ARCHIVES
of
FOUNDRY ENGINEERING

10.24425/afe.2024.151322

Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences

ISSN (2299-2944)
Volume 2024
Issue 4/2024

142 – 152

19/4

Model Studies of Metallurgical Processes Based on the Example of Blowing Steel with Argon

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Received 26.08.2024; accepted in revised form 05.12.2024; available online 31.12.2024

Abstract

The task facing steel producers, which is to limit the negative impact of their production on the environment, necessitates changing the technologies used so far. These changes often require knowledge of the mechanisms of physical phenomena, mainly hydromechanical ones, occurring in steel reactors. Identification of these mechanisms in industrial conditions is difficult and often impossible for fundamental reasons. A frequently used research tool in such cases are water physical models of metallurgical reactors used in steel production. Such models are built in accordance with the principles of similarity and fluid mechanics. The article presents an overview of achievements in the field of physical modelling of steelmaking processes (including blowing liquid steel with inert gases), mathematical principles constituting the basis for the construction of steelmaking reactor models and the latest trends in their application. As an example, the results of model tests on the possibility of using a new solution in the construction of a slot-type gas-permeable module (KS diffuser) in the process of blowing liquid steel with inert gases in a steel ladle are presented. The tested process is aimed at preparing liquid steel for casting and largely determines the quality of the semi-finished product, which is a steel ingot.

Keywords: Ladle furnace, Cleanliness of steel, Porous plug - slot-type, Water models, Physical modelling

1. Introduction

The steel industry, as an important factor in the development of civilization, is a progressive and constantly improved industry. Steel production in the world is growing and in 2021 it amounted to 1 billion 951 million Mg, which was a new record for crude steel production in the history of global steelmaking. Steel production on the European market increased by as much as 15% compared to 2020, reaching over 152 million Mg [1]. The increase in steel production on a global scale is illustrated in Figure 1.

This development is accompanied by a continuous increase in new types of steel. Their number is currently estimated at over 3.5 thousand. As steel production increases, intensive efforts are being made to limit the negative impact of this production on the environment. The aim is to develop an expanding sector of the production of so-called green steel, in which the main emphasis is placed on the use of energy from renewable sources and reducing the carbon footprint by replacing this fuel with alternative fuels, e.g. hydrogen.

Therefore, the modern steel industry faces great challenges to meet the growing market requirements in terms of quality (metallurgical purity) and physicochemical properties of manufactured steel products, to meet stringent ecological standards while maintaining economic competitiveness on the market of construction materials. This involves the need to introduce many innovative technical and technological solutions into current industrial practice. Introducing such fundamental changes in steel production methods requires not only extraordinary effort from the entire steel sector, but also strong scientific support.

This development is accompanied by a continuous increase in the number of new steel grades. So far, their number is estimated at over 3.5 thousand. As steel production increases, intensive efforts are made to reduce the negative impact of this production on the environment. Efforts are being made to develop the growing production sector of the so-called green steel, in which the main emphasis is on the use of energy from renewable sources.

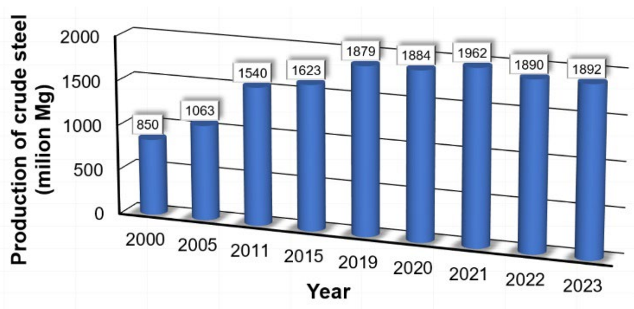

Fig. 1. Global production of crude steel [1]

The technological processes of smelting, refining and casting steel are extremely complex. The phenomena occurring during them are subject to laws recorded in many fields of science. Physics, chemistry, thermodynamics, fluid mechanics are just the basics. The mechanism of these phenomena has a decisive impact on the ability to control the process and its effectiveness. Therefore, introducing changes aimed at applying innovative solutions in steel production technology requires precise identification of the factors determining the course of these phenomena. For this reason, research carried out in industrial conditions is of key importance. Thanks to progress in the field of metrology and the use of modern measuring equipment, it is now possible to carry out measurements of the ongoing process in very difficult physical conditions. Often, however, especially in metallurgy, the identification of phenomena using direct methods is impossible for obvious reasons. These reasons are: high temperature up to 2000°C, aggressive environment of the metal bath, isolation of the working space of metallurgical reactors from the influence of the environment, factors related to the uninterrupted course of the process during research and, importantly, the safety of researchers carrying out measurements is of particular importance. Therefore, information necessary for the development of implemented technologies should be obtained by other methods. Physical modeling techniques are perfect for this purpose.

