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MODEL STUDY OF TUNDISH STEEL INTERMIXING AND OPERATIONAL VERIFICATION

MODELOWE STUDIUM MIESZANIA STALI W KADZI POŚREDNIEJ I WERYFIKACJA WYNIKÓW W WARUNKACH PRZEMYSŁOWYCH

The aim of this paper will be to present new knowledge and experience from numerical and physical modelling of metallurgical processes at the Department of Metallurgy, VSB – Technical University of Ostrava in Czech Republic and to explain especially the principle of tundish process simulations. The numerical modelling was realized by the CFD program FLUENT. The paper describes the pre-processing, processing and post-processing phases of numerical modelling. The physical modelling of the steel flow verification is based on a monitoring of the time dependency of concentration changes during experiments for individual tundish outlets. There exist two basic methods of KCl concentration change utilization in this "water" physical tundish modelling methodology. The utilization of mentioned methods are discussed and possible future developments are outlined for research of tundish steel intermixing.
Keywords: Steel, tundish, intermixing zone, modelling, CFD, ANSYS FLUENYT, RTD

Celem artykułu jest przedstawienie wyników i doświadczeń z numerycznego i fizycznego modelowania procesów metalurgicznych w Zakładzie Metalurgii, VSB – Uniwersytet Techniczny w Ostrawie (Republika Czeska) i wyjaśnienie zasady symulacji procesów mieszania stali w kadzi pośredniej. Program CFD FLUENT posłużył do modelowania numerycznego. W artykule opisano pre-processing, processing i post-processing modelowania numerycznego. Weryfikację modelowania fizycznego przepływu stali dokonano w oparciu o eksperymenty, w których monitorowano zmianę stężenia w czasie dla poszczególnych stref kadzi. Istnieją dwie podstawowe metody wykorzystania zmian stężenia KCl w wodzie. Omówiono wykorzystanie wymienionych metod i możliwości przyszłego rozwoju badań mieszania stali w kadzi pośredniej.

1. Introduction

The attention of the Department of Metallurgy of the VSB – Technical University of Ostrava has for a long time been focused on the study of steel flow nature in the tundish using physical and numerical modelling. The sophisticated methodology of the experiments and the well-selected system of physical and numerical modelling results, transformed into the operational experience with the verified use of similarity theory, offers the opportunity to address other fundamental technological problems.

This paper brings the main information about the setting of the numerical and physical modelling of the steel flow through the tundish and the determination possibilities of the extent of the intermixed zone, the possibilities of steel flow optimization using an inner configuration of tundishes or the boundary conditions of casting to minimize the extent of the intermixed zone in continuous cast steel billets.

The intermixed zone originates during a sequence casting when the various steel grades are cast in a single sequence, without the interruption of the casting, and without consecutive restarts. This casting technology causes a mixing of the old and new steel grades in the tundish, and in the continuous cast billet it creates so called the intermixed zone. The physical and numerical modelling of two different melts intermixing in the tundish have been successfully used for the improvement of control systems in terms of intermixed zones under conditions of a continuous casting machine (CCM) No.2

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and CCM No.1 located in TRINECKE ZELEZARNY (TZ).

The steel flow optimization in the tundish of the CCM is necessary to achieve the homogeneous minimum residence time in all casting strands (CS). The low values of the minimum residence times are associated with the risk of so-called short-circuit flow. To prevent the short-circuit flow, the baffles or turbostop can be inserted into tundish.

2. Principe of steel flow verification

Various methods can be used to verify the extent of the intermixed zone. The possible ways of modelling such processes are based upon methods of physical or numerical modelling. In case of physical modelling a change in concentration of the tracing substance is made in the basic model liquid at the entry of model of a tundish, whereby at the outlets from tundish there is registered the response of such change and its feature with the time elapsed. When taking into account the theory of similarity this route provides in a relatively quick manner the fundamental idea about origination of the intermixed zone, idea about the effect of tundish configuration, the effect of weight of liquid steel, the role of different steel temperatures at the entry of tundish and similarly.

