dispersion in the model fluid, and gas bubble fragmentation. Quantitative criteria included the minimum time for complete mixing of the tracer in the model fluid volume and the proportion of slow-flow regions (dead zones) in the metal bath volume.

Keywords: secondary metallurgy, ladle, porous plug, physical modeling, numerical modeling

1. INTRODUCTION

The liquid steel blowing process has been used for many years to improve the homogenization and refining of liquid steel [1]. Basically, it is carried out at the ladle furnace station [2,3]. It also serves as a kind of buffer between the stage of steel melting in the primary steelmaking reactor (oxygen converter or electric arc furnace) and the continuous steel casting device. This enables smooth control of the steel production process throughout the entire technological line of the steel plant [4,5]. Numerous research studies conducted so far have made it possible to achieve a very high level of efficiency of this process [6-10]. This is mainly due to the complex design of gas-permeable fittings installed in the bottom of the steelmaking ladle [11,12]. Further progress in this field is possible by changing the approach to existing design models of gas-permeable fittings and developing an innovative solution. A proposal that addresses this need is a modular device for injecting inert gas into liquid steel in a steel ladle [13]. The main feature that distinguishes this solution from previous ones is the ability to significantly increase the active surface area, i.e., the area at the bottom of the steel ladle through which the gas is injected.Thanks to its modular design, this solution allows for an even distribution of the gas stream into micro-slits of significantly greater length, and consequently, the coverage of a larger volume of the bath by the gas cone. At the same time, it allows for increased gas bubble dispersion, which promotes its dispersion in the molten steel. This article presents the results of model tests confirming the validity of the assumptions made for the proposed modular solution and the impact of its location at the bottom of the ladle on its operational efficiency.

2. RESEARCH OBJECT AND RESEARCH METHODOLOGY

Preliminary studies – numerical simulations were carried out using a 1:1 scale ladle (**Figure 1**) and a hot metal-argon system. The standard method of gas introduction through a slot-type porous plug (12 crevices, slot layout area ϕ 0.07 m) was compared with a new design solution – a module (8 crevices, slot layout area 0.11 x 0.21 m). The module and the porous plug are described in detail in [13].

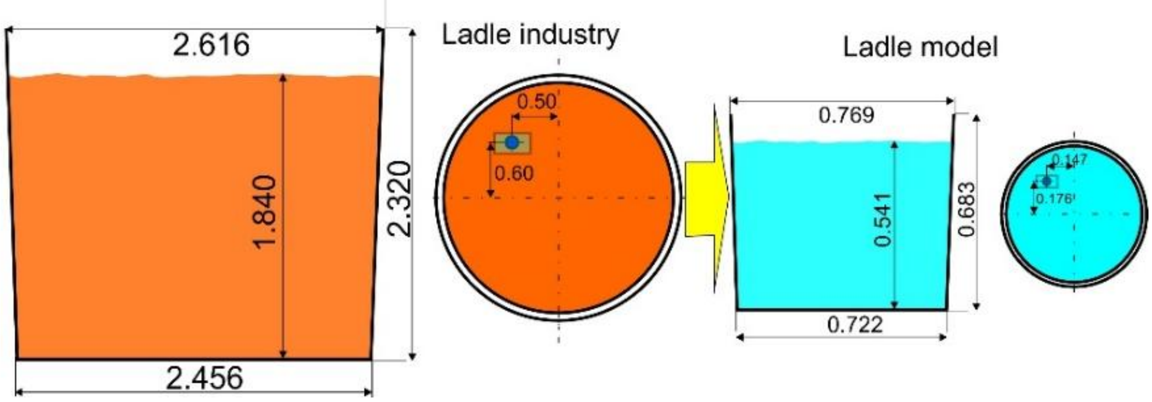

Figure 1 Parameters of the industrial ladle geometry and the water model

Before proceeding to the main simulations, a verification of the computational mesh density was carried out. The analysis showed that numerical result stability was achieved with 466,300 cells. The numerical simulations were performed using Ansys Fluent (Academic Associate version) [14]. The numerical model is described in detail in article [13].

To directly compare the results of both simulation cases (porous plug/module), identical fluid parameters were defined in the numerical model. For liquid steel, density was assumed to be 7011 $kg \cdot m^{-3}$, viscosity 6.7 $kg \cdot m^{-1} \cdot s^{-1}$ and temperature 1853 K. Argon at a temperature of 300 K and a density of 1.634 $kg \cdot m^{-3}$ was introduced into the system at a constant volumetric flow rate of 200 $dm^3 \cdot min^{-1}$.

