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Numerical and Water Modelling Study on Electromagnetic Stirring Technology in Steelmaking

Numerické a vodní modelování technologie elektromagnetického míchání používané při výrobě oceli

Monika Zielinska[1,2], **Lidong Teng**[3], **Lukasz Madej**[2], **Lukasz Malinowski**[1]

[1] ABB Corporate Technology Center, ABB Sp. z o. o., 1 Żeganska Street, 04-713 Warsaw, Poland, *Contact e-mail: monika.zielinska@pl.abb.com

[2] Department of Applied Computer Science and Modelling, AGH University of Krakow, Mickiewicza 30 av., 30-059 Krakow, Poland

[3] ABB Metallurgy, Process Automation, ABB AB, Terminalvägen 24, SE-72159, Västerås, Sweden

Abstract

Electromagnetic stirring (EMS) technology has been applied for electric arc furnace (EAF), ladle furnace (LF) and tundish. The general purpose of such an application is to increase mixing and improve process control, while there is a specific demand for each type of analysed devices. A numerical study is executed for EAF, LF and tundish, focusing on stirring speed, specific stirring energy and mixing time evaluations. The comprehensive research is extended with water modelling for both LF and tundish. The results confirm the good performance of the electromagnetic stirring solutions and full control of the flow inside the metallurgical devices.

Keywords: *electromagnetic stirring, electric arc furnace, ladle furnace, tundish, computational fluid dynamics*

Abstrakt

Technologie elektromagnetického míchání (EMS) se uplatňuje v elektrických obloukových pecích (EOP), pánvových pecích (LF) a mezipánvích. Obecným cílem těchto aplikací je zvýšení intenzity promíchání a zlepšení řízení procesu, přičemž pro každý typ zařízení existují specifické požadavky. Byla provedena numerická studie pro EOP, LF a mezipánve se zaměřením na vyhodnocení rychlosti míchání, specifické energie míchání a doby homogenizace. Výzkum byl dále rozšířen o fyzikální modelování na vodních modelech pro LF i mezipánve. Výsledky potvrzují vysokou účinnost elektromagnetického míchání a možnost efektivního řízení proudění uvnitř metalurgických zařízení.

Klíčová slova: *elektromagnetické míchání, elektrická oblouková pec, pánvová pec, mezipánev, numerická analýza proudění*

1. Introduction

Nowadays, the steelmaking industry is one of the most significant industries globally. The demand for steel has been increasing over the last 50 years, and currently, steel accounts for approximately 95% of total metal production. Importantly, this growing demand is anticipated to continue in the near future, driven by the rapid development of various industries [1]. Conversely, steelmaking processes are highly intensive in carbon dioxide emissions, accounting for up to 10% of the total global emission [2-4]. A similar scenario exists regarding greenhouse gas emissions, which account for 7% of the global total. Consequently, restrictive environmental regulations have been implemented, compelling the steelmaking industry to make substantial changes in both local and global operations [5].

Meeting these regulations will require significant effort from the steel industry to comply and enhance technologies to reach the established goals [6, 7]. All of these factors indicate that the steelmaking industry is in a transition phase, with the primary goal of significantly reduction of the CO_2 emissions and achieving climate neutrality as much as possible [2, 5, 8, 9]. Reducing CO_2 emissions and greenhouse gases requires the exploration of new technologies. One solution is electric steelmaking. This technology is based on electricity and currently accounts for 28% of global steel production, resulting in CO_2 emissions of about 7% [10]. However, to effectively replace blast furnace technology, large EAF units ranging from 150 to 350 tons are necessary. In this scenario, processes like stirring are essential to maintain high efficiency and steel quality. Without stirring in the EAF, the process efficiency would be considerably lower than that of the basic oxygen furnace [11, 12]. Further mixing can be achieved with neutral gas injection or enhanced electromagnetic stirring (EMS) technologies [13]. For the electric arc furnace (EAF), supplementary equipment such as a ladle furnace (LF) and tundish is necessary to improve steel quality. In these processes, stirring technologies play a vital role.

The above factors drive the rapid development of EMS technologies for EAF, LF, and tundish, including the need for efficient mixing throughout the bath and enhancing steel productivity while maintaining high-quality final products.

Given the challenges in conducting real experiments, this work presents a numerical approach that will be extended to water modelling for selected devices.

