INFLUENCE OF THE ACTIVE SURFACE OF THE PURGING PLUG ON THE EFFECTIVENESS OF THE ARGON BLOWING PROCESS IN THE LADLE

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Abstract

The basic procedure of secondary metallurgy is blowing liquid steel with inert gases. This treatment is applied in the ladle at the ladle furnace station. The main task of the injected gas is to homogenize the liquid steel both in terms of temperature and chemistry, and to capture and transfer non-metallic inclusions (NMIs) to the slag phase. The effectiveness of the liquid steel blowing process in the ladle depends on many factors. The main of them is the energy of the injected gas stream, under the influence of which the hydrodynamic conditions for mixing liquid steel in the ladle are formed. As well as the size and number of gas bubbles that flow out, which determine the efficiency of refining liquid steel with NMIs.

The article presents the results of tests carried out on a laboratory stand equipped with a physical water model of a ladle. The research was aimed at determining the importance of the size of the active surface of the purging plug used when blowing argon into the ladle to the above-mentioned factors. The criteria for evaluating the effectiveness of the liquid steel blowing process were the minimum time of complete mixing of the model liquid in the ladle model and the degree of gas dispersion in the volume of the model liquid. The minimum mixing time was determined on the basis of the determined mixing curves, and the degree of gas dispersion in the liquid was determined on the basis of visualization tests.

Keywords: Secondary metallurgy, steel, ladle, argon, physical modelling

1. INTRODUCTION

Research on hydrodynamic phenomena occurring during the implementation of steelmaking processes is very difficult and requires large financial outlays. The justification for this statement is the fact that they are usually carried out on a mass scale, in physical conditions that are very difficult from the point of view of research possibilities (high temperature, aggressive environment, construction of steelmaking reactors, etc.), forcing the use of appropriate, unique measuring equipment, resistant to mentioned conditions.

Such research is also associated with the risk of a serious disruption of the production process carried out by steel companies, which in turn may lead to a situation where the costs of research far outweigh the possible benefits. Finally, advanced research work carried out during the production process always interferes with its normal course, which can lead to unexpected risks to the safety of the working crew. Taking into account the above risks, the use of some research methods that enable obtaining the necessary information for effective optimization of the tested process or implementation of innovative solutions is impossible in industrial conditions. Therefore, a commonly used method of solving such problems is the method of modelling metallurgical processes [1-6].

This method (physical modeling) was used in own research on the influence of the size of the active surface of the purging plug on the efficiency of the inert gas blowing process into liquid steel. By active surface is meant the area of distribution of crevices on the face of the purging plug. The constructions of purging plugs used so far have reached a very high technological level [7-9]. Thanks to the progress in the field of engineering refractory and porous materials, their further development seems to be extremely difficult. A characteristic feature of the present solutions is that they cover a relatively small area of the bottom of the ladle. Therefore, it seems logical that the development of methods of blowing inert gas into liquid steel, and thus further improvement of the efficiency of this process, can be achieved by increasing the active surface of the purging plug.

The aim of the research presented in the article was to verify the thesis that the greater the value of the ratio of the active surface of the purging plug to the entire surface of the ladle bottom, the greater the efficiency of the blowing process. The criteria for evaluating the effectiveness of the liquid steel blowing process were the minimum time of complete mixing of the model liquid in the steel ladle model and the degree of gas dispersion in the volume of the model liquid. The minimum mixing time was determined on the basis of the determined mixing curves, and the degree of dispersion of gases in the liquid was determined on the basis of visualization tests.

2. MODEL DESCRIPTION AND RESEARCH PROGRAM

The experiments were carried out on a test stand equipped with a physical water model of ladle with the possibility of blowing the model liquid with inert gases, made on a linear scaled-down scale S_L = 1:3.4. The control and measurement equipment installed at the test stand enables smooth regulation and recording of the gas flow at the inlet to the model, as well as monitoring and recording of changes in water conductivity under the influence of the added tracer at selected points of the model. **Figure 1** shows a diagram of the test stand. The executive part of the stand, i.e. the ladle model, is built in accordance with the requirements of the theory of dynamic and kinematic similarity, it also meets the condition of geometric similarity [10-11].