Physical tests were conducted on the test stand schematically shown in **Figure 2.** This stand is equipped with a water model of the ladle, constructed at a linear scale of S_L = 1:3.4. This model represents an industrial ladle with a capacity of 65 Mg of liquid steel. The model's bottom design allows for the assembly of model components (module/porous plug) in various configurations. The key dimensions of the industrial ladle and its water model are shown in **Figure 1**. The applied structural solution of the model bottom allows for the installation of model elements (module/porous plug) in various arrangement configurations. The most important dimensions of the industrial ladle and its water model are presented in **Figure 1**.

The model module for physical testing was developed by Łukasiewicz Research Network - Institute of Ceramics and Building Materials. The device was constructed in accordance with patent claims no. PL 229475 [15]. The geometric scale of the module is identical to the scale of the ladle model. Structural limitations of the test stand necessitated a change in the location of the gas supply port - it was placed on the side wall (in the real object, the inlet is located at the bottom). The construction of the element and its main dimensions are illustrated in **Figure 2c**.

The condition of dynamic similarity of both systems was ensured by maintaining the identity of the criterion values [16]. In the model studies, a modified Froude number was used as the main characteristic criterion [17,18]. The kinematic similarity of the gas flow in the ladle model was determined using the scale method [19]. The studies analyzed two values of the gas-air flow rate. The first was 3.7 $dm^3 \cdot min^{-1}$ (industry (argon) – 200 $dm^3 \cdot min^{-1}$), while the second was 4.7 $dm^3 \cdot min^{-1}$ (industry (argon) – 250 $dm^3 \cdot min^{-1}$).

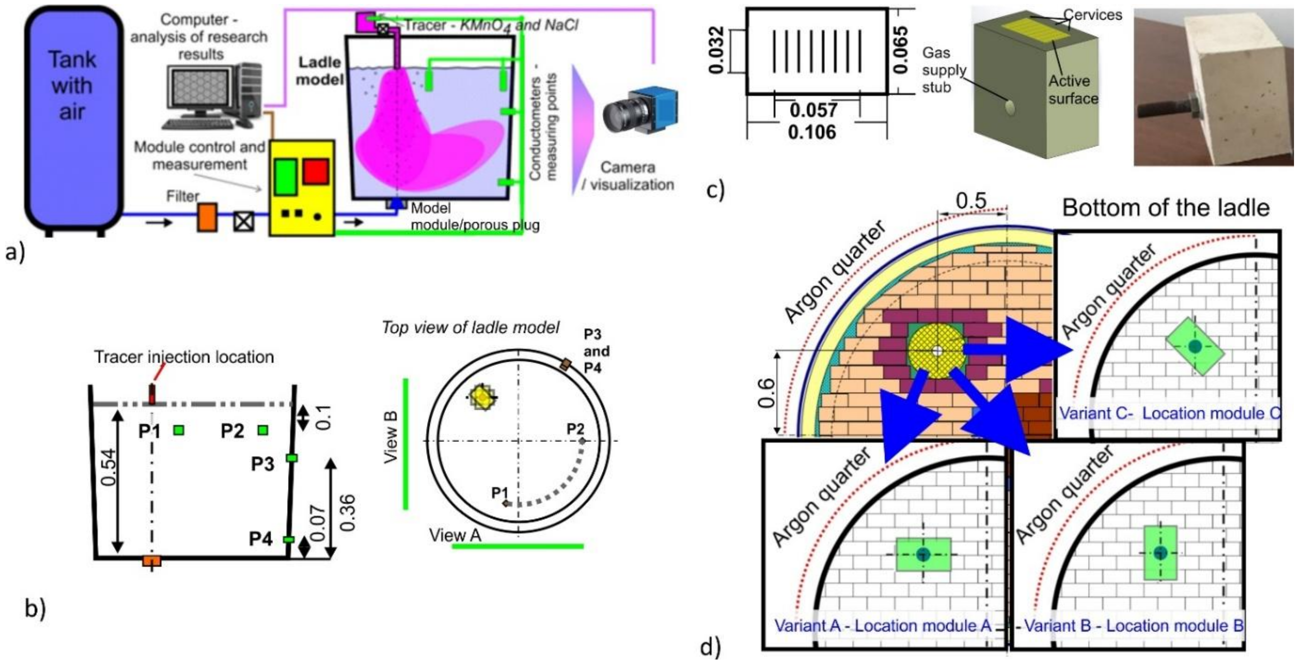

Figure 2 Schematic diagram of: a) water model experimental equipment, b) marking measurement points and planes for qualitative testing, c) model module, d) position of the module at the bottom of the ladle analyzed in physical tests