The numerical modelling can be suitably completed by application of the CFD-programs (Computational Fluid Dynamics) that are provided with various computing models of flowing built-in and their selection is made by the user. Solution in the CFD-FLUENT program is based in principle on simulation of a change in concentration at the entry of tundish and the calculated determination of variations in concentration and/or temperature fields inside of tundish and in its outlets. From the character of the transition curves being one of the outcome of simulation, the change in concentration at the outlets of tundish can be predicted and thus, even the extent of intermixed zone in the blanks. The accuracy of numerical modelling can be influenced by a correcting set of boundary conditions and by selection of the proper computing model.

The direct full-scale measurement seems to be a suitable method for verification of extent of the intermixed zone. There can be applied the orthodox concentration or the radio-nuclide method at which a marking substance (Cu, radionuclide) is implemented into liquid steel, whereby the variation in its concentration and/or the level of radiation is determined in the cooled-down blanks. Such methods are relatively precise; however, they need perfect preparatory work incl. of well-adapted procedure at determination of points in blanks where the addition was applied. This problem is rather complex as there is necessary to follow all the casting streams at tundish simultaneously and even due to the fact that the casting rate can fluctuate during the experiment. Last but not least the shrinkage in volume of steel with a drop in temperature should be taken into consideration here. The following part of our paper details the main knowledge from full-scale measurements carried out at No.2 CC-machine of the TZ when casting billets of 150×150 mm in sizes, along with the method of treating the results obtained from regression and correlation analyses and subsequently comparing these with the numerical modelling results [1].

2.1. Setting of numerical modelling

The numerical modelling of the steel flow in the tundish during the sequence casting of the steel billets cast under conditions of CCMs in TZ was realized by CFD program FLUENT. Generally, the numerical solution of each task is divided to the three stages [2]: *pre-processing* includes the geometry modelling and the computational grid generation process; *processing* involves its own definition of the flow model and the computation in the solver; *post-processing* focuses on the results evaluation.

The geometry modelling and the generation process of the tundish computational grid were done in the GAMBIT pre-processor. The computational grid of the geometry for 15 tons of steel in the tundish CCM No.2 and the detail of the nozzle geometry are shown in Fig. 1. The geometry for 20 tons of steel in the tundish CCM No.1 and the detail of the computational grid of the nozzle geometry are shown in Fig. 2.

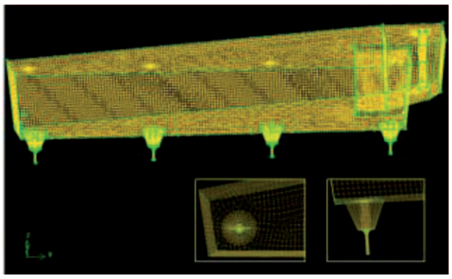

Fig. 1. The computational grid of the tundish geometry of CCM No.2 with the view detail on the computational grid of the tundish nozzle

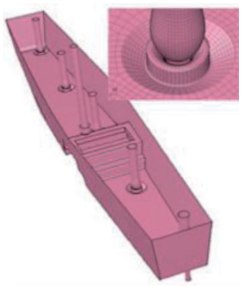

Fig. 2. The tundish geometry of CCM No.1 with the surface at 0.6 m level– variant for 20 tons of steel in the tundish

It is necessary to specify the inlets, outlets and walls for the tundish geometry in the GAMBIT pre-processor in order to subsequently define the boundary and operational parameters in the solver (FLUENT). The walls and the melt surface of the tundish have been defined as the WALL, the tundish volume was specified as the FLUID, the output from the shroud as the VELOCITY-INLET and the nozzles on the tundish bottom as the OUTFLOW. The complete computational grid of the tundish geometry was saved in the *.msh format and imported in CFD programme FLUENT.