2. Methodology

The study was conducted on specific full-scale industrial devices, including a 450-ton electric arc furnace (EAF), a 160-ton ladle furnace (LF), and a 40-ton multi-strand billet caster tundish. **Fig. 1** shows the geometries of these devices along with the position of the EMS stirrer.

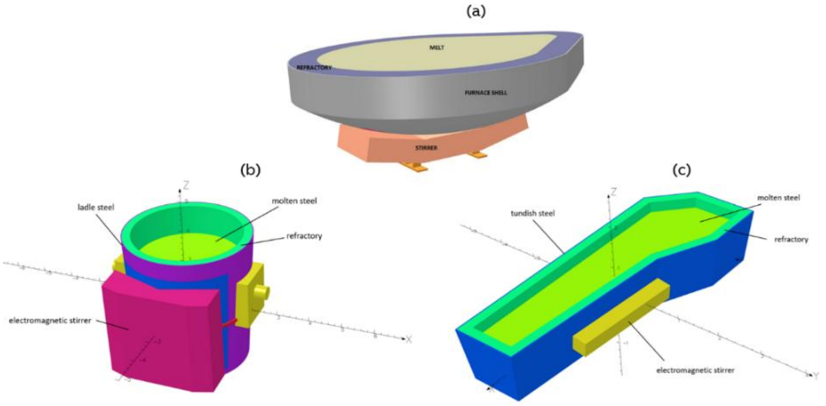

Fig. 1 Geometry of the selected devices: (a) 450-ton EAF, (b) 160-ton LF and (c) 40-ton tundish

Obr. 1 Geometrie vybraných zařízení: (a) 450 t EOP, (b) 160 t pánvová pec a (c) 40 t mezipánev

3. Numerical simulation approach

The numerical simulations rely on the computational fluid dynamics (CFD) method and are conducted using the commercial software ANSYS Fluent. However, the modelling of the electromagnetic forces influencing the melt and driving the steel flow in the EMS approach is accomplished through User Defined Functions (UDFs) developed in this work, which are thoroughly detailed in the paper [14].

The CFD numerical investigations focus on analyzing the melt behavior. The refractory, shell, and geometry of the stirrer are included only for illustration and are not part of the analysis. Additionally, the slag layer is not considered in this research. The electromagnetic forces are represented by an additional source term that acts on the melt. The numerical method incorporates both single-phase and multiphase models to predict mixing and temperature uniformity throughout the entire geometry of the furnace. For the multiphase approach, this model is further enhanced to include phases of steel and top gas. It features defined boundary conditions to accurately represent real-world conditions. The external surfaces of the melt are treated as walls with no-slip boundary conditions, except for the top surface, which is modelled as a wall with zero shear stress in the single-phase model and as a pressure outlet in the multiphase model to accurately reflect the external atmosphere of the furnace.

The molten steel is treated as an incompressible, viscous fluid because of the turbulent flow within the vessel. For the simulation, where the temperature distribution and temperature homogenization are considered, additional properties such as specific heat and thermal conductivity are defined. The material properties are gathered in **Tab. 1**.

Tab. 1 Material properties of steel used in the numerical simulation
Tab. 1 Materiálové vlastnosti oceli použité pro numerickou simulaci

Material properties	**EAF**	**LF**	**Tundish**
Melt density [kg/m^3]	6900	6900	7200
Melt viscosity [kg/(m s)]	0.0072	0.0069	0.0072
Specific heat [J/(kg K)]	792	-	692
Thermal conductivity [W/(m K)]	35	-	35

In the numerical study, to confirm the effectiveness of the stirring, three different analyses are conducted:

1. EAF – temperature homogenization, where the temperature gradient between the bottom temperature equal to 1560 °C and the top temperature equal to 1620 °C is assumed as a starting point. The goal of the simulation is to measure the homogenization time, when the difference between the maximum and minimum temperature in the bath is less than 5 °C. The simulation with an electromagnetic stirrer is compared to the simulation with a non-stirred bath, whereas a natural stirring, assuming 5% of the maximum EMS power, is considered and is treated as a reference.
2. LF – the mixing time simulation involves an additional tracer defined by the User Defined Scalar (UDS), with concentration monitored over time at specific locations. The initial UDS concentration is defined in the designated open-eye area [15], after which it is mixed and tracked throughout the entire melt domain. The dimensionless concentration of the tracer allows to determine the mixing time when 95% of the homogenization is achieved [16]. The numerical simulation of the tundish with vertical and horizontal EMS systems is compared to the reference case with gas stirring.
3. Tundish – similar to LF, the numerical simulation for tundish is prepared to assess the mixing efficiency realized by the UDS tracer. However, for tundish, the flow control theory [17, 18] is included to designate the active and dead zones in the volume of tundish. The CFD simulation with the EMS system is compared to the reference case without any flow control device.