Physical modeling, as one of the basic research techniques for industrial steel processes, is often understood as carrying out experiments using specially constructed stations - models, reflecting the features of devices used in these processes. This reasoning is only partially correct, because modeling covers a much wider range of activities and is a process that begins when the decision is made to use this technique to solve technological problems, and carrying out experiments is its final stage. Although modeling of industrial processes concerns specific technical issues, it is essentially a mental activity and involves moving from the sphere of abstraction to the concrete and vice versa, i.e. from model to reality and from reality to model. The design and construction of a research stand must be preceded by a deep mental analysis of the complexity of various connections and interactions occurring in the technological process under study, their precise formulation using the language of mathematics, and then their use in practical activities to construct a model. During this process, it is necessary to determine the possibility of making structural simplifications of the model, while maintaining its functionality from the point of view of the reliability of the obtained research results.

Using this methodology, a number of studies were carried out using physical modeling techniques, aimed at determining the hydrodynamic conditions of the two-phase liquid-gas system in a steel ladle during blowing of liquid steel with argon.

The aim of the article was to investigate a new innovative design solution of a slot-type gas-permeable module (KS diffuser) in terms of identifying hydrodynamic parameters influencing the course of the refining process (degree of gas dispersion in liquid steel, mechanism of gas bubble and gas column formation, minimum mixing time of liquid steel).

It is expected that the use of a new type of plug in industrial conditions will improve the refining and homogenization capabilities of the system and, consequently, improve the quality of produced steel without the need to invest in energy-intensive post-furnace processing equipment.

2. Designing physical models of steelmaking equipment

The basic purposes for which physical models of steelmaking equipment are built can be divided into three groups:

- for design purposes, where the model is used to optimize the structure and parameters of the constructed facility and is a tool for assessing the quality of the structure, eliminating weak links, designing supervision systems (functional and reliability models),
- for operational and control needs, using the model to make decisions with the operated facility (scope of maintenance activities, operational decisions, etc.),
- for diagnostic purposes, the model determines the current and future state of the facility.

In steelmaking processes, the basic phenomena occurring in specific reactors and affecting their proper operation are the flow and mixing of liquid steel. Therefore, the mathematical basis for building models of these reactors is based on the laws of fluid mechanics. By definition, fluid mechanics deals with the analysis of their motion, equilibrium states and their action on the confining walls and bodies immersed in them. All these phenomena also occur in steel reactors. Therefore, it is natural to use these laws when building physical models of metallurgical reactors containing liquid metal.

To describe physical phenomena occurring in nature, fluid mechanics uses models reflecting them written in the form of mathematical equations. The assumptions of these equations contain certain simplifications that make it possible to solve them. One of such simplifications is the assumption made in the description of the properties of liquids, which assumes that the volume of liquids changes slightly under the influence of external forces, therefore in calculations they are generally treated as incompressible bodies (principle of constant density). Another simplification is the assumption that the liquid is a continuous medium. This simplification lies in the fact that molecular structures and disordered molecular movements are not taken into account in the considerations [2]. The properties of liquids are basically determined by two factors: physicochemical properties and external factors determining these properties. Based on these statements, water is most often used as a liquid representing liquid steel to build physical models of steel reactors. Therefore, these models are also called water models. Therefore, assuming, in accordance with the fundamental theorem of fluid mechanics, that both liquid steel and water behave in accordance with the principle of conservation of mass, conservation of momentum and the continuity hypothesis at a constant value of the viscosity coefficient, it can be assumed that the mathematical basis for the construction of physical models of metallurgical reactors is the Navier–Stokes (N-S) equation [2,3]:

$$\rho \cdot \frac{\partial v_x}{\partial t} + \rho \cdot \left(\frac{\partial v_x}{\partial x} \cdot v_x + \frac{\partial v_x}{\partial y} \cdot v_y + \frac{\partial v_x}{\partial z} \cdot v_z \right) = \rho \cdot g_x - \frac{\partial p}{\partial x} + \eta \cdot \left(\frac{\partial^2 v_x}{\partial x^2} + \frac{\partial^2 v_x}{\partial_y^{\ 2}} + \frac{\partial^2 v_x}{\partial z^2} \right) \quad (1)$$

where: x, y, z - coordinates of the system, v_x, v_y, v_z- velocity components, ρ - density of the liquid, η - dynamic viscosity of the liquid, g_x - component of the acceleration due to gravity.

This equation is of key importance from the point of view of further design of physical models of metallurgical reactors. The functionality of such models is achieved by meeting the principles of hydraulic similarity, i.e. geometric, kinetic and dynamic similarity [4,5]. The dynamic similarity of the model to the industrial device is determined based on the dimensional analysis of the N-S equations. Dimensional analysis of these equations allows for the determination of similarity criteria in the form of dimensionless criterion numbers. The consistency of the values of these numbers in the model and the industrial device ensures the dynamic similarity of these objects. This means that the forces acting in them are proportional to each other at every moment of time.

One of the main theorems used in dimensional analysis is Buckingham's theorem [5,6], which states that: if there is an equation described by a certain number of independent physical parameters (n), then this equation can be expressed using dimensionless modules (criterion numbers), whose the number is equal to the number of these physical parameters minus the basic dimensions. Criterion numbers are most often quotients of physical quantities with the same dimensions, e.g. forces, which are important for a given problem. Considering the dynamic similarity of the constructed physical models of metallurgical reactors to their industrial counterparts, after applying the described method, an equation of criterion numbers is obtained in the form:

$$Eu = f\,(Str,\ Fr,\ Re) \quad (2)$$

where: Eu – Euler number, Str – Strouhal number, Fr – Froude number, Re – Reynolds number.