The flow was considered to be incompressible, viscous, and turbulent. The calculations included the effect of the natural convection [2].

In the numerical simulations, three models of turbulence have been tested: the RNG k-ε model, the k-ω model completed with the definition of the transitional flow, and the shear-stress transport (SST) k-ω model. The aim of these test computations was to verify their influence on the final character of the steel flow, and to find the optimal settings for the whole model.

The principle of the numerical modelling of the sequence casting is the simulation of steel flow in the tundish during a change of chemical composition of incoming steel. The simulation of the change in steel grade lies in changing the input concentration of the component from value 0 up to value 1. To simulate the change in the cast steel grade, it was necessary to define two components: the old and the new melt. To distinguish the old from the newly supplied melt the descriptions OLD MELT and NEW MELT were used. The simulation of the change in the concentration was done using the Species Mass Fraction function from value 0 (MELT) up to value 1 (NEW MELT) [2].

The operating conditions and material properties were entered. The steel density was defined as a profile function of temperature using the Piecewise-linear function. The inlet parameters of the steel flow into the tundish through the shroud were already defined as the VELOCITY-INLET. This condition takes into account the constant value of the flow velocity, of the temperature and of the turbulence parameters across the whole cross-section. The value of the turbulence intensity of the incoming flow was I =1 %. The hydraulic diameter of 0.04 m corresponds to the internal diameter of the shroud.

The transfer and conduction of heat were assumed by through convection as well as conduction. The heat losses were considered to be through the walls of the tundish and through the melt surface. The value of the heat losses through the bottom and walls of the tundish was 2.500 $W.m^{-2}$. The heat loss through the free melt surface was selected to be 15.000 $W.m^{-2}$. FLUENT solves the system of differential equations of the flow using the finite volume method. The SEGREGATED-IMPLICIT solver was used to solve the task. The simulations were carried out in a non-stationary regime with convergence at each time level [1].

2.2. Physical modelling of flow pattern in the tundish

In applied research conducted within the Department of Metallurgy, the results of scientific research in the field of numerical modelling are verified not only using operational experiments in a real plant, but also using the sophisticated modelling of physical processes in the tundish. The Department of Metallurgy has three physical models of tundishes currently available.

The first model is the one of a four-strand asymmetric tundish of the CCM No.2 operating in TZ. The CC-machine No.2 of TZ is of an eight-strand design, set for billets, a radial type with the radius of curvature of 9 m, and is equipped with two asymmetric four-strand tundishes for casting [3]. These tundishes are filled with the melt from a single casting strand and the tundishes have the partition wall between the impacting point and the outlet node of casting strand No.5. The Plexiglas model is constructed on the Ml = 1:3 scale with regard to a real tundish (see Fig. 3a). Department of Metallurgy has also performed an extensive experimental work (publications) in other two models of the real tundish, which is installed to be part of CCM No.1 in the TZ. The former Plexiglas model was constructed on a scale of 1:5. The more recent model was constructed on a scale of 1:4 (Fig. 3b). To simulate the flow of steel, it is possible to use the water that has suitable physical properties.

To study the flow nature of the modelled fluid, a conductivity method is employed, which uses a weak aqueous solution of KCl, and the changes in concentration of the substance during the experiment. The conductivity and concentration is measured by probes located at the inlet and outlets the tundish. The concentration of KCl is recalculated. The resulting concentration of KCl in aqueous solution is used to identify the characteristics of the so-called retention times, and to obtain the time-dependent changes in concentration at the outlet of the tundish – the RTD curve. In practice, the physical modelling of steel flow in a tundish commonly uses both methods [3].

a) b)