The schematic presentation of the LF numerical setup with the location of the measurement points is presented in **Fig. 2**.

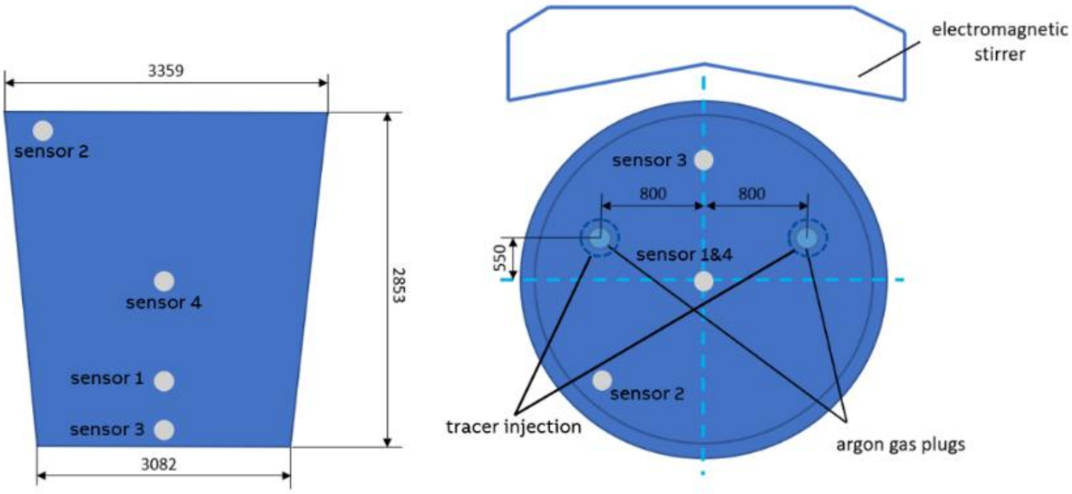

Fig. 2 The scheme of the 160-ton LF geometry with position of the sensors to monitor of the tracer concentration injected above the gas plugs position

Obr. 2 Schéma geometrie 160 tun pánvové pece s umístěním senzorů pro monitorování koncentrace indikátoru vstřikovaného nad dmyšnými elementy

4. Water modelling

The water model experiment was conducted in the dedicated water laboratory and executed only for LF and tundish. Water serves as an effective alternative to molten steel because the kinematic viscosity of water at 20 °C is similar to that of steel at 1600 °C [19]. An added benefit of this solution is that the experiment can be conducted at room temperature under isothermal conditions or with temperature variations, without the need to heat to extremely high temperatures like those required for steel to achieve a liquid state. This makes it easy to prepare and safe for individuals [20].

Both models for the LF and tundish are geometrically scaled. Additionally, to maintain similarity between the numerical and water models, the conditions for the submerged water pumps, which create the EMS stirring, must be accurately scaled. Since the primary aim of the analysis is to comprehend the flow behaviour and demonstrate mixing efficiency, the Froude number is chosen to ensure flow behaviour similarity [21-24]:

$$Fr = \frac{u_m}{\sqrt{gD_m}} = \frac{u_s}{\sqrt{gD_s}}, \tag{1}$$

where: Fr – Froude number, u_m – velocity in the water model [m/s], u_s – velocity in the steel [m/s], g – gravitational acceleration [m/s^2], D_m – diameter of the water model [m], D_s – diameter of the real furnace [m].

The numerical simulations allowed for the selection of a specific area in the furnace to assess the steel's velocity. This same area was examined in the water models, where the velocity in key regions was measured using a velocity meter.

In the water model experiments, the setup of the analysis reflects the process simulated by the CFD approach.

