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EXPERIMENTAL METHODS OF VALIDATION FOR NUMERICAL SIMULATION RESULTS ON STEEL FLOW THROUGH TUNDISH

The article presents experimental results on the impact of tundish flow regulator influencing the liquid steel flow course. The research was conducted based on the hybrid modelling methods understood as a complementary use of Computational Fluid Dynamics (CFD) methods and physical modelling. Dynamic development of numerical simulation techniques and accessibility to highly advanced and specialized software causes the fact that these techniques are commonly used for solving problems related to liquid flows by using analytical methods. Whereas, physical modelling is an important cognitive tool in the field of empirical identification of these phenomena. This allows for peer review and specification of the researched problems. By exploiting these relationships, a comparison of the obtained results was performed in the form of residence time distribution (RTD) curves and visualization of particular types of liquid steel flow distribution zones in the investigated tundish.

Keywords: continuous casting, tundish, physical modelling, numerical modeling

1. Introduction

The specificity of operation of metallurgical reactors being characterized, among other, by: high temperature, aggressive environment, isolation of working areas in the reactor, potential risk for researchers conducting experimental tests, high costs associated with possibility of jeopardizing, caused by disturbances in the technology and excessive breakage, etc.; these are basic factors that often prevent from performing research tests in industrial conditions and justify utilization of model-based tests. Therefore, physical modelling is an important research and cognitive tool in terms of empirical identification and analysis of phenomena occurring in metallurgical reactors. Dynamic development of numerical modelling techniques, the accessibility to highly advanced and specialized software, and significant raise of processing capabilities of computer devices have led to the situation that numerical studies are commonly used for solving metallurgical problems by using analytical methods.

The advancement in steel smelting and casting technology driven mostly by increasing customer demands requires a constant deepening of knowledge about phenomena occurring in the course of metallurgical processes and more and more precise identification of parameters that control these processes. Due to this reason, at this stage of the study, it is impossible to employ explicitly a single modelling technique in the research process on numerous phenomena. Thus, in the Institute of Metals Technology at the Silesian University of Technology, the Model-based Testing Laboratory - being established many years ago – was modernized to facilitate implementation of the method based on hybrid modelling,

and this significantly improved research capabilities of the laboratory.

The research works published in this scope of research study generally concern the problem of identifying hydrodynamic phenomena, which are present during performance of various metallurgical processes acting on liquid steel. The rules governing implementation of similarity factors between the model and industrial objects are in the field of applied mathematics, commonly known as similarity theory. Therefore, both physical as well as numerical models are based on mathematical models. Mathematical modelling consists of describing the investigated phenomena as mathematical symbols and dependencies (functions) and determining principles for controlling them. In the case of solving hydrodynamic problems related to liquid steel flow in metallurgical reactors, the basic mathematics model is based on the Navier–Stokes equations and the continuity equation [1-2], expressed by the formulas:

$$\rho \cdot \frac{\partial v_x}{\partial t} + \rho \cdot \left(\frac{\partial v_x}{\partial x} \cdot v_x + \frac{\partial v_x}{\partial y} \cdot v_y + \frac{\partial v_x}{\partial z} \cdot v_z \right) =$$

$$\rho \cdot g_x - \frac{\partial p}{\partial x} + \eta \cdot \left(\frac{\partial^2 v_x}{\partial x^2} + \frac{\partial^2 v_x}{\partial y^2} + \frac{\partial^2 v_x}{\partial z^2} \right) \tag{1}$$

where: x, y, z,   - coordinates,
v_x, v_y, v_z,- velocity components, m · s^{-1},
ρ - density, kg · m^{-3},
η - dynamic viscosity, kg · m^{-1} · s^{-1},
g_x - gravitational acceleration, m · s^{-2},
p - pressure, kg · m^{-1} · s^{-2}.