The mathematical form and physical interpretation of the designated criterion numbers are presented in Table 1.

Meeting all similarity criteria poses a number of difficulties. Hence the so-called partial similarity consisting in making a compromise decision regarding the determination of the dominant criterion. Due to the nature of the phenomena occurring in metallurgical processes, the dominant criterion determining the similarity of the model to the considered real object is the Froude criterion [8,9,10]. Therefore, equation (2) simplifies and takes the form:

$$\varphi(Fr) = 0 \quad (3)$$

Table 1.
Mathematical form and physical interpretation of the designated criterion numbers [7]

Criterial number	Definition	Physical Interpretation
Euler	$Eu = \frac{\Delta p}{\rho \cdot v^2}$	A measure of the ratio of hydraulic resistance to the kinetic energy of a stream
Froude	$Fr = \frac{v^2}{g \cdot L}$	A measure of the ratio of the force of inertia to the force of gravity
Strouhal	$Str = \frac{v \cdot t}{L}$	A measure of the rate of change of the velocity field in a fluid
Reynolds	$Re = \frac{v \cdot L}{\vartheta}$	A measure of the ratio of the inertial force to the internal friction force

where: p – pressure, ρ – density of the liquid, v – velocity, g – acceleration due to gravity, L – characteristic dimension, t – time, s; ϑ – kinematic viscosity.

This approach is appropriate for model studies of single-phase phenomena. In the case of multiphase flows, the similarity of the properties of individual phases should be taken into account when establishing the criteria. The classic Froude similarity criterion then requires modification. The method of making these modifications depends on the purpose of the research. In the case of research on the process of blowing inert gas into liquid steel through the bottom of a steel ladle, they may concern parameters such as: phase density, which is related to buoyancy forces. The Froude criterion then takes the form [11, 12]:

$$Fr_N = \frac{\rho_g \cdot V^2}{\rho_l \cdot g \cdot L} = C \cdot \frac{Q^2}{L \cdot d^4} \quad (4)$$

where: ρ_g - gas density, ρ_l - liquid density, g - acceleration due to gravity, L - liquid height in the model, Q - volume flow of gas, V - gas injection velocity, M - molar mass of the gas, d - inside diameter of the nozzle, C - constant.

The water flow in the model according to the adopted scale is therefore:

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

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.

Similarly, the Froude number is modified due to the difference in gas expansion under the influence of temperature in industrial conditions and in the model. This expansion is described by the expression [13]:

$$Q_g = \frac{\grave{Q}_g}{(\beta T + 1)} \tag{6}$$

where: Q_g - gas volumetric flow rate at 25°C, Q`g - gas volumetric flow rate at 1600 °C, T – temperature, °C; β – constant = 1/273.

Another parameter modifying the Froude criterion may be the properties of the porous material or the diameter of the nozzles through which the inert gas is blown. A similar procedure is then used as for modifying the buoyancy force as a criterion. The constant C is determined taking into account the radii of the capillaries (nozzle) according to the formula [14]:

$$\frac{Q_m^2}{Q_p^2} = \left(\frac{C_p}{C_m}\right)\left(\frac{L_m \cdot d_m^4}{L_p \cdot d_p^4}\right) \tag{7}$$

where: d_m – diameter of capillaries in the model, d_p – capillary diameter in industry.

The relationships presented above make it possible to determine the air flow value in the water model, but knowledge of the gas flow value in the industrial reactor is required.

Due to the fact that fluid motion can be considered from two different points of view, two methods are used to study it, named after their creators as the Euler and Lagrange method [14,15]. This is important from the point of view of the nature of model research carried out using physical models of metallurgical reactors.

Depending on the method used, the course of experiments using physical models varies, which should be taken into account when designing measurement systems for physical models of metallurgical reactors. Typically, these systems are built using automation elements based on the input/output system. This involves stimulating the system with an appropriate input signal and recording the time characteristics of the response to a given signal. As a result, data are obtained to plot curves characterizing the hydrodynamic conditions in the tested reactor, called Residence Time Distribution (RTD) curves [14,15,16]. In practice, this process is carried out by appropriately introducing a marker into the model and recording the change in the nature of the movement of the model fluid under its influence.

3. Examples of the use of water physical models of steel reactors - a literature review

Due to the high value of research results obtained using physical models of steel reactors, this method is an important tool for the development of steel production methods and technologies. It is used in various research centers around the world, resulting in a very rich literature on this subject.

The dimensional analysis of the N-S equations shows that the dominant influence on the nature of the fluid motion is its kinematic viscosity and pressure. The kinematic viscosity of water at ambient temperature (20ºC) is similar to the kinematic viscosity of liquid steel at the casting temperature (1600ºC) and is $0.72 \cdot 10^{-6}$ m^2s^{-1} and $1.002 \cdot 10^{-6}$ m^2s^{-1}, respectively. From the point of view of the similarity theory, the convergence of these values allows the use of water as an analogue of liquid steel in physical modelling.