To assess the effectiveness of the EMS stirring, the following analyses are conducted:

1. LF – the mixing time measurement is realized by the injection of the 20% salt solution on the surface of the water in the same position as in the CFD simulation. Again, the dimensionless concentration of the salt is measured in the same places as in the numerical simulation. The same condition of 95% of the homogenization is included to be able to compare the obtained results with the numerical solution.
2. Tundish – again, the setup of the water model experiment includes tracking of the injected salt solution. Based on the measurements, the active and dead zones based on the flow control theory were designated to compare the laboratory experiment to the numerical simulations. Moreover, the additional analysis with the injection of the dye via the inlet into the tundish enables the measurements of the mixing time. The measurements were performed for a reference case without stirring and for a case with stirring.

The water model setup for LF and tundish is presented in **Fig. 3**.

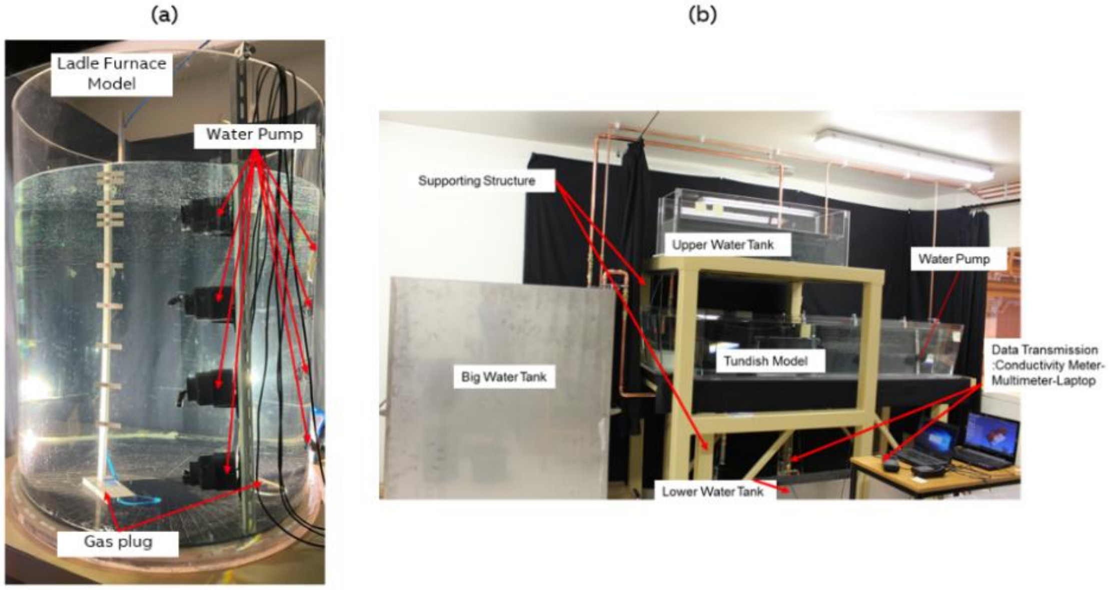

Fig. 3 The water model setup prepared for (a) ladle furnace and (b) tundish

Obr. 3 Sestava vodního modelu: (a) pánvová pec a (b) mezipánev

5. Results

The numerical simulation of the EAF, assuming a temperature gradient at the beginning of the simulation, enables the investigation of the temperature homogenization time, when the temperature difference between the maximum and minimum values in the bath is less than 5 °C. The temperature changes in time for two cases: 5% of the EMS corresponding to the natural processes inside the furnace and 100% of the EMS acting from the slag door to the EBT (Eccentric Bottom Tapping) direction is presented in **Fig. 4**, while the graphical interpretation of the changes is presented in **Fig. 5**.

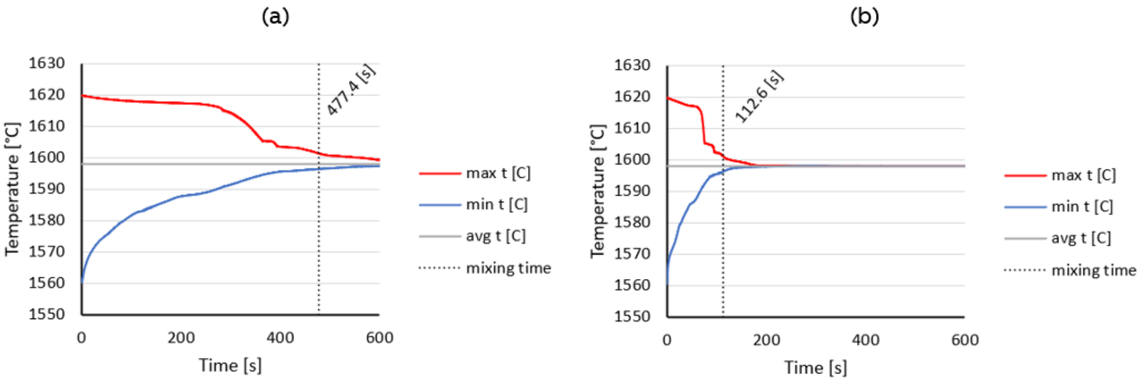

Fig. 4 The temperature changes in time for (a) 5% of the EMS power corresponding to the natural processes and (b) 100% of the EMS power with the direction of stirring from door to EBT in the 450-ton EAF

