A R C H I V E S O F M E T A L L U R G Y A N D M A T E R I A L S
Volume 60 2015 Issue 4
DOI: 10.1515/amm-2015-0466

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LARGE-EDDY SIMULATIONS OF A FLOW CHARACTERISTICS IN A MULTI-STRAND CONTINUOUS CASTING TUNDISH

BADANIA NUMERYCZNE CHARAKTERYSTYK PRZEPŁYWU W WIELO-WYLEWOWEJ KADZI POSREDNIEJ METODĄ WIELKICH WIRÓW (LES)

In order to increase the efficiency and quality of the steel-making process a numerous studies are conducted at the various stages of the process, including continuous casting of steel. Researchers still search for new models and improve existing one, so that the specific of the process is accuratelly reproduced. One way to increase the accuracy of numerical simulation, is to apply the LES (Large Eddy Simulation) method to simulate steelmaking processes.

The article presents the results of numerical analysis on the flow characteristics (RTD curves) of liquid steel in the tundish facility for the continuous casting of steel. Numerical simulations have been performed using RANS (Reynolds-averaged Navier-Stoke) and LES methods, and those results have been verified in industrial conditions.

Keywords: tundish, steel flow, numerical modelling, industrial measurements, RTD curve

W celu zwiększenia efektywności i jakości procesu wytwarzania stali prowadzone są liczne badania modelowe różnych etapów tego procesu, w tym ciągłego odlewania stali. Wciąż poszukuje się nowych modeli i udoskonala dostępne, tak aby możliwie najbardziej wiernie oddać specyfikę procesu. Jednym ze sposobów na zwiększenie dokładności obliczeń numerycznych, jest zastosowanie do symulacji procesów stalowniczych metody wielkich wirów LES (Large Eddy Simulation).

W artykule, przedstawiono wyniki badań numerycznych dotyczących analizy charakterystyki przepływu (krzywe RTD) ciekłej stali w kadzi pośredniej urządzania do ciągłego odlewania stali. Do badań wykorzystano metody RANS (Reynolds-averaged Navier–Stoke) oraz LES, a wyniki zweryfikowano w warunkach przemysłowych.

1. Introduction

Continuous casting method belongs to modern steel making technologies and unchallenged, helped to increase the efficiency and quality of metallurgical steel making process and steel products.

Tundish is an important element in this process. Currently tundish became an independent metallurgical reactor, in which the final metallurgical treatments are made, just before solidification of liquid steel in the mould crystallizer. Its proper operation ensures high quality of continuous ingots. Both flow and mixing of liquid steel in the tundish are a very complex phenomena [1-4].

Qualitative and quantitative assessments of the flow and mixing of liquid steel in the tundish are carried out on the basis of a set of characteristics. The most important of these include: theoretical and actual average residence time of the steel in the tundish, Residence Time Distribution curves (RTD), and produced on the basis of these curves a volume fraction zones of different types of flows in the tundish [5]. It is known that certain elements of the steel stay for a longer time in the tundish, and others stay for a shorter time moving along different trajectories, therefore the average length of elements staying in the facility is only an approximate assessment. More reliable is a residence time distribution of steel (RTD), whose role in the investigation of mechanisms of the processes occurring in the tundish is hard to overestimate. The characteristics of this type provide valuable information about the work of tundishes and also are used to verify the experimental studies (industrial and physical) and numerical simulations [6-11].

Results presented in the article are continuation of the research results presented in [12], on the choice of turbulence model used in the numerical calculations. In those studies to describe the turbulence behavior, RANS (Reynolds-averaged Navier-Stokes) and LES (Large Eddy Simulation) models have been used.

The results of simulation were verified with experimental data, by comparing the RTD curves (F type) obtained by numerical modeling and industrial experiment.

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2. Description of the problem

The investigated object is a six-strand continuous casting tundish of a channel-shaped type, equipped with two overflow partitions. The tundish is symmetrical relative to the transverse plane. In its base configuration the tundish is equipped with a pair of dams. It feeds simultaneously six moulds for the production of billets with a cross section of 280 x 300 mm.

The shape of the tundish together with its basic dimensions are shown in Fig. 1. Table 1 shows the technological operating conditions of the tundish, used also in numerical simulations.