Tables 2 and 3 present a synthetic overview of selected purposes for which model tests are carried out at individual stages of steel production (from the oxygen converter, through secondary metallurgy to continuous steel casting). This review is supplemented with selected literature references. Due to the wide scope of research carried out using physical models of metallurgical reactors, this review is limited for fundamental reasons. However, it illustrates the extraordinary importance of the use of water models for the development of steel industry in the world.

The objectives of research on phenomena occurring in oxygen converters, presented in Table 2, are aimed at optimizing the pig iron refining process. The goal is to obtain as much reaction surface as possible between the oxygen blown through the lance and the metal bath. This effect is achieved by appropriately selecting the number and configuration of nozzles in the head of the oxygen lance and determining the best distance from the lance's front to the liquid pig iron mirror. The refining process is also intensified by mixing liquid pig iron with inert gases blown through appropriately designed nozzles placed at the bottom of the converter. Correct determination of their number and geometry of arrangement is possible thanks to research using water models of the oxygen converter.

Recently, great emphasis has been placed on the need to produce the so-called green steel. Therefore, one of the basic activities is to use the possibilities of recycling steel products. For this purpose, attempts are made to increase the share of steel scrap in the charge. To maintain the appropriate heat balance of the converter, it is necessary to add fuel in pieces. The selection of its type and dosing method is also determined on the basis of water models. Applying the obtained results to industrial conditions allows to shorten the refining process. This reduces the consumption of input materials in the form of fluxes and energy while increasing efficiency. Consequently, this improves the economic balance and helps reduce the negative effects of the process on the environment.

Based on the above list of research objectives, it can be concluded that currently modeling the process of refining liquid steel using argon focuses on three main problems:

- mixing and homogenization of liquid steel in a ladle - the influence of the number of shapes and their arrangement on the mixing time and the type and flow of gas bubbles,
- behavior of gas bubbles from the moment of detachment from the plug whole to the gas-liquid cone - frequency of gas bubbles detaching from the plug whole, bubble rising speed, behavior of gas bubbles in the gas-liquid cone,
- behavior of inclusions at the interface of liquid steel with slag and in liquid steel - the influence of various parameters (size of gas bubbles, concentration of solid particles, size of inclusions) on the mechanism and effectiveness of removal of inclusions, formation of a slag eye.

The effects of applying the results of model tests to industrial conditions can be considered in two aspects. The first is to improve the economic balance of the steel production process by increasing its efficiency, reducing the consumption of expensive alloying elements, reducing the consumption of technological materials and fluxes, reducing energy consumption and obtaining steel with very high metallurgical purity. Therefore, research using water models as well as numerical research is carried out not only in the field of steel production technology, but also in the process of casting, solidification and crystallization [42-46]. The second aspect resulting from the first is to reduce the negative impact of steel production on the environment.

Table 2.
Summary of the main objectives of research using water models of the oxygen converter

Process/Purpose of research	Ref.
Refining of steel using the basic oxygen process	
Determination of: • optimal position of the oxygen lance at individual stages of blowing, • optimal number of de Laval nozzles in the head of the oxygen lance • optimal angle of inclination of de Laval nozzles in the head of the oxygen lance • • optimal intensity of blowing oxygen depending on the number and arrangement of de Laval nozzles in the lance head	[17] [18] [19]
Process with combined blowing	
Determination of: • optimal number of nozzles at the bottom of the converter • arrangement of nozzles at the bottom of the converter • optimal flow rate of gas blown into the converter	[20] [21] [22] [23]
Slag splashing	
Determination of: • optimal position of the nitrogen lance in the converter • optimal number of de Laval nozzles in the nitrogen lance head • optimal angle of inclination of de Laval nozzles in the nitrogen lance head • optimal nitrogen blowing intensity through the lance • the area of the refractory lining covered by slag splashing depending on the gas flow rate, the number of nozzles and the position of the lance in the converter	[7] [22] [24] [25] [26]
Use of lump fuel to increase the share of scrap in the charge	
• Optimization of basic process parameters described above • Determining the method of dosing lump fuel to converter • Determination of the required granulation of lump fuel • Research on the kinetics of the process supported by the addition of lump fuel	[7] [27] [28]

The mixing process is a complex phenomenon and it is difficult to describe this phenomenon fully based on available tools (physical and numerical modelling). The calculated mixing times may differ significantly depending on the literature [31,34,35]. The degree of liquid mixing may be different at different points of the tank volume as a function of the gas flow [29]. The location of sensors and the point of adding the marker may cause errors in estimating mixing times [36]. Therefore, research works using modelling will continue to appear, because even if this tool is not fully precise, it allows us to approximately understand the phenomena occurring during the refining process, which is so important for obtaining steel.