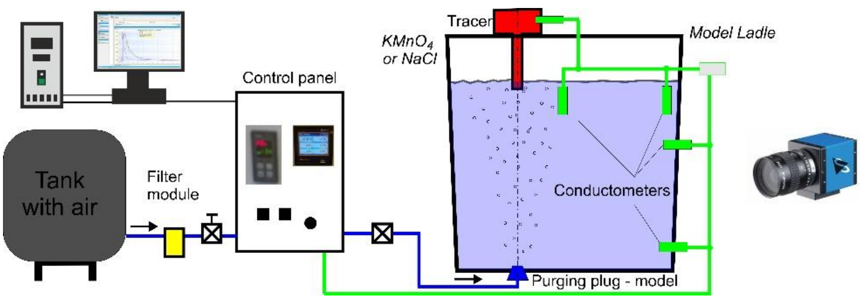


Figure 1 Scheme of the test stand (ladle model)

In order to maintain the similarity of the work of the ladle model to the real object, the insertion point of the tracer was placed in the axis of the purging plug. This location corresponds to the industrial conditions for introducing alloying additions to the metal bath. The tracer is inserted below the surface of the model liquid (water). A set of conductivity meters was installed to determine the mixing curves in the ladle model and a system of video cameras for visualization tests was installed. The modified Froude criterion expressed by the formula [11] was adopted as the dominant criterion of dynamic similarity:

$$Fr_M = \frac{\rho_S \cdot v^2}{\rho_l \cdot g \cdot L} \quad (1)$$

where: ρ_S – gas density (g·cm^{-3}); ρ_l – liquid density (g·cm^{-3}); v – gas velocity, (cm·s^{-1}); g – gravitational acceleration (cm·s^{-2}); characteristic dimension (cm).

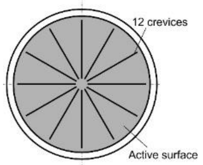
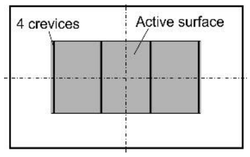
Kinematic similarity of the gas stream flow in the model ladle were determined using the scaling method according to the equation:

$$Q` = \left(\frac{c`}{c}\right)^{-\frac{1}{2}} \cdot S_L^{\frac{5}{2}} \cdot Q \qquad (2)$$

where: $Q`$ - volumetric gas flow rate for the water model ($m^3 \cdot s^{-1}$); $Q$ - volumetric gas flow rate for the industrial ladle ($m^3 \cdot s^{-1}$); $c`$ - constant for water model, (-); c – constant for industrial ladle (-); S_L – geometric scale.

Two types of purging plug models were used for the study, differing in the size of the active - working surface. The first is a "crevice" purging plug with a circular cross-section, which corresponds to an industrial purging plug used in the ladle station in industrial conditions - variant A. Whereas variant B is a plug made by Łukasiewicz - Institute of Ceramics and Building Materials (ICBM). It is a purging plug "crevices" type with a rectangular cross-section that differs significantly from the currently used plugs - construction details are described in patent no. PL 229475. Purging plug "crevices" type - variant A was made using the incremental 3D printing method. The plug-variant B was made by ICBM. Both model plugs used for the model tests took into account the scaled-down scale of the ladle model. The diagram of plugs of active (working) surfaces and basic dimensions are shown in **Table 1**.

Table 1 Scheme and basic dimensions of plugs with marked active (working) surfaces

Parameters		Plug variant A		Plug variant B	
Scheme					
		Industry scale 1:1	Model scale 1:3.4	Industry scale 1:1	Model scale 1:3.4
Number of crevices (-)		12		4	
Length of crevices (mm)		30	8.8	110	32.4
Total length of crevices (mm)		360	105.9	440	129.4
Active surface parameters (mm)	diameter	ϕ 70	ϕ 21	-	-
	length	-	-	110	32.4
	width	-	-	195	57.3
Active surface of the crevice (mm^2)		3,847	346	21,450	1,856
Ladle bottom surface (mm^2)		4,735,070	409,208	4,735,070	409,208

The inert gas flow rate for both variants was set at the same level. In industrial conditions it is 250 $dm^3 \cdot min^{-1}$. After converting this value in accordance with equation (2) for the purposes of the experiment using the water model and taking into account the fact that argon used in industry was replaced with air, the value of 4.7 $dm^3 \cdot min^{-1}$ was obtained.

The research was divided into two stages. The first of them was aimed at determining the method of shaping the gas column and assessing the degree of gas dispersion in the volume of the model liquid. These studies were visualizations. Their course consisted in recording the course of the experiment in various planes using a system of cameras, and then computer processing of the recorded material and its interpretation. The second stage of the research was carried out in order to determine the effectiveness of the homogenization process of the model liquid under the influence of blowing gas. It consisted in determining the value of the minimum mixing time of the tracer in the model liquid based on the analysis of the mixing curves obtained as a result of the experiment.