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$$Q = \frac{V}{t} = \text{const} \qquad (2)$$

where: Q - flow rate, $m^3 \cdot s$,
        V - volume, m^3,
        t - time, s.

The quality of mathematical models depends mainly on the accuracy and precision for determining initial and boundary conditions of the modelled process called as expressions defining the quality indicator. Therefore, the quality indicator is a measure expressed in an explicit analytical form of a specific function or functional decision-based variables. This is particularly important for constructing computational fluid dynamics codes in numerical simulations. Whereas, in physical modelling, the equation (1) is a subject of dimensional analysis based on Buckingham thesis, also known as π theory, which allows for determination of criteria for dynamic similarity [3]. In physical modelling of hydrodynamic phenomena occurring in the course of implementing metallurgical processes, the dynamic similarity between the model and industrial application is obtained on the basis of compatibility of values of criterion-based numbers determined for these objects.

The developed physical model of COS device is a segment-based model. This indicates that individual components of the model are divided into segments, which means that – in terms of their functionality within the working space- they fulfil different tasks. Basic constructional elements (components) of the model are: a model design of tundish and model designs of ingots serving as main segments. Other components of the model, namely: hydraulic infrastructure, fluid reservoirs utilized as steel tundish models, control system, measuring systems, flow control devices for the model liquid, and so on, serve as auxiliary segments. The model fluid flow control device operates on the basis of automatic adjustment based on measurement data being obtained through flow meters installed at proper points in the hydraulic system. Signals that facilitate plotting RTD curves are generated by conduct meters, mounted at relevant points in the hydraulic system. All input and output signals are sent to central panel for data control and registration. The data are stored in the device memory and can exported (over WiFi) to a computer, where they are subject to further processing. On the other hand, visualization of the process consists of registering the course of experimental tests with a set of cameras. The film material obtained in such manner undergoes further computational processing. The research results derived during tests are verified by using numerical methods. For this purpose, computational codes of the ANSYS Fluent CFD software package are applied. Detailed description of such a course of research tests is presented in [4-9].

2. Research methodology

Water modelling continuous casting is developed in such a way to satisfy the conditions for dynamic similarity of the modelling liquid flow in main segments – tundish and its corresponding industrial application. The theoretical foundations of these problems are found in fluid mechanics [1]. The medium (water) flow velocity was determined based on the designated criteria of similarities between the model and test industrial applications. The view of the test stand of the continuous casting device is presented in Fig.1. By using the physical model, there were performed research tests based on visualization and tracer concentration distribution was determined in the form of Residence Time Distribution (RTD) characteristics (of type F [10,11]). Aqueous solutions of $KMnO_4$ [12] and NaCl are used as markers in the model.

Fig. 1. Physical model of the investigated device

2.1. Geometrical description of the model tundish

The test object is a six-strand continuous casting tundish with a nominal capacity of 24 Mg. It is a typical delta-type tundish, which is used in the domestic metallurgical industry. Steel is poured into the tundish through a ceramic shroud positioned in the device's plane of symmetry. This tundish is symmetrically relative to the transverse plane. The tundish is designed for continuous casting of slabs intended for small cross-section rolled products. Figure 2 presents geometry of the model constructed in the scale of 1:3 and flow control devices analysed in the research tests.
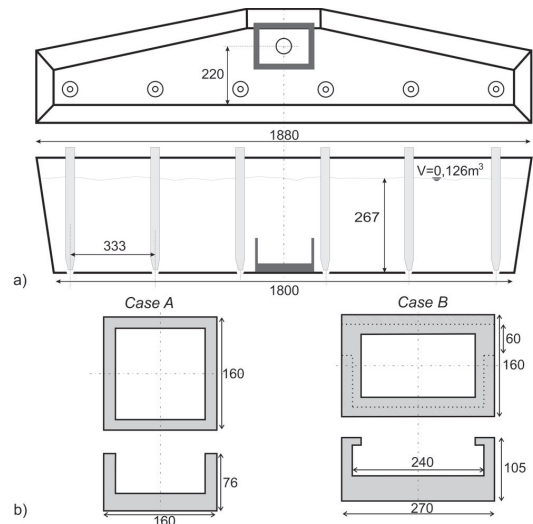