Table 3.
Summary of the main objectives of research using water models of secondary metallurgy devices

Process/Purpose of research	Ref.
Inert gas injection	
Research of: • mechanism of gas column formation • degree of gas dispersion in the volume of liquid steel • fragmentation of gas bubbles depending on the size of the injected gas stream • the influence of the location of the porous plug on the effectiveness of the process • slag eye formation • phenomena occurring on the metal-slag interface under the influence of the gas column • innovative design solutions for porous plugs Determination of the minimum mixing time of the bath under the influence of blown gas Testing the quality of porous plugs Determining the size of flow zones	[29] [31] [32] [33] [34] [35] [36] [37] [38] [39]
RH proces	
• Investigation of the influence of the value of the injected gas stream on the bath circulation speed and process efficiency • Determining the duration of the process depending on the value of the injected gas stream	[40] [41]

4. Examples of the use of a water physical model of a ladle - own research

The article presents exemplary research results carried out using a model water of ladle, regarding the process of blowing inert gas into liquid steel using an innovative solution – a slot-type gas-permeable module (KS diffuser) replacing the standard gas-permeable plug at the ladle furnace station (LF). 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 Branch Łabędy Gliwice.

4.1. Subject of research and research methodology

A diagram of the test stand - a water model of a ladle is shown in Figure 2. This model is made on a linear reducing scale S_L = 1:3.4. It is built in accordance with the requirements of the theory of dynamic and kinematic similarity, and also meets the condition of geometric similarity [4, 47]. The test stand is described in detail in [48]. The model faithfully reproduces the real object with a capacity of 65 Mg of liquid steel. The tests used water from the water supply network. Additional modification due to its physical properties was not necessary at this stage of the tests.

The new technological solution - a module (KS diffuser) for gas injection differs from traditional gas-permeable plugs currently used in steelworks in terms of geometric parameters, external and internal structure and, most importantly, active surface. The active surface means the surface of the slots on the front of the blowing plug (module). The research analyzed two variants of gas-permeable modules differing in the width of the slots. In both cases, the number of slots was 8. The reduction scale of the ladle model was taken into account in the model modules (S_L = 1:3.4).

It should be noted that the active surface for a traditional gas-permeable plug is 346 mm^2, while for a designed and manufactured slot-type module it is 1856 mm^2.

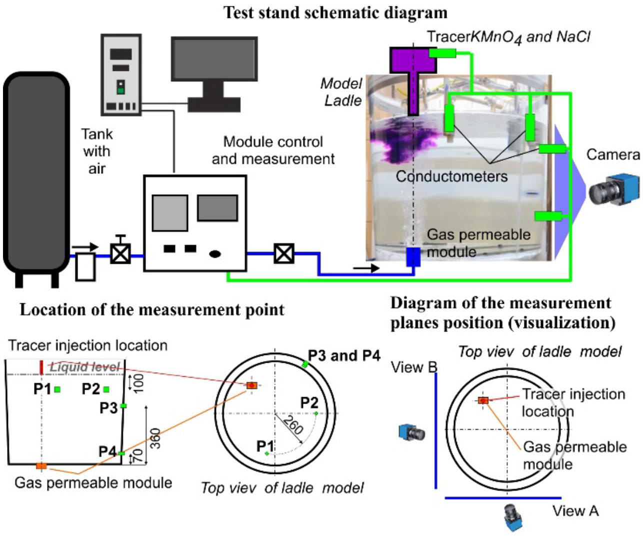

Fig. 2. Test stand schematic diagram (water model ladle)

The model of slot modules were made by the Łukasiewicz Research Network - Institute of Ceramics and Building Materials, in accordance with patent no. PL 229475 [49]. Figure 3 shows a view of the slot model module with more important notations.

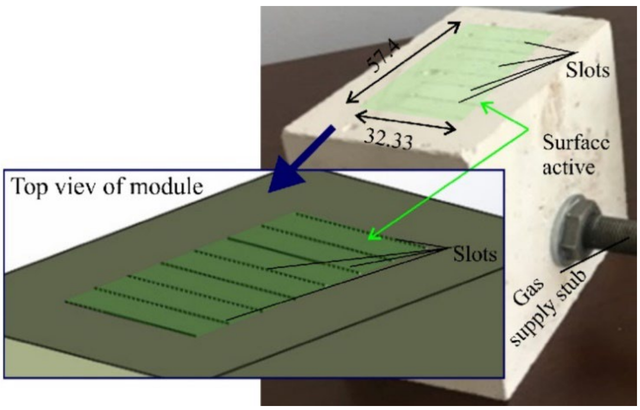

Fig. 3. View of the slot-type module (KS diffusor)

The module is placed at a distance of 2/3 of the radius from the axis of the ladle. The tracer ($KMnO_4$ or NaCl depending on the type of test) is introduced in the module axis under the water surface through a specially designed pouring system ensuring its application to the model liquid surface at the same point and in the same volume for each experiment (015 dm^3).

The course of the research was recorded using cameras placed in two planes (see Figure 2). The research carried out allowed for full identification of the process of gas bubble formation, their dispersion in the volume of the model liquid, the formation of a column of bubbles, the persistence of the mirror surface and the time needed to completely mix the tracer in the modeled ladle. For each variant, a series of research tests were carried out, each with three experimental attempts.

The tests analyzed two values of gas flow rate, which were calculated according to equation (4). The gas flow rate values for the industry conditions and model are presented in Table 4.

