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Recenzované výzkumné a vědecké články

Modeling of Steelmaking Process Conducted at the Department of Metallurgy and Recycling of the Silesian University of Technology

Modelování metalurgických procesů na Katedře metalurgie a recyklace Slezské polytechniky

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Abstract

Modern metallurgical technologies are progressive in nature, requiring continuous improvement to enhance both product quality and production efficiency. The successful implementation of innovations in this field depends on a deeper understanding of the phenomena occurring during technological processes. The key sources of such knowledge are industrial practice and scientific research. The Laboratory of Metallurgical Process Modelling, operating for many years within the Department of Metallurgy and Recycling at the Silesian University of Technology, provides valuable opportunities to study the mechanisms that occur during steel production and secondary refining. Physical (water) modelling plays a crucial role in this research, as industrial installations are becoming increasingly complex. Conducting experimental studies under real operating conditions is often difficult due to the presence of high temperatures, dense fumes, and the atomization of metal and slag, as well as being prohibitively expensive. This article presents selected results of research conducted using physical (water) models that simulate processes taking place during oxygen converter operations, secondary steel refining in furnaces, and the continuous casting of steel. Both quantitative and qualitative findings are discussed to illustrate the potential of physical modelling in understanding and optimizing metallurgical processes.

Key words: *steel; physical modelling; continuous steel casting; tundish; modelling*

Abstrakt

Moderní metalurgické technologie jsou progresivní povahy a vyžadují nepřetržité zlepšování s cílem zvýšit jak kvalitu výrobků, tak i efektivitu výroby. Úspěšná realizace inovací v této oblasti závisí na hlubším pochopení jevů probíhajících během technologických procesů. Klíčovými zdroji takových poznatků jsou průmyslová praxe a vědecký výzkum. Laboratoř modelování metalurgických procesů, která již mnoho let působí na Katedře metalurgie a recyklace Slezské technické univerzity, poskytuje širokou škálu možností studia mechanismů probíhajících při výrobě oceli a její následné sekundární rafinaci. Fyzikální (vodní) modelování hraje v tomto výzkumu zásadní roli, protože průmyslová zařízení se stávají stále složitějšími. Provádění experimentálních studií za reálných provozních podmínek je často obtížné z důvodu vysokých teplot, hustých dýmů a rozstřiku kovu a strusky, a také mimořádně nákladné. Tento článek představuje vybrané výsledky výzkumu prováděného pomocí fyzikálních modelů, které simulují procesy probíhající během provozu kyslíkových konvertorů, sekundární metalurgie a kontinuálního odlévání oceli. Jsou diskutovány kvantitativní i kvalitativní poznatky s cílem ukázat, jak fyzikální modelování přispívá k pochopení a optimalizaci metalurgických procesů.

Klíčová slova*: ocel; fyzikální modelování; plynulé odlévání; mezipánev; modelování*

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1. Introduction

The technological processes of smelting, refining, and casting metals are inherently complex. The phenomena occurring during these processes are governed by laws established in many fields of science, including physics, chemistry, thermodynamics, and fluid mechanics [1, 2]. Knowledge of these phenomena plays a key role in process control and its effectiveness in terms of expected results. Therefore, the implementation of innovative solutions requires a precise identification of the factors that determine the course of metallurgical phenomena. For this reason, conducting research under industrial conditions is of great importance. However, such studies are often extremely challenging due to the high temperatures involved—reaching up to 2000 °C—the aggressive environment of the metal bath, the isolation of the metallurgical reactor workspace from external influences, the need to maintain the uninterrupted progress of industrial processes during testing, and, above all, the safety of researchers performing the measurements [3]. Therefore, the information necessary for modernization or innovation is obtained through modelling. The goal of modelling is to analyse a given process with reduced financial outlays and a reduced risk of failure. Modelling enables visualization of the flow structure or tracer propagation, which allows for a better understanding of the analysed problem [4]. This applies to both real-time models (used for ongoing process control) and models used for problem analysis, i.e., predicting various variables and process parameters (finding optimal designs or configurations of process procedures).

2. Physical Modelling – Basics

Studies using physical models require compliance with the principles of similarity, which refer to the characteristic features of the real object and have a significant impact on the phenomena occurring in the studied process. The similarity conditions are geometric, mechanical, kinematic, thermal, or chemical. To accurately reproduce the phenomena under study, it is necessary to strive for complete similarity between the model and the real system. Achieving full similarity in industrial conditions, however, is extremely difficult; therefore, the dominant parameter governing the studied process is usually selected [5, 6]. To satisfy the principles of similarity, it is sufficient to ensure the equality of the relevant dimensionless criterion numbers for both the model and the actual object. Under these conditions, the results obtained from experiments performed on physical models can be reliably extrapolated to real processes. From the perspective of reactor design in steelmaking and the hydrodynamics of metal flow, the key dimensionless numbers describing the process are the Froude, Reynolds, and Weber numbers, as presented in **tab. 1**.