Obr. 4 Změny teploty v čase při (a) 5% výkonu EMS, což odpovídá přirozeným procesům a (b) 100% výkonu EMS se směrem míchání od struskového k odpichovému otvoru u 450 t EOP

The 5% of the EMS power as an indicator of natural mixing processes was designated based on a separately conducted experiment for a 90-ton furnace, where a copper tracer was implemented into the molten steel.

The measurements of the Cu content confirm that the homogenization time for EMS power on is equal to 62 s, while with EMS power off is equal to 260 s. It means that the mixing time with EMS is 24% of the time without EMS, which can be directly compared to the CFD simulation and confirms that the 5% of the EMS power is a correct assumption to include the impact of natural mixing inside the bath. The measurements are treated as a validation of the numerical approach [25].

The numerical and water model study conducted for LF enables a comparison of the efficiency of the EMS solution with the reference case that includes gas stirring. The dimensionless mixing time curves were prepared to assess the efficiency of the homogenization of the composition of the steel in the case of the alloy additions mixing process.

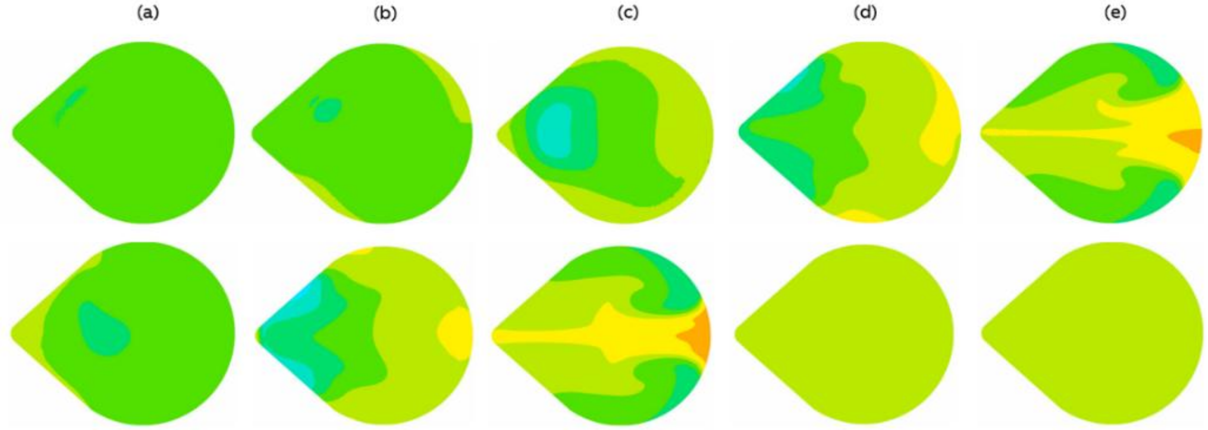

Fig. 5 Temperature distribution in time for 5% of EMS (top) and 100% of EMS (bottom) with the stirring direction from door to EBT in the 450-ton EAF for (a) 5 s, (b) 20 s, (c) 50 s, (d) 100 s and (e) 200 s

Obr. 5 Časový průběh rozložení teploty pro 5% EMS (nahoře) a 100% EMS (dole) při směru míchání od struskového k odpichovému otvoru u 450 t EOP po (a) 5 s, (b) 20 s, (c) 50 s, (d) 100 s a (e) 200 s

The numerical results and the water modelling confirm, that the EMS stirrer is definitely a more efficient solution for mixing. Moreover, the new proposed horizontal stirring in ladle furnace, which is characterised by an elongated mixing time, is expected to have a controllable flow pattern and can be beneficial in refining processes [14, 26]. The comparison between the mixing curves for numerical simulation and water experiment is presented in **Fig. 6**.