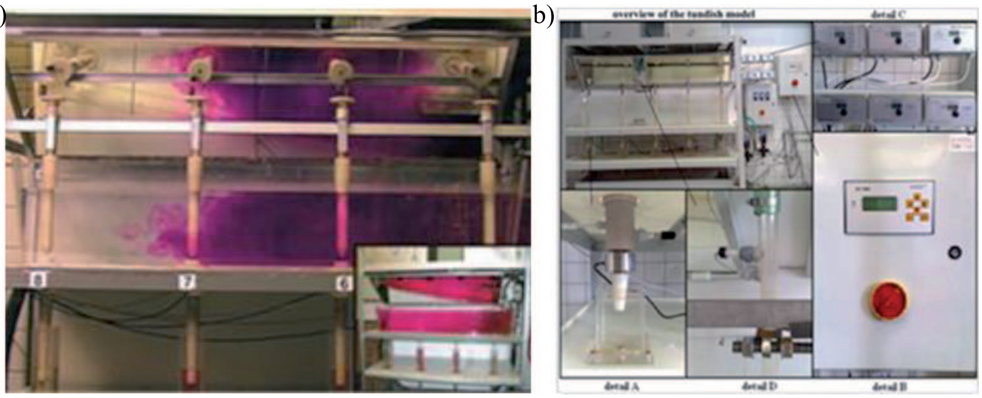

Fig. 3. a) The view on the model of asymmetric four-strand tundish of CCM No.2 on scale of 1:3; b) Overview of the tundish model in 1:4 scale, along with detailed views on: outlet node of immersion nozzle (detail A), central measuring station (detail B), measuring units of inductive flow meter (detail C), shroud (detail D)

2.3. Operational verification

The full-scale experiment was aimed at verification of the actual extent of transition zone in the billets of 150×150 mm cast at the No.2 CC-machine of the TZ. The principle of experiment consisted in the method of cross alloying the melts by nickel and copper and to evaluate the concentration of these elements over the length of cast billets.

In line with the technological procedure two steel heats of P2-09Si grade (heat-no. 12489 and 12490) were melted for the sake of full-scale verification of the transition zone. The heats were melted in current regime and at tapping the steel was alloyed by 410 kg nickel (heat-no. 12489) and by 380 kg copper (heat-no. 12490). The resulting content of nickel and copper prior to casting at the CC-machine were as follows: Heat-no. 12489 – 0,24 % Ni, 0,05 % Cu, heat-no. 12490 – 0,02 % Ni, 0,22 % Cu. Heat.-no. 12489 was cast in its entire sequence as the second in the order and heat-no. 12490 as the third in the order. Casting into individual convex moulds was performed through calibrated teeming nozzles of 19,5 mm in dia and with casting rates reaching the average values of the individual casting streams of 2,7 up to 3,04 m.min^{-1}.

The measurements were performed with the help of mobile spectrometer ARC-MET 900. One analysed point was re-measured 2 or 3-times at least and in some cases almost 7 analyses were made. The evaluated blanks are illustrated in Fig. 4a.

The experimental data on the chemical composition were processed in form of a graph showing the change in concentration of copper and nickel over the length of blanks – see Fig. 4b. The vertical line segments of the grate of plot represent the boundaries of the average lengths of the individual blanks [1].

3. Results processing

The shape of the transition curve obtained from physical, numerical or plant full scale modelling can be then used to reversely deduct the basic data on the transition zone extent. The transition zones are most commonly defined as restricted areas within the blanks where

a) b)