Fig. 2. a) Schematic view of modeled tundish, b) working areas variants

3. Validation with CFD

The gathered experimental material was confronted with data from numerical simulations carried out under identical conditions. In order to perform direct comparison of results derived from numerical simulations and experiments, the marker concentration and times were converted into dimensionless characteristics, utilizing for this purpose appropriate recalculations [10]. Figure 3 presents dimensionless RTD characteristics of F type for experimental tests and numerical (CFD) simulations. Comparing the research test results with numerical simulations by using RTD graphs, it can be stated that they indicate good conformity. This proves correctness of the assumptions adopted for the research study.
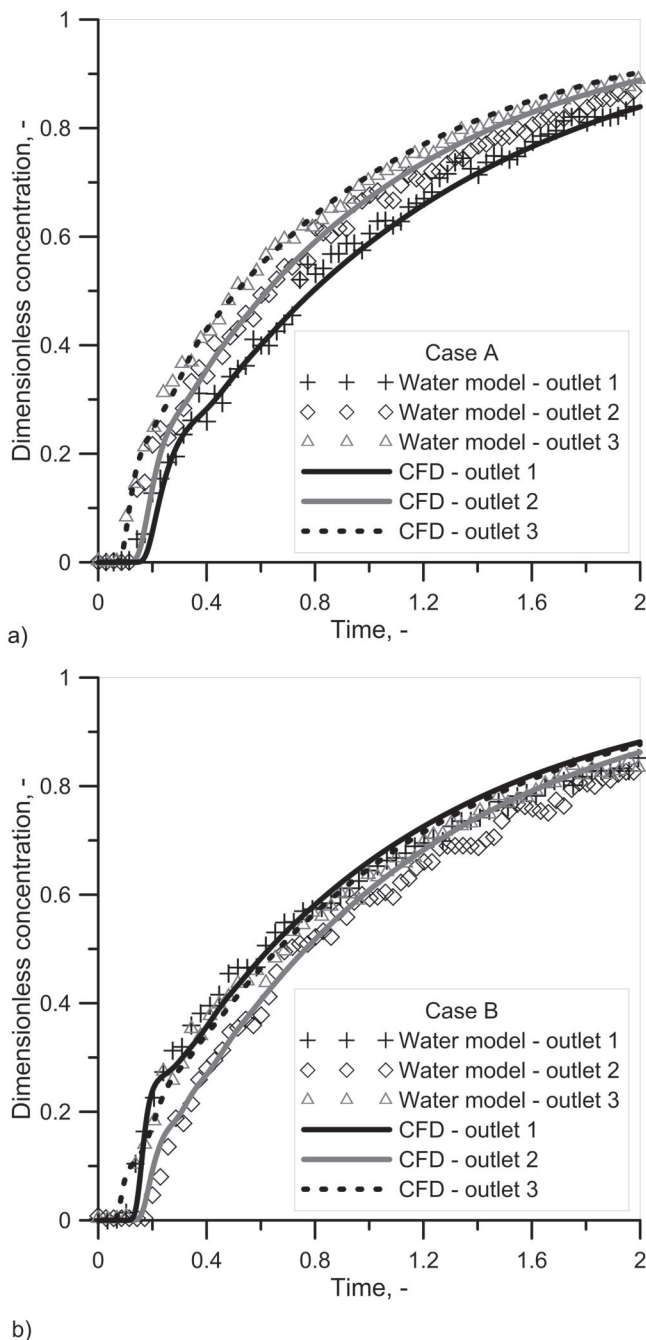
The designated F curves (Fig. 3) also allow for quantitative assessment of the kinetics in stirring of the liquid steel according to the researched flow regulators of the tundish working area. Table 1 compares the designated values characterizing the kinetics in stirring of the liquid steel (sizes of transition zone) in the tested working area. The reference range was time period needed to obtain the maximum concentration values of 0.2 and 0.8. It was designated by taking into account the average theoretical length of residence time, which for the model amounted to 524 s and for the CFD tests 675 s.