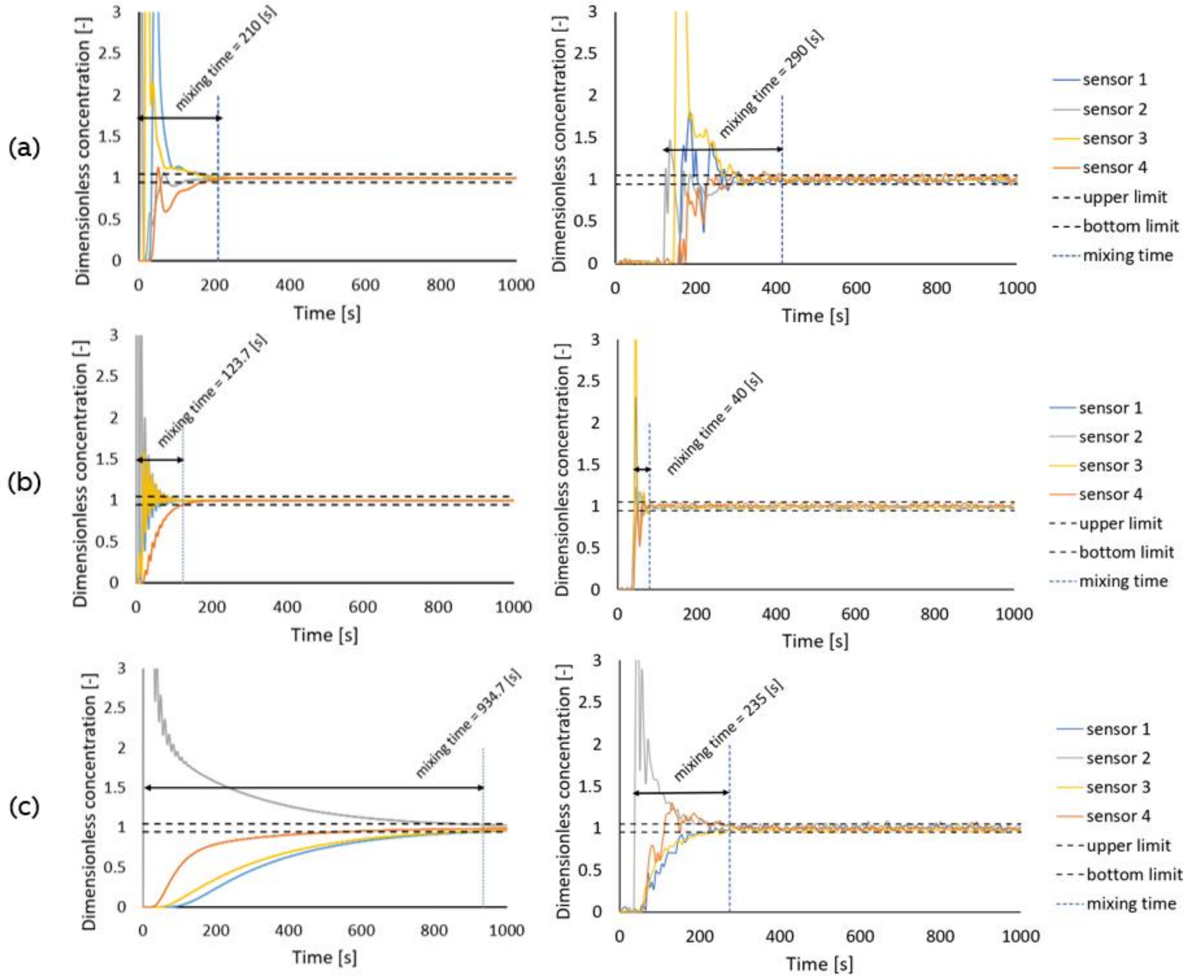

Fig. 6 Mixing time comparison for numerical simulation (left) and water experiment (right) for (a) reference case with gas stirring, (b) vertical EMS stirring and (c) horizontal EMS stirring in the 160-ton ladle furnace

Obr. 6 Srovnání doby míchání v numerické simulaci (vlevo) a na vodním modelu (vpravo) pro (a) referenční případ s mícháním plynem, (b) vertikální míchání pomocí EMS a (c) horizontální míchání pomocí EMS u 160 t pánvové peci

The additional analysis focuses on the numerical simulation and water experiment for the 40-ton multi-strand tundish. In similarity like in the LF, the tundish is investigated in the efficiency of the mixing process. The RTD curves are measured based on the salt concentration to be able to assess the active and dead zones.