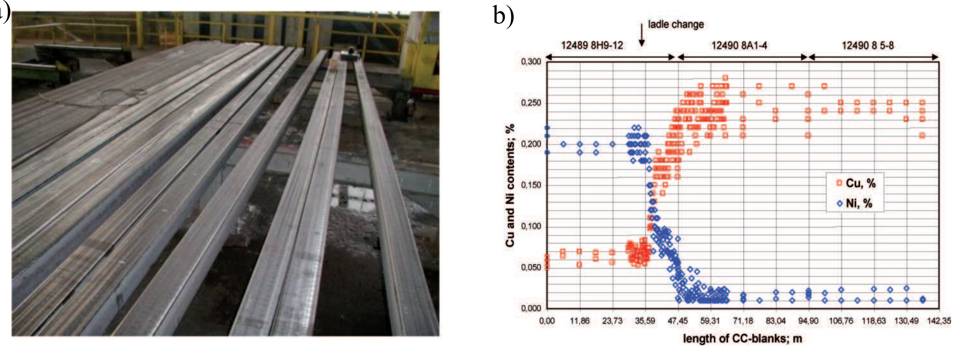

Fig. 4. a) View of a part of evaluated blanks put on a pilling grate; b) Graphic illustration of the course of variations in the content of nickel and copper in blanks of no.8 casting stream at transition from heat-no. 12489 to heat-no. 12490

the chemical composition is out of the tolerance specified for the individual steel grades cast. If the tolerances are available, it is recommended that dimensionless specifications of the chemical compositions be established for both the old and new steel grades, these taking values falling to a range stretching from 0 to 1.

$$\tilde{C}_{old,i} = \max\left\{\frac{C_{old,i} - C_{old,i,\min}}{C_{old,i} - C_{new,i}}, \frac{C_{old,i} - C_{old,i,\max}}{C_{old,i} - C_{new,i}}\right\};$$

$$\tilde{C}_{new,i} = \min\left\{\frac{C_{old,i} - C_{new,i,\min}}{C_{old,i} - C_{new,i}}, \frac{C_{old,i} - C_{new,i,\max}}{C_{old,i} - C_{new,i}}\right\}$$

where:

$\tilde{C}_{old,i}$ – dimensionless specification of element i for the old steel grade (previous heat);

$\tilde{C}_{new,i}$ – dimensionless specification of element i for the new steel grade (following heat);

$C_{old,i}\, C_{new,i}$ – real concentration of the given element i in old and new steel grades (for example heat analysis); %wt.

$C_{old,i,\min}\, C_{old,i,\max}$ – minimum and maximum permissible concentration for the given element *i* in the old steel grade; %wt.

$C_{new,i,\min}\, C_{new,i,\max}$ – minimum and maximum permissible concentration for the given element *i* in the new steel grade; %wt.

The dimensionless specifications must be calculated for all relevant elements so that it could be possible to establish the critical element displaying the highest $\tilde{C}_{new} - \tilde{C}_{old}$ variance value, thus determining the maximum possible extent of the transition zone. The transition steel and the corresponding transition zone will be localised between these $\tilde{C}_{old}$ and $\tilde{C}_{new}$ values [1].

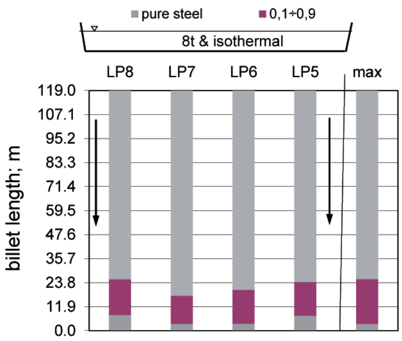

Fig. 5. The extent and the position of the intermixed zone in the steel billets cast under isothermal conditions with 8 tons weight of steel in the tundish [2]

The results obtained from numerical simulation and physical modelling are analogously processed and handled with the specific research needs. The data obtained from the modelling of the steel flow character in the tundish are obviously used for the determination of the characteristic time moments or steel weight cast in dimensionless concentration intervals of 0.1 to 0.9 or 0.3 to 0.7. The extent and the position of the intermixed zone were evaluated for the "stricter" dimensionless concentration {0.1; 0.9}. For the easier visual orientation, the deducted values of the beginnings and the ends of the intermixed zones of the individual casting strands were processed into the column graphs, as is shown in Fig. 5.