Three module positions in the ladle were considered in the physical model tests. In variant A, the longer side of the module was positioned parallel to the horizontal diameter of the ladle, in variant B perpendicularly, and in variant C at a 45-degree angle. As a result, the geometric center of the active surface of the module is located at a distance of 2/3 of the radius from the ladle axis, which coincides with the position of the axis of the currently used porous plug. The method of connecting and positioning the module to the existing gas infrastructure was designed so as not to require any structural modifications to the shell of the industrial ladle. **Figure 2d** illustrates the module positions (locations) in the ladle bottom considered in the study.

3. RESEARCH RESULTS

The criterion for comparing the proposed technology with the previously used solution was the identification of dead zones of steel mixing within the working space of the ladle. The proportion of dead zones in the conducted tests was determined based on the analysis of slow-flow regions. A velocity of 0.05 $m \cdot s^{-1}$ was adopted as the threshold for separating slow-flow regions - below this value, the fluid motion is considered stationary, and the area where it occurs is regarded as a dead zone. The distribution of these regions within the ladle volume and the values for the cases studied are shown in **Figure 3**.

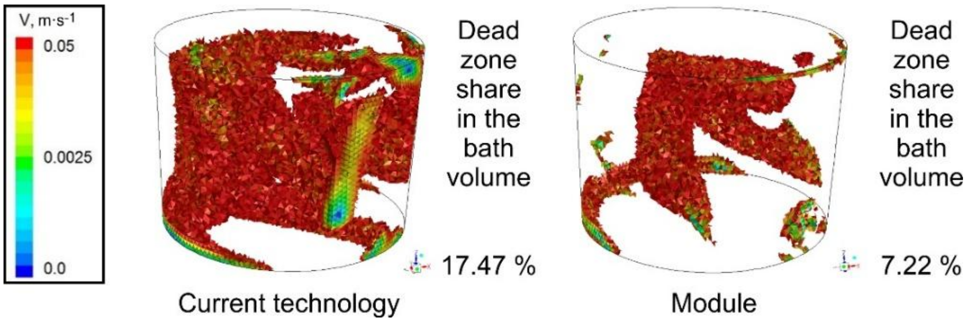

Figure 3 Velocity distribution in stagnant areas (dead zones) – results of numerical modeling of the flow in the ladle

Comparative analysis (**Figure 3**) demonstrated a significant advantage of the proposed module solution over the previously used slot-type porous plug technology. The proportion of dead zones in the ladle working space was reduced by over 10 percentage points (from 17.47% to 7.22%). Such a dramatic reduction in low-flow areas demonstrates significantly more effective mixing intensification, which guarantees higher process efficiency through the proposed module solution.

In connection with the above, studies were conducted using a physical ladle model. **Figure 4** presents example results of the visualization of the mixing mechanism of the model liquid at successive time steps.

Analyzing the results of the visualization study (**Figure 4**) of the formation of a cone of gas bubbles, attention was paid to their number and size (diameter) as they exited the diffuser slots, their outflow rate, and their growth on the way towards the model liquid surface. A significant improvement in the mechanism of gas bubble formation was observed for all module position variants compared to current technology. Very good fragmentation and the expected pattern of outflow towards the model liquid surface were observed. A significantly more favorable gas column formation was also observed at low gas flow rates compared to the previously used porous plug blowing technology – current technology.

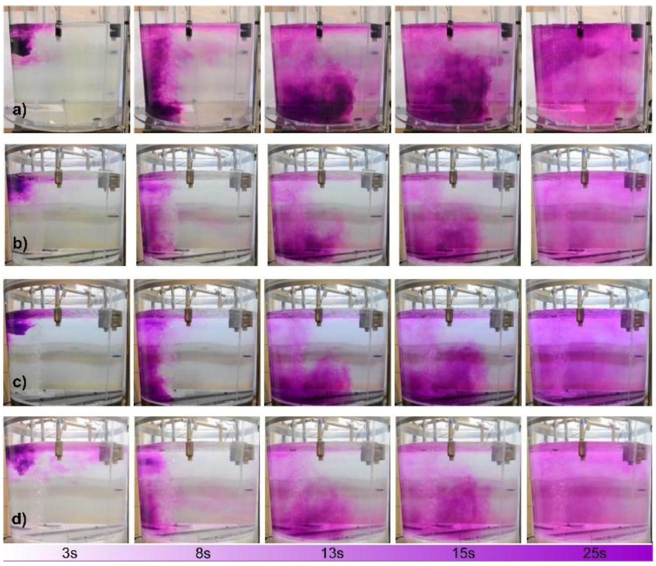

Figure 4 Visualization of mixing in view A, gas intensity 3.7°dm^3·min^{-1}: a) Current technology, b) Variant A, c) Variant B, d) Variant C