Tab. 1 Characteristics of criterion numbers for physical models used in steel metallurgy

Tab. 1 Klíčová kritéria podobnosti používaná u fyzikálního modelování metalurgických procesů

Number	Characteristics	Equation
Reynolds	in the self-modelling range - the range in which it is not necessary to achieve exact equality of the criteria number	$Re = (\rho \cdot u \cdot L)/\eta$
Froud	in the reduced model, the liquid flow rate should be reduced accordingly	$Fr = u^2/(g \cdot L)$
Weber	the ratio of the inertial force to the surface tension force	$We = (\rho \cdot u^2 \cdot L)/\sigma$
where: u – flow rate, ρ – density, σ – surface tension, L – characteristic dimension, g – gravitational acceleration, η – dynamic viscosity coefficient		

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In the system under study, the flow is constant and the Reynolds number is within the self-modelling range (the region in which a given phenomenon is practically independent of the similarity criterion value), so there is no need to achieve equality of the criterion numbers in this region.

The Weber number, characterizing the effect of surface tension on liquid flow, is a criterion number confirming the achievement of the required similarity of the model to the real object; the dominant criterion determining the similarity of the tested model to the real object is the Froud criterion (this number is equal in water and liquid steel for each model).

The modelling studies focused on:

– visually determining the degree of dispersion (mixing) of gas bubbles in the liquid volume – tests for steel ladle,
– visually observing the degree of coloration of the solution by $KMnO_4$ (purple), which allowed for the visualization of gas bubble mixing in the liquid and comparison of dispersion times – tests for steel ladle,
– determining the mixing time curves based on conductivity measurements by adding an aqueous NaCl solution to the model liquid – tests for steel ladle.

Modelling studies can be divided into two groups. Qualitative studies include visualization (introducing the $KMNO_4$ tracer). Quantitative studies include developing mixing time characteristics (for steel ladle) and E and F RTD characteristics (for tundish).

Based on these, it is possible to obtain values of interest to the researcher, such as the tracer mixing time in the ladle, the time it takes the tracer to reach individual tundish nozzles, the extent of the transition zone, or to determine the type of flow in the tundish.

RTD curves F and E type are macromixing characteristics that provide information on the time a fraction of the liquid (substance) volume spends in the reactor, without specifying its geometric position [7, 8]. This allows for determining the device's performance. Analysis of RTD curves E type allows for the assessment of the performance of any flow device, including the flow type [9]. The following flow types are distinguished:

– *plug flow* – each element of the flowing liquid metal moves at almost the same speed, covers a comparable distance, and has a very similar residence time,
– *well mixed flow* – the tracer introduced into the bath is immediately and evenly distributed throughout the bath; this flow rate should not exceed a small volume of the bath; however, significant mixing can disrupt the continuity of the slag layer, resulting in secondary metal gasification,
– *stagnant (dead) flow* – when the tracer residence time is at least twice as long as the average residence time, the lowest possible percentage of this type of flow is desirable,
– *bypass flow* – the tracer is characterized by a very short residence time compared to the average residence time (such flow can quickly transport non-metallic inclusions in the liquid metal to the area of the outflows).

Typical examples of the research results described above are shown in **fig. 1**.