The conducted research confirms the high efficiency of the EMS stirring, as the mixing curves are similar to those of ideal mixing. Moreover, all strands are characterized by similar behaviour, what confirms the great homogeneity of the flow. The comparison between the numerical and water models is presented in **Fig. 7**.

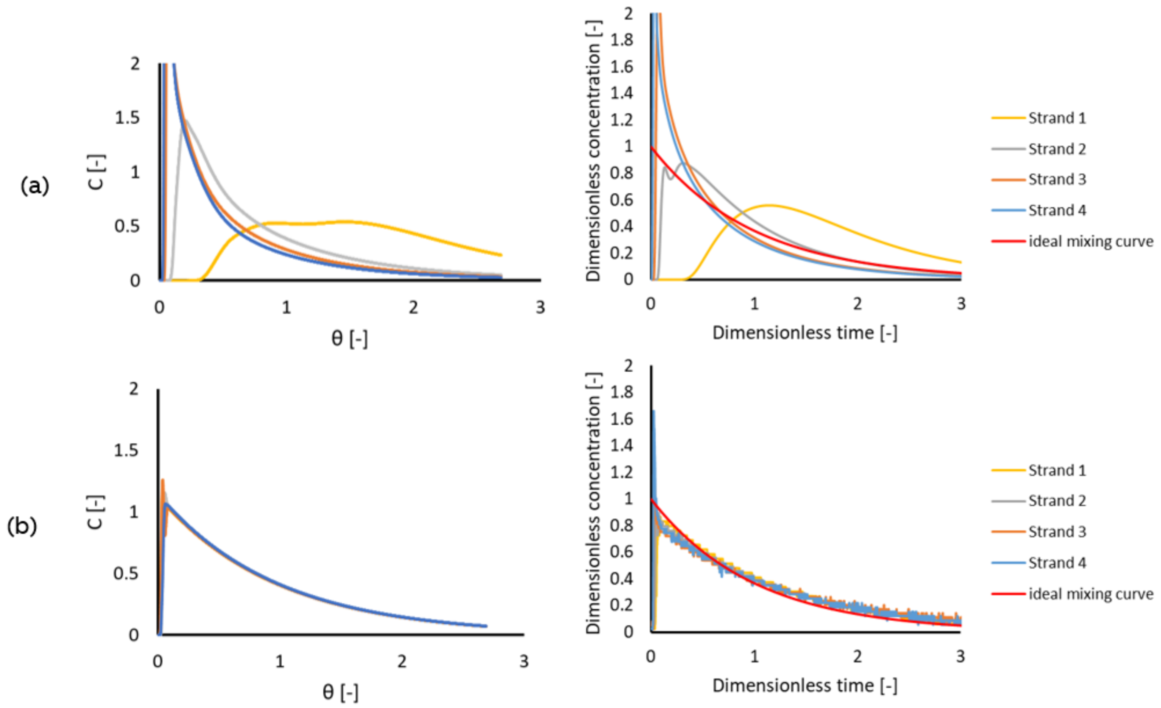

Fig. 7 RTD curves comparison for numerical simulation (left) and water experiment (right) for (a) reference case without any control device and (b) EMS stirring in the 40-ton multi-strand billet caster tundish

Obr. 7 Porovnání RTD křivek získaných numerickou simulaci (vlevo) a vodním modelem (vpravo) pro (a) referenční případ bez jakéhokoli regulačního zařízení a (b) míchání pomocí systému EMS ve víceproudé mezipánvi

To extend the research, mixing time measurements were conducted using the dye implementation via the inlet to the water. The study confirmed, that the homogenization time for EMS stirring is only 29 s, while for reference case without stirring, the mixing time is around 567 s.

6. Conclusions

- The conducted research clearly confirms that the EMS stirrer implementation improves the performance of the metallurgical vessels and is characterized by the high efficiency of the mixing on different stages of the molten steel path.
- The processes can be easily controlled by the EMS power changes and can be fitted to the existing furnace's geometries and capacities, which can be beneficial in the case of the replacement process of blast furnaces by EAFs.
- Moreover, thanks to the additional electromagnetic stirring, a more homogeneous composition of the steel is expected, which can directly influence the quality of the final product and reduce operational issues during the processes.

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