Table 4.
Data set for research using the water model

Exp. variant	Slot width - model, μm	Slot width - industry, mm	Gas (O_2) intensity - model, $dm^3 \cdot min^{-1}$	Gas (Ar) Intensity - industry $dm^3 \cdot min^{-1}$
A_150_37	150	510	3.7	200
B_50_37	50	170		
A_150_42	150	510	4.2	225
B_50_42	50	170		

4.2. Results of modelling research

The presented results of research carried out using the ladle water model were divided into two stages. The first included a qualitative analysis ($KMnO_4$ tracer) of mixing the model liquid, assessment of the mechanism of formation of a cone of gas bubbles (gas column) and their dispersion degree in the model liquid. The second stage is quantitative analysis (NaCl tracer) - mixing time assessment based on the determined mixing curves.

Figure 4 presents exemplary research results, showing the mechanism of formation of the cone of the spreading gas column and the degree of their dispersion in the model liquid (water) for the analyzed variants of our own model research experiments.

Based on the visualization (see Figure 4), a more favorable mechanism of gas column formation was observed for variant B. Greater fragmentation of gas bubbles and their even flow towards the model liquid mirror were observed. In the case of variant A, gas bubbles on the module surface were found to combine into larger conglomerates, which intensified as the injected gas stream increased. This results in their excessive growth and reduction in their number. It was also observed that the gas column tended to rotate as the gas flow rate increased. The visualization of the mixing of the model liquid in the ladle model for the analyzed test variants is presented in Figures 5-6.

Observations of the movement of the model liquid (see Figures 5-6) under the influence of the blown gas for variant A allowed for the identification of unfavorable tendencies towards uneven spreading of the tracer. It is caused by the formation of circulation flow zones in the area of the walls of the steel ladle model. This, in turn, contributes to the formation of dangerous dead zones in the volume of the model liquid. This movement is not conducive to effective homogenization of the liquid phase. These threats increase as the injected gas stream increases.

Comparing the characteristics of the movement of the model liquid in variant A and variant B, a significant improvement should be noted in favor of variant B. In this variant, the classic flow of the tracer in the model liquid was observed. The gas column forces the circulation of the liquid phase in the up-down direction. The circulation of the liquid phase promotes its even homogenization. As the flow rate of the gas stream increases, as expected, the mixing efficiency also increases. In this test variant, no danger of excessive dead flow zones formation was observed. Due to this, mixing covers a larger volume of the model liquid than in the case of variant A, which is another factor contributing to more effective homogenization of the liquid phase in the ladle.

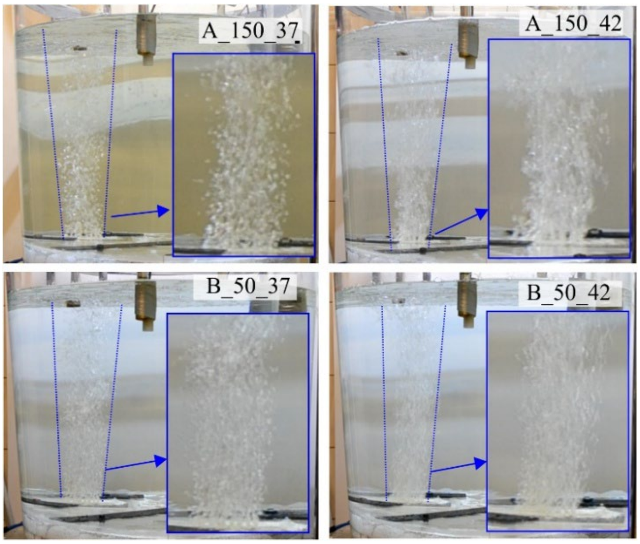

Fig.4. The mechanism of formation of a cone of gas bubbles (gas column) and their degree of dispersion in the model liquid for the considered test variants

In the second stage of the research, experiments were carried out in such a way that it was possible to plot RTD mixing curves enabling the determination of the minimum mixing time of the tracer in the model liquid. The value min = 0 means water without marker, while the value max = 1 means the marker is mixed in the entire volume of the model liquid. The minimum mixing time of the tracer was treated as a criterion for assessing the effectiveness of the liquid steel homogenization process. The range from y=0.95 to y=1.05 was adopted to determine the value of the minimum mixing time for which the system reaches a plateau. In practice, this means that the value of the determined time is recorded when all the curves reach a value from the given range and remain in it for 3 s. The experiment at this stage of the research was carried out in series of five replications for each variant. At the beginning a peak occurs when a marker with a high concentration reaches the first sensor. Then its concentration in the volume of the model liquid decreases due to mixing in a larger volume of liquid. At the end of experiment, all curves converge in the given range of values.