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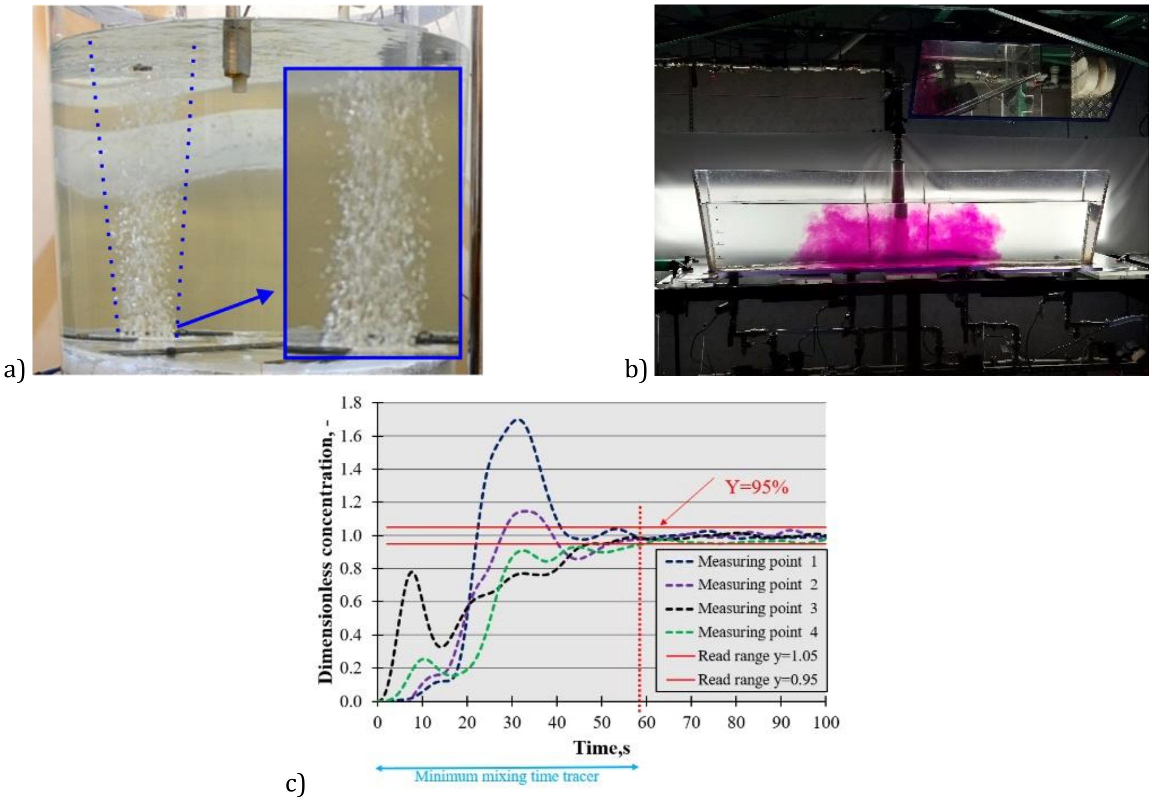

Fig. 1 Example results obtained during model tests: a) dispersion of gas bubbles introduced through a gas-permeable plug in the ladle, b) distribution of the tracer ($KMnO_4$) in the tundish, c) mixing curves plotted during argon purging

Obr. 1 Příklad výsledků získaných během modelování metalurgických procesů: a) rozptyl bublin plynu injektovaného do licí pánve přes dmyšný element, b) distribuce trasovací látky ($KMnO_4$) v mezipánvi, c) koncentrační křivky během míchání lázně oceli argonem

3. Characterization of the Metallurgical Process Modelling Laboratory

The establishment of the Metallurgical Process Modelling Laboratory proceeded in several stages. In the 1980s, this process culminated in the construction of a unique water-based model of an oxygen converter. The model was made of PMMA on a linear scale of 1:10 and is still in use today. Initially, measurements of the model liquid's mixing were recorded using a tracer that alternated between alkalinity and pH sensors. However, due to low accuracy and sensor contamination issues, these sensors were replaced with conductivity meters, and an aqueous NaCl solution was used as the tracer [10].

The 1980s also saw the beginning of work on modelling ladle processes. The first models of steel ladles were created to study phenomena occurring during the argon process. In the following years, this activity expanded significantly, and today the Laboratory for Modelling Metallurgical Processes houses several stations for this type of research. Due to the dynamic development of continuous steel casting methods in the Polish steel industry at the turn of the 21st century, industry interest in modelling this process increased. In 1998, construction began on the first comprehensive physical model of a continuous steel casting (CSC) machine. Given previous experience with recording phenomena occurring in a model oxygen converter using pH meters, the CSC device model incorporated an innovative solution in the form of optoelectronic sensors that recorded changes in marker concentration based on changes in its colour. This allowed for real-time results to be obtained during the experiment.

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However, a drawback of this model was that it was dedicated to only one industrial device. Therefore, the next solution was a station for modelling the flow of liquid steel in the CSC device, which allowed for easy replacement of the tundish model, i.e., the main segment. During this time, tundish models were also developed for virtually all devices operating in Poland. In 2016, the Laboratory underwent a major renovation, bringing the facility into the 21st century and adapting it to ergonomics and exceptional safety.

Newly installed plumbing and electrical systems ensure safety in the event of a leak from the models installed in the laboratory. Mobile power sources were also installed, allowing for connection of necessary equipment anywhere in the laboratory. At the same time, construction began on a modern research station for modelling phenomena occurring during the continuous steel casting process. This system meets the latest requirements for such stations and is fully automated.