3. RESEARCH RESULTS

Figure 2 presents exemplary 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 (gas column) for the analyzed purging plugs.

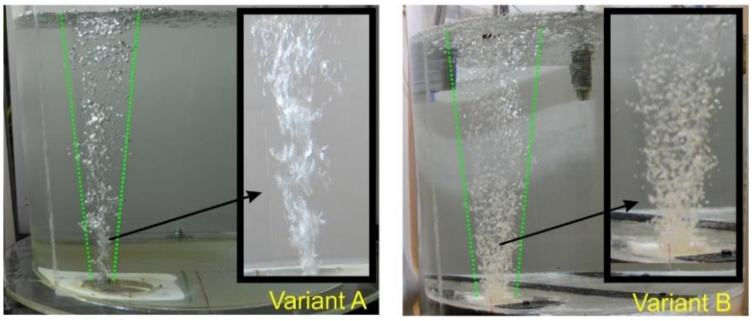


Figure 2 Exemplary results of visualization - the formation of gas bubbles in relation to the gas column depending on the plug type

Based on the analysis of the visualization test results, it was found that the size of the bubbles flowing out of the crevices of the purging plugs models in both variants is similar. Considering the fact that similar parameters of crevices and the same value of the blowing gas stream are used, a similar way of forming gas bubbles on the active surface of the purging plugs models is justified.

The situation is different in the case of analyzing the phenomena accompanying the formation of a gas column in the volume of the model liquid. It has been observed that the size of the active surface of purging plugs is significant in this case. In variant A, the forming gas column covers a smaller volume of the model liquid and clearly expands as it approaches the bath surface. This proves that the conditions are more favorable than in variant B for the growth of gas bubbles on the path of their outflow. In variant B, the column expands slightly less but achieves a higher degree of dispersion in the volume of the model liquid. This results in an increase in the contact area and an increase in the mutual interaction of the two phases, and consequently the need to overcome the increasing forces associated with surface tension. Growth of gas bubbles in the upper zone of the gas column is hindered in this case.

Further research was aimed at identifying the phenomena affecting the mechanism of liquid mixing in the volume of the ladle model caused by the stream of blowing gas. To enable the observation of this process, tracer - water solution of $KMnO_4$ was introduced into the model liquid. **Figure 3** shows exemplary results of the visualization of the model liquid mixing mechanism for both analyzed plugs. When analyzing the results (**Figure 3**) of the visualization of the formation of a cone of gas bubbles, attention was paid to their number and size (diameter) at the time of leaving the crevices of the purging plug model, the speed of their outflow and growth on the way towards the model liquid surface.

Based on the test results (**Figure 3**) of the visualization of the model liquid mixing mechanism under the influence of blowing gas, no significant differences were found for both variants of the experiment. However, it was noticed that, especially in variant B, the precision of inserting the tracer in the axis of the gas column affects the way of its circulation in the volume of the ladle. Interpreting this fact from the point of view of the possibility of effective influence of the gas column on the alloying additives introduced into the bath, i.e. their even distribution in the steel bath, one can indicate the danger that the gas column in variant B of the experiment will behave like a gas curtain. This interaction can be harmful and impede the chemical homogenization of liquid steel. In summary of this stage of research, it should be stated that the hydrodynamic conditions in the volume of the model improve, which are conducive to more effective removal of nonmetallic inclusions (NMIs). Although the method of circulation of the model liquid in both variants of the experiment is similar, the mechanism of formation of the gas column in variant B shows more features considered beneficial from the point of view of effective refining of liquid steel in the ladle.

In the second stage of the research, the experiments were carried out in such a way that it was possible to plot the mixing curves enabling the determination of the minimum mixing time of the tracer in the model liquid. The minimum mixing time of the marker was treated as a criterion for evaluating the effectiveness of the liquid steel homogenization process. For this purpose, changes in the concentration of tracer - water solution of NaCl - as a function of time were monitored by measuring changes in the electrical conductivity of the model liquid (which is an analog of this concentration) at four points (**Figure 1**). The obtained data were processed in order to determine the mixing curves characterizing the hydrodynamic conditions prevailing in the ladle model during the experiments.