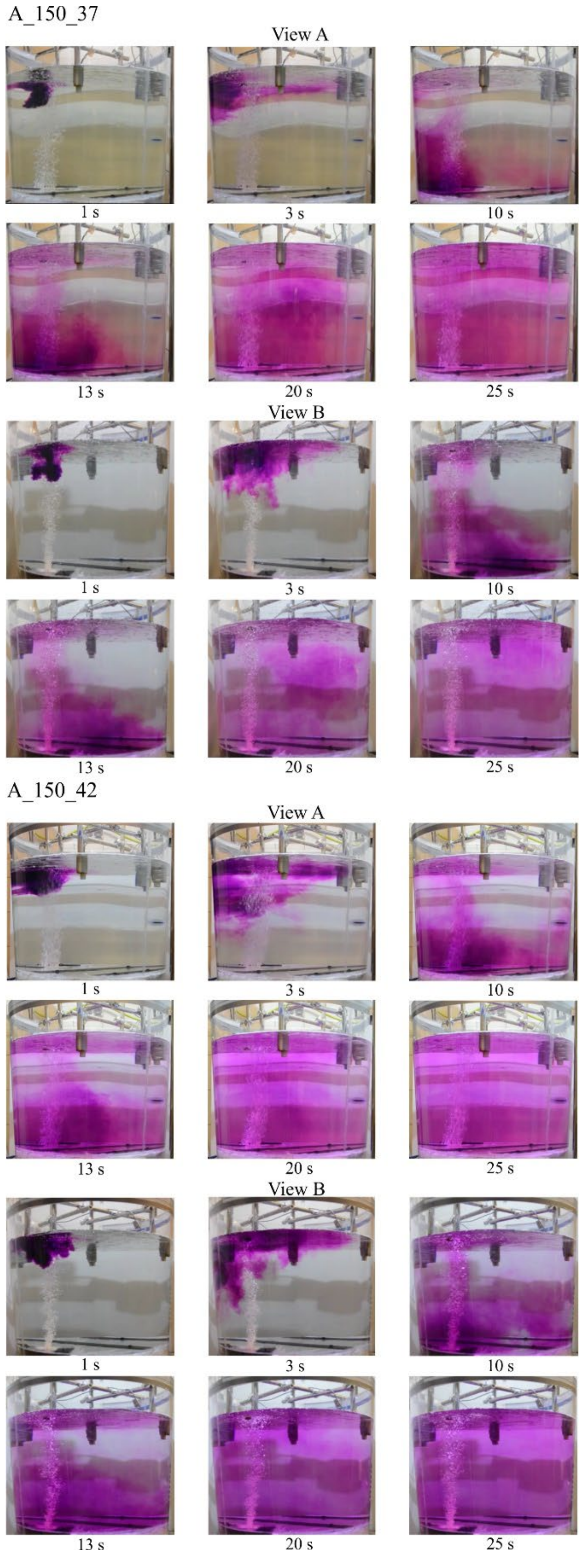

Fig. 5. Visualization of mixing in KS diffuser – type A depending on the experiment variant

B_50_37

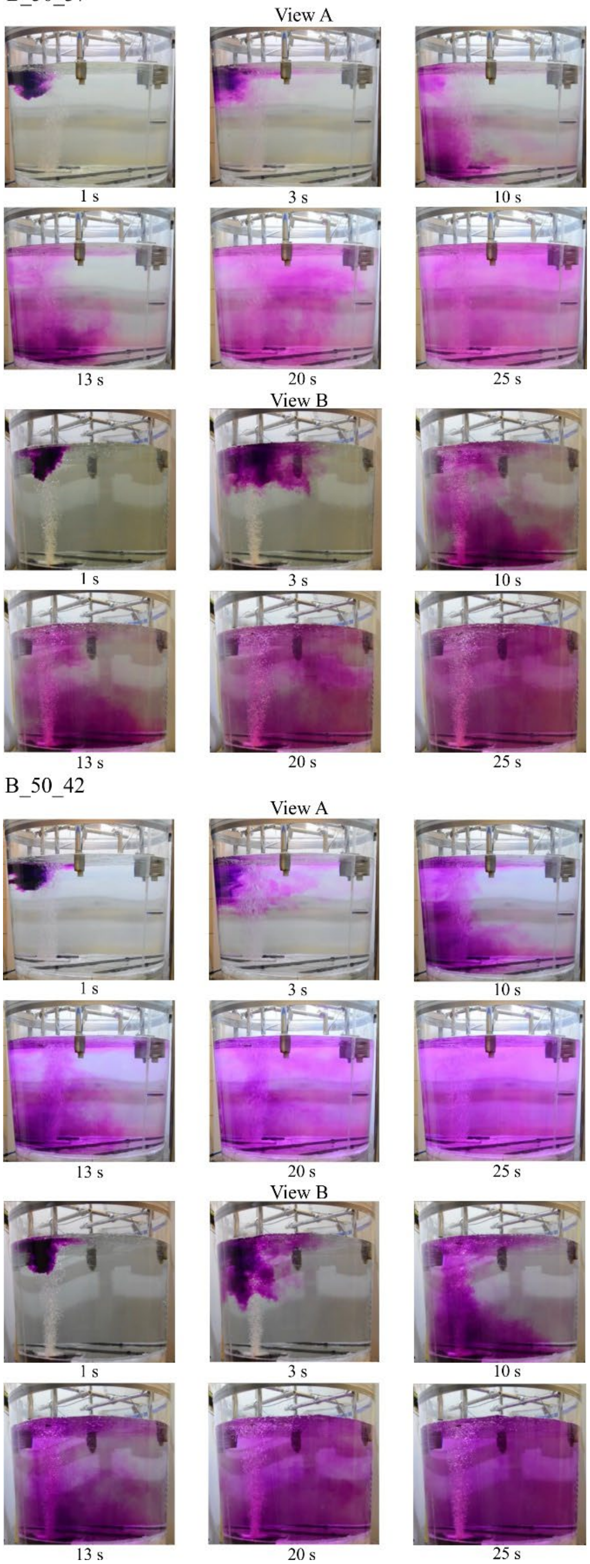

Fig. 6. Visualization of mixing in KS diffuser – type B depending on the experiment variant

An example result of the determined mixing curve is shown in Figure 7.