As a result, a modern model laboratory was established, enabling research on the full range of technologies used in steelmaking enterprises. This includes phenomena occurring during pig iron smelting in a blast furnace; phenomena occurring during steel production in a basic oxygen converter; phenomena occurring during secondary steel processing – both in a ladle furnace and in the vacuum process in a RH device; and finally, phenomena occurring during steel casting using traditional methods, particularly in a continuous casting machine. A view of the currently operating laboratory is shown in **fig. 2**.

a)

b)

Fig. 2 View of the Metallurgical Process Modelling Laboratory: a) models of the oxygen converter, ladle furnace and RH device, b) models of the CSC and crystallizers

Obr. 2 Vybavení Laboratoře modelování metalurgických procesů: a) modely kyslíkového konvertoru, licí pánve a RH zařízení, b) modely plynulého lití a krystalizátorů

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4. Research Capabilities of the Modelling Laboratory

The Metallurgical Process Modelling Laboratory currently possesses extensive research potential. Over the years, the laboratory has conducted numerous studies as part of projects funded by the National Science Centre (NCN), the Ministry of Science and Higher Education, the National Centre for Research and Development (NCBiR), and commissioned by industry. In addition to the aforementioned completed projects financed from external sources, research is also conducted using funds allocated to the Faculty's statutory activities. Moreover, the Laboratory functions as an important teaching facility, supporting engaging and effective learning for students pursuing engineering projects, master's and doctoral theses, and professional development courses.

4.1 Oxygen Converter Model

Fig. 3 illustrates the oxygen converter model together with representative test results obtained during its operation. The model supports a broad spectrum of experimental investigations and is fitted with interchangeable nozzles in the oxygen lance head, facilitating visualization of the interaction between the injected gas stream and the modelled liquid surface. Furthermore, a configurable nozzle system mounted at the bottom of the converter model allows for testing of combined blowing processes.

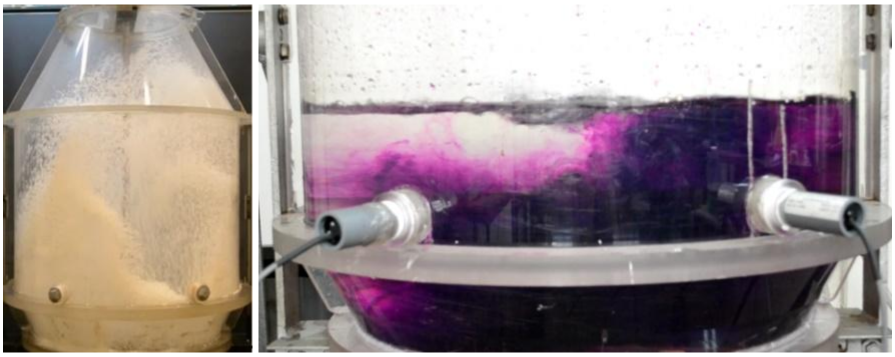

Fig. 3 Visualization of the flow of the model liquid in the oxygen converter

Obr. 3 Vizualizace proudění modelové kapaliny v kyslíkovém konvertoru

4.2 Modelling the Process of Blowing Steel with Argon in a Steel Ladle

Fig. 4 presents a model of argon purging in a steel ladle along with sample test results obtained using this setup. The model enables a wide range of studies — from mixing and homogenization in the ladle (examining the effect of the number and arrangement of porous plugs on mixing time, the type and pattern of gas bubble flow, and the method of tracer introduction into the liquid), through investigations of gas bubble behaviour from the moment of detachment at the plug opening to their movement within the gas–liquid cone (including the frequency of bubble detachment, bubble rise velocity, and bubble dynamics within the cone), to studies of inclusion behaviour at the steel–slag interface and within the molten steel (analysing the influence of parameters such as bubble size, solid particle concentration, and inclusion size on the rate and mechanism of inclusion removal), as well as the formation of a slag eye. Furthermore, determining the mixing time under industrial conditions is challenging, as numerous processes occur simultaneously — including oxidation and deoxidation reactions, dissolution of added components, flotation of non-metallic inclusions, and temperature variations. Therefore, experimental studies using physical models are commonly employed to estimate the actual mixing time in industrial settings.