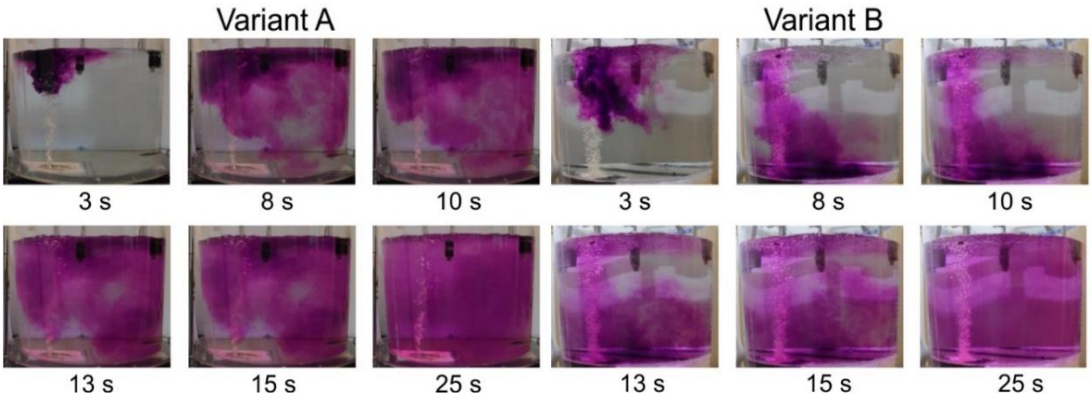


Figure 3 Exemplary results of visualization - mixing mechanism

In order to objectively compare the results of individual experiments, the obtained conductivity values were transformed into a dimensionless form [12-13]. Normally, mixing is considered to be provisionally complete [13] when a 95% degree of homogenization of the bath is reached. **Figure 4** shows an exemplary characteristic of the change in the dimensionless concentration of the tracer at four measurement points for a 95% degree of homogenization.

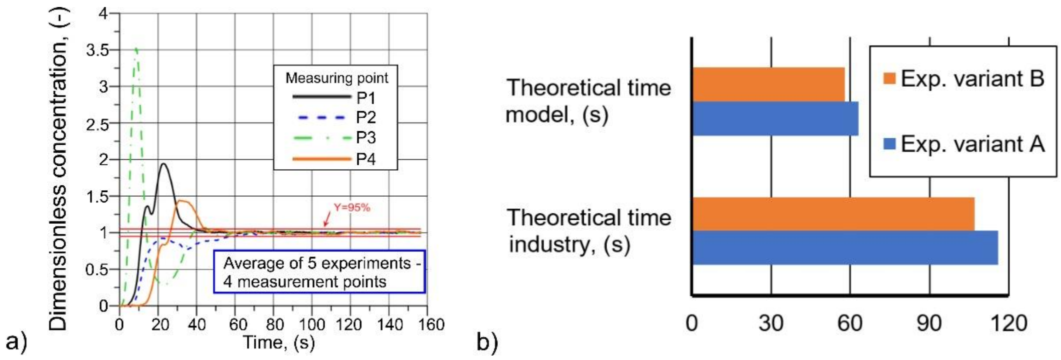


Figure 4 a) An example of the mixing efficiency graph showing the minimum mixing time, b) the average values of the minimum mixing time of the tracer for the analysed variants of the experiment

Experiments at this stage were carried out in series of five experiments for each variant. The analysis of the obtained RTD graphs allowed to determine the average values of the minimum time of mixing the tracer in the model liquid for each of them. **Figure 4b** shows the results of this analysis graphically. A shorter minimum time of mixing the tracer in the model liquid was obtained for variant B of the experiment. Therefore, it can be concluded that increasing the active surface of purging plugs has a positive effect on the ability to homogenize liquid steel in a ladle.

4. CONCLUSION

Based on the model tests carried out, it should be stated that the size of the active surface of the purging plug in the content of the article has been confirmed. Despite the observation of similar sizes of gas bubbles formed on the active surface of purging plugs in both variants, the degree of their dispersion in the volume of the model liquid and the mechanism of formation of the gas column is more favorable in variant B. The larger volume of the gas column and the lower tendency for the bubbles to coalesce on the way to the bath surface, allows us to conclude that the probability of the collision of gas bubbles with NMIs increases in variant B. This fact allows to expect an increase in refining efficiency in a ladle equipped with an in purging plug with a higher active surface. Finally, the analysis of the mixing curves also confirmed a faster homogenization process of the model liquid in variant B of the experiment.

However, it should be remembered that the conducted research concerns only the hydrodynamic aspect of the studied process. Its application in industrial practice requires very advanced technical changes in the construction of the industrial ladle.

The research results presented in the article are therefore the basis for further considerations on improving the efficiency of the inert gas blowing procedure into liquid steel.

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