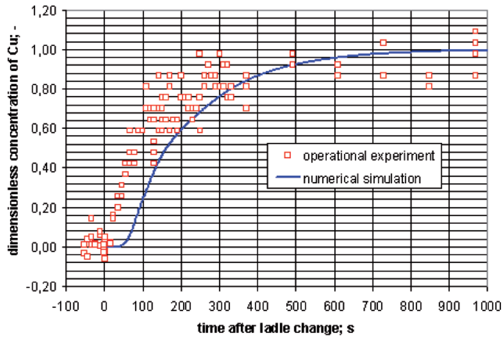

Fig. 6. Graphical comparison of operational results with those obtained from numerical simulation of transition zone origination for the CS No.6 [1]

4. Results discussion

As already mentioned above, the individual simulation variants were focused on clarifying the extent of the intermixed zone, depending on the weight of steel in the tundish during the casting ladle replacement, on non-isothermal flow of steel in the tundish and when one or two stopped casting strands. Fig. 6 shows graphical comparisons of the operational results with those obtained from numerical simulations under the conditions of constant tundish bath weight of 8 t. The particular numerical simulation variant has been chosen intentionally to reflect the monitored critical moment in the course of tundish change at the operational experiment when the real tundish weight dropped down to 7.87 t. As shown in the Fig. 6, the pattern of the transition curve obtained from the numerical simulation fairly correlates with the experimental field data, particularly in the field and beyond its point of inflection. Certain discrepancy was observed at the initial stage where the transition curve was somewhat delayed compared to the experimental data, which may presumably be related to a variation in the conditions of the first field experiment and the numerical simulation juxtaposed. In the field experiment, the tundish was, after the ladle change, refilled by applying an increased flow rate (4.5 t.min^{-1}), which resulted in achieving the nominal tundish steel weight (approx.13 t) in 3 to 4 minutes. The numerical simulation conditions were, on the contrary, reduced to the stable tundish steel weight (8 t), which corresponded to lower flow rate into the tundish, namely 1.75 t.min^{-1}. The substantially higher flow rate in the field experiment resulted in markedly enhanced tundish flow dynamics and reduced retention times, which might have in the end been reflected in more rapid concentration increment at the tundish outlets. It is rather difficult to simulate the tundish refilling process using FLUENT in this way; test trials are being undertaken in the time being.

5. Conclusion

The presented work introduced the knowledge from the modelling of the steel flow at tundishes under conditions of Department of Metallurgy on Faculty of Metallurgy and Material Engineering of VSB - Technical University of Ostrava. The numerical modelling is carried out in the CFD programme FLUENT. The physical modelling uses the water models from Plexiglas in different geometric scales. The experimental work uses the orthodox concentration or the radio-nuclide method. The main advantage of numerical modelling is the opportunity to easily change the setting of the boundary conditions. On the other hand, the result from numerical modelling is best confirmed using a different method, in this case physical modelling or plant experiment. To transfer the practicable results into a real plant system, it is also necessary to have the most accurate information about the physical properties of substances involved in the production process. The scientific and technical background of the Department of Metallurgy and Department of Physical Chemistry and Theory of Technological Processes at the Faculty of Metallurgy and Materials Engineering VSB - Technical University of Ostrava, as well as the extensive experience of applied research enabled these workplaces to participate in a major project conducted under the Regional Materials Science and Technology Centre name (RMSTC), particularly through the establishment of the workplace "Laboratory for Modelling of Processes in the Liquid and Solid Phases". Associated with the solving of the research project RMSTC, the next support of the Laboratory for Modelling of Processes in Liquid and Solid Phases will be realized. The Laboratory will use modern analytical instruments to precisely identify the specific physical properties of studied systems. These instruments will conclude the high temperature equipment for measuring of thermo physical properties STA449 F3 Jupiter from Netzsch Gerätebau GmbH, a high-temperature viscometer for metals and slag, a physical model for the modelling of metallurgical processes during the production, processing and solidification of steel, and in the last case the numerical software for the simulation of filling and solidification of steel in mould.

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