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a) 

b) 

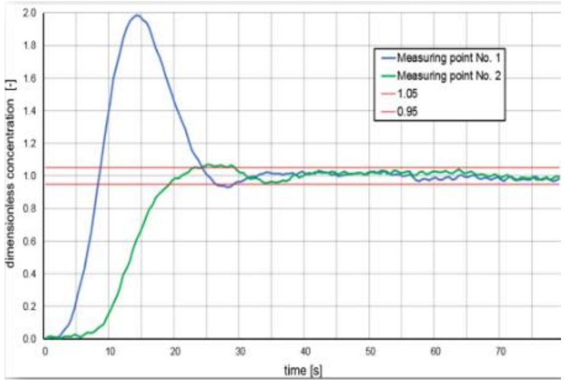
c) 

Fig. 4 Steel ladle model: a) experimental setup for the argon purging process with control and measuring equipment, b) investigation of slag eye formation, c) example of determined mixing curves

Obr. 4 Model licí pánve: a) sestava experimentálního modelu pro homogenizaci lázně argonem včetně řídícího a měřícího zařízení, b) výzkum oblasti struskového oka, c) příklad koncentračních křivek

4.3 Tundish Model

Fig. 5 shows a view of the tundish model and sample test results obtained using it. This model enables research on: the method of mixing liquid steel in the tundish working space; estimating the extent of individual flow zones (well-mixed, plug, and dead) and selecting the appropriate proportions between well-mixed and plug flow, which affects steel purity and homogenization; selecting the appropriate type of tundish structure (turbulence inhibitors, dams, weirs, baffles) to achieve similar liquid steel inflow times to individual outlets; simulating the optimization of the transition zone size during the casting of two steel grades in a single sequence; and diagnostic testing, for example, refractory lining leaching.

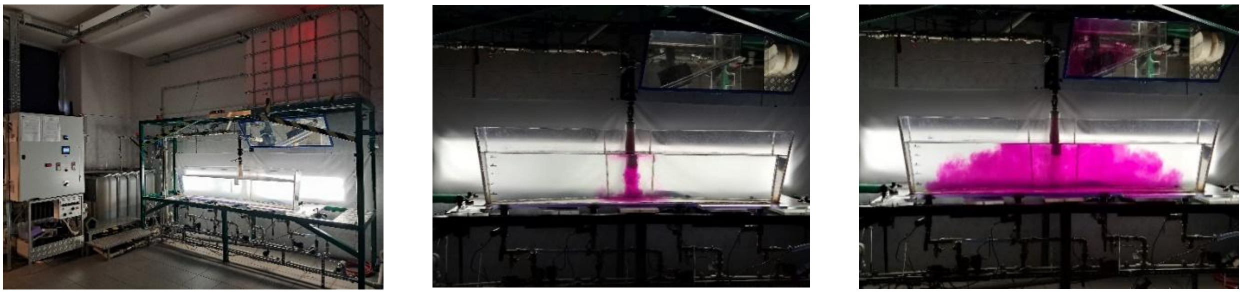


Fig. 5 A tundish model and an example study of the range of occurrence of individual flow zones (well-mixed, plug and dead) and the selection of appropriate proportions between flows

Obr. 5 Model mezipánve a příklad studia rozsahu výskytu jednotlivých zón proudění (dokonale promíchaná, pístová a mrtvá) a výběr vhodných poměrů mezi těmito proudy

5. Summary

The Laboratory of Metallurgical Processes Modelling is a modern laboratory enabling research across the full range of technologies used in metallurgical enterprises. It meets the basic criteria of compactness, versatility, and mobility. It consists of a set of control and measurement devices constituting a single multifunctional control module, which allows for the installation and expansion of individual components. The laboratory is fully versatile, offering a wide range of applications for the designed control and measurement equipment. It meets the requirements of various research stations located in metallurgical furnaces, secondary furnaces, and continuous casting processes. The models can operate in isothermal and non-isothermal conditions and are characterized by mobility, meaning the entire set can be easily moved and connected to individual physical models.

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INFORMATIVNÍ ČLÁNEK

Thyssenkrupp a Salzgitter vedou napjatá jednání o prodeji podílu v HKM

11. prosince 2025

ThyssenKrupp Steel chce odejít ze společného podniku v Hüttenwerke Krupp-Mannesmann (HKM) v Duisburgu, zatímco Salzgitter usiluje stát se jeho jediným vlastníkem. Mezi oběma stranami probíhá i arbitráž kvůli nároku ve výši přibližně 1,6 miliardy EUR, což podle šéfa ThyssenKruppu Miguela Lópeze komplikace zbytečně prodlužuje. Pokud ThyssenKrupp svůj podíl prodá, zůstane i nadále aktivně zapojen do restrukturalizace, na kterou vyčlenil rezervy ve stovkách milionů EUR.

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