Analyzing the results in terms of the mixing of the model liquid (**Figure 4**), carried out to assess the system's ability to achieve the required bath homogenization, demonstrated a certain advantage of the proposed solution - the module. Due to the larger active surface area, the gas cone encompasses a larger volume of model liquid, and due to the greater dispersion of gas bubbles, the mixing process is more uniform throughout the bath volume than in the previously used solution. The obtained test results allow to determine the correct mechanism for model liquid circulation for all tested variants A, B, and C. However, it should be noted that the module's location in variant C at the bottom of the ladle poses the greatest challenge compared to the other variants; the cost-effectiveness of implementing this solution should be considered.

In the second stage of the study – quantitative – analysis of the obtained mixing curves allowed to determine the minimum mixing time of the marker in the model liquid. It was assumed that mixing was achieved when the degree of bath homogenization reached 95% [5,20]. In the analysis, the minimum mixing time was assumed to be the longest mixing time obtained from all measurement points. **Table 1** presents the average results of this analysis.

Table 1 Average values of the minimum mixing time for the analyzed variants.

Flow rate of gas ($dm^3 \cdot min^{-1}$)	**Minimum mixing time (s)**			
	Current technology porous plug	Variant A Module A location	Variant B Module B location	Variant C Module C location
3.7	79	54	56	58
4.7	63	55	57	55

Analysis of the results (**Table 1**) shows a clear advantage of the new module solution over the currently used technology (porous plug). Regardless of the module position (tested variant) and gas flow rate, the mixing time is reduced by 9.5% to 31.6% compared to the current technology.

The best performance was achieved for variant A, which reduces mixing time by over 30% at a lower gas flow rate compared to the standard porous plug. It should be noted that the differences between variants A, B, and C are minimal (1-4 seconds).

It should also be noted that the percentage improvement in mixing time for the module at a gas flow rate of 4.7 $dm^3 \cdot min^{-1}$ compared to current technology is significantly smaller (for variant A: 12.7% vs. 31.6%). This is because the standard porous plug becomes more efficient at higher gas flow rates (4.7 $dm^3 \cdot min^{-1}$) (mixing time is reduced from 79 to 63 s). Therefore, it can be concluded that using the module allows for greater efficiency at lower gas flow rates. This means that, in industrial conditions, gas (argon) consumption can be reduced while simultaneously improving mixing conditions in the ladle.

In summary, the obtained test results allow to conclude that all tested module positions (variants A, B, and C) can be used in industrial conditions. However, at the same time, it is necessary to take into account the problems with installing the module in the bottom of the industrial ladle - in the C position variant - set at an angle to the laying of the refractory lining bricks.

4. CONCLUSION

The analysis of the results of the conducted model tests allows the following conclusions to be drawn:

The proposed module solution effectively reduces the volume of dead zones in the ladle compared to existing technology. Although the location of these areas remains unchanged, their share in the ladle working space decreases by approximately 40%. This demonstrates that the use of the module ensures significantly improved metal circulation within the ladle volume.

Compared to the current porous plug technology, this module (for all analyzed variants A, B, and C of its position) provides a more effective mechanism for forming a gas column, generating a significantly finer bubble structure and their uniform flow towards the surface of the model liquid. Furthermore, for all variants of the module position, no risk of excessive washing of the gas column against the ladle walls was observed.

The use of the proposed solution (module) demonstrates its high effectiveness in generating hydrodynamic conditions conducive to steel bath homogenization within the workspace of the ladle. The minimum mixing time of the alloy addition is reduced (for all analyzed variants, from 9.5% to 31%) compared to the current technology.

The module location in option A is optimal in terms of bath homogenization rate at a given gas flow. However, the difference between the best option A and the worst option C is only 5%, which is negligible on an industrial scale. Therefore, the selection of the appropriate module location may be determined by other technical, economic, and technological parameters specific to the steelworks.

Using the module in industrial settings allows for a reduction in gas flow rate. This translates directly into a reduction in specific argon consumption while simultaneously improving mixing conditions, which shortens the processing cycle at the ladle furnace station by achieving homogenization parameters in a shorter time.

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