Based on the analysis of the presented in Table 1 research results, a worth-noting fact was observed that despite a slight deterioration in the kinetics of the steering liquid steel in tundish (case B), intervals describing time needed for the marker to enter each nozzle of the tundish were equalized. In this case, the obtained convergence of results was also satisfactory and did not exceed ± 10%, which for industrial conditions is a sufficient accuracy.

Kinetics of steel mixing (transient zone)

Tundish configuration	Kinetics of steel mixing (transient zone) [s]			
	Outlet			average for the outlets
	No.1	No.2	No.3	
Water model				
Case A	745,8	710,8	679,9	712,2
Case B	781,5	785,5	808,7	792,3
CFD				
Case A	850,5	830,3	789,8	823,5
Case B	891,0	904,5	891,0	897,8

Application of the ($KMnO_4$) marker in the model allowed performing qualitative analysis – in the form of visualization study on liquid steel flow in the tundish. Figure 4 visualizes an exemplary flow of marker in the time of performing the experiment, being related to numerical simulation results.

Comparison of visualization research tests on liquid steel flow in the tundish performed by using water model with visualization gained from numerical simulation derived positive results too. There was observed similar flow pattern of the model liquid in both research methods.

4. Summary

Hybrid modelling targeted for solving the same problem by using at least two techniques is a powerful research tool, which facilitates obtaining reliable results. Combining the physical model with numerical simulations is the best example for this. Obtaining convergent results in this type of research process demonstrates self-verification attributes. By applying interchangeably one or the other method, it allows for determining data, not able to be calculated with one method, needed for obtaining proper solution to problems. An example can be acquiring data for precise formulation of initial and boundary conditions of computational codes for numerical simulations derived from research tests based on physical modelling. Conversely, numerical calculations are a very important source of data required for proper

Fig. 3. Results coming from water model and CFD - mixing-time characteristics for: a) Case A, b) Case B

development of physical models and adequate implementation of the experiment.

Obviously, final verification of the obtained results of each type of model research tests is possible explicitly in industrial conditions. However, hybrid modelling allows omitting numerous stages of such verification and makes it much safer and less expensive, which is not insignificant.

Analysing the obtained results in terms of their proprieties, it should be stated that each of the tested flow regulators could basically be the subject of industrial application. However, it should be emphasized that to gain improvement in the flow of liquid steel in the working space of the tundish is impossible to be obtained in terms of simultaneous fulfilment of all desired effects, including: increasing the refining capacity, limiting the extent of the transition zone, and high degree of homogeneity of the liquid steel cast in term of chemical and temperature properties. Comparing the results obtained by applying the tundish flow regulator – Case A – which nowadays serves as an industrial application with the results derived from the Case E, a slight improvement in flow conditions can be observed in favour of Case E. However, the results of research tests based on visualization indicate substantial enlargement of dead flow zones, which occur just in Case E. Therefore, some improvement was achieved in flow conditions- in terms of conducting sequential process with transition zone; however conditions favouring proper homogenization of liquid steel cast in the tundish working space and the refining capacity were deteriorated. Therefore, when analysing the issue of optimization of tundish operational capacities in terms of flow regulators being mounted therein, it should be aimed to obtain a certain balance between the positive characteristics of the flow regulators and the negative features, which always are present.

By taking into consideration the obtained research results and following the foregoing reasoning, it should be stated that tundish flow regulator design solutions currently applied in the industry are optimal solutions. The balance between advantages and disadvantages of a potential change in flow regulator system does not justify financial spendings needed for its modernization.

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