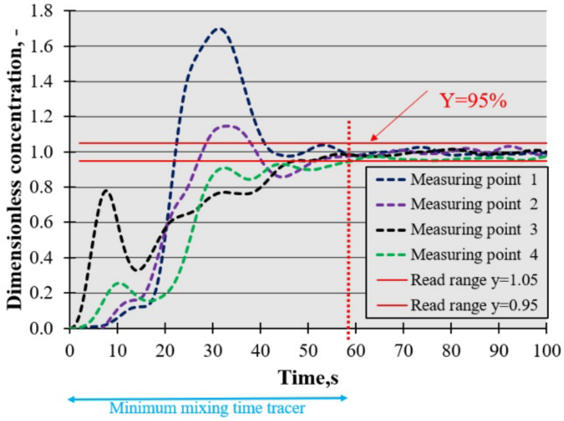

Fig. 7. Water model of mixing-time characteristics – variant B_50_37

The criterion for direct quantitative comparison was the comparison of the average values of the minimum marker mixing time in the ladle model for the analyzed variants. These values are presented in Table 5.

Table 5.
Average values of the minimum marker mixing time for the analyzed variants

Exp. variant	Gas intensity in model, $dm^3 \cdot min^{-1}$	Average value of the minimum mixing time, s
A_150_37	3.7	63
B_50_37		54
A_150_42	4.2	59
B_50_42		56

The values of the minimum marker mixing time determined based on the analysis of RTD curves (see Table 5) confirmed the previously performed observations. Significantly shorter mixing times were obtained for variant B compared to variant A. This applies to both values of gas flow rate. On this basis, it can be concluded that variant B of the KS diffuser generates more favorable hydrodynamic conditions from the point of view of the effectiveness of the liquid phase homogenization. During the analysis of the mixing times for the tested variants of the experiment, an unexpected tendency was noticed. As the flow rate of the injected gas increases, the mixing time in variant A is shortened and in variant B it is extended. As the mixing mechanism of the model liquid is related to the energy of the blown gas stream, a greater part of this energy is used to fragment the gas bubbles and increase their number in variant B than in variant A. This is confirmed by studies on the visualization of the mechanism of gas cone formation. As a consequence of the observed trend, despite a slight reduction in the effectiveness of the homogenization process in variant B with increasing gas flow rate, the refining efficiency of this variant is further improved, which was not observed in variant A.

5. Conclusions

To sum up, it can be said that physical modeling using water models of metallurgical aggregates offers great opportunities to study hydrodynamic phenomena occurring in industrial reactors. The method of physical modeling of metallurgical processes is widely used in activities related to the introduction of innovative solutions into industrial practice. This is evidenced by extensive literature, a small fragment of which is presented in this publication.

The presented own results obtained using the water model clearly show that this trend is correct and provides great opportunities to test new solutions, such as the proposed gas-permeable modules. However, it should be mentioned that research of this type requires supplementation/verification with another research technique, e.g. numerical modeling or/also experiments in industrial conditions.

Based on the obtained model test results, it can be concluded that:

- The new design of the slot-type module (KS diffuser) may be an effective alternative to currently used solutions.
- An important design feature of the KS diffuser is the proper selection of slot widths, which has a direct impact on the effectiveness of its operation.
- The width of the slots must be determined based on the results of tests carried out for specific working conditions, taking into account the specificity of the steel plants using them.
- For a ladle with a nominal capacity of 65 Mg and specific geometric parameters (own research), the slot module variant B is a better solution in every respect.
- The minimum mixing times determined for the analyzed ladle and the visualization of the movement of the model liquid in the ladle volume indicate the high effectiveness of the slot-type module in generating hydrodynamic conditions conducive to homogenization of the bath.
- For the analyzed module variant (KS diffuser) B, the results of own research show that the method of gas column formation allows predicting the required refining efficiency.

To sum up, it should be stated that research using physical models of steel water reactors is a very important cognitive tool that allows for a sufficiently precise determination of the mechanisms of formation and course of hydrodynamic phenomena occurring in liquid steel during the investigated technological process. The results obtained serve the development of these technologies and enable the introduction of many innovative solutions into industrial practice.

Acknowledgements

The presented research results are the result of research and development work funded by the National Center for Research and Development, grant number 1/POIR/08/2018 beneficiary Cognor SA Ferrostal Łabędy Gliwice Branch.

The article was also supported by funds from work 11/020/BK_24/0129 (Silesian University of Technology).

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