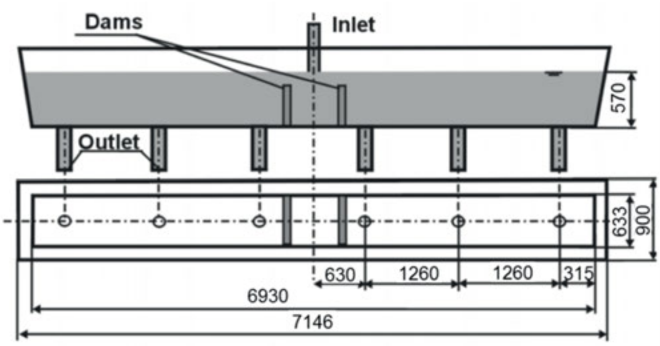

Fig. 1. Characteristic dimensions of the investigated tundish [12]

TABLE 1
Dimensions of the 34 t continuous casting tundish.

Parameters	Value	Units
Nominal capacity	34	ton
Molten steel level	570	mm
Shroud diameter	86	mm
SENs diameter	36	mm
Number of tundish nozzles	6	-
Casting speed	0.7	m/min
Dam height	300	mm
Dam width	100	mm

Numerical results presented in [12], performed with two different turbulence methods – RANS and LES – have shown the differences for both investigated phenomena: flow field and temperature distribution. It has been shown that LES method indicate more particularly the fluid movement in regions of the tundish which are characterized with higher difference of the calculated variables.

Based on that, further CFD simulations were performed in order to obtain the RTD F-type curves for investigated test object. The results of simulation were verified with experimental data.

The verified mathematical model (for which the turbulence is described in a sense of LES method) in the next stage of research will be used to analyze the separation of non-metallic particles, and ultimately to optimize the tundish process conditions in terms of increasing purity of ingots.

3. Experimental work – industrial measurements

The experimental measurements were carried out under the plant production conditions and consisted in taking of metal samples from the billets at specified time intervals. Steel grade chosen for investigation differs in Mn concentration. The steel grades chemical composition is given in Table 2.

TABLE 2
Chemical composition of the steel grades

Steel grade	C	Mn	Si	P	S	Al
S275JR	0.18	0.52	0.21	0.014	0.024	0.006
SE03	0.13	0.81	0.15	0.12	0.016	0.006

The study aimed to develop the F curve, which identifies the transitional zone during sequential casting of different steel grades in the tundish. As a tracer, for measuring a variation in the transitional zone, the concentration of manganese is monitored. This is due to the fact that the cast casted steel grades vary significantly in the content of this element.

Spectrotest analyzer of chemical composition of steel has been used to analyze the change of content of manganese in cast billets (during the transition zone). Measurements have been performed for probes taken from continuously cast ingots (billets 280x300 mm) cast on the three different strands (number 1, 2 and 3).

4. Numerical modeling procedures

The detailed describion of the model used in numerical simulations can be found in the work [12]. First, computations were carried out for steady state (stable production) casting conditions. This resulted in the spatial distributions of temperature and velocity fields of liquid steel inside the tundish.

After that simulations have been performed for calculating the RTD characteristics. Residence Time Distribution is a statistical representation of time spent by an arbitrary volume of the fluid in the tundish. It is obtained by changing the conditions at the inlet and measuring the system response at the outlet as a function of time. To develop the tracer concentration characteristic in a bath a scalar model is used. The inlet boundary condition was set with concentration equal 1 (C=1) during whole simulation time. Model solves the following equation for the time evolution of the species mass fraction C, giving the steady flow velocities calculated previously from the turbulence model [13,14]:

$$\frac{\partial(\rho_c C)}{\partial t} + \frac{\partial(\rho_c u_i C)}{\partial x_i} = \frac{\partial}{\partial x_i}\left(\rho_c D_{eff} \frac{\partial C}{\partial x_i}\right) \qquad (1)$$

The turbulent diffusion coefficient is determined from the following relationship (assuming that the turbulent Schmidt number equals unity).

$$\frac{\rho D_{eff}}{\mu_{eff}} \cong 1 \qquad (2)$$

where:

D_{eff} - effective diffusion coefficient ($D_{eff} = D_m + D_t$),
D_m - molecular diffusion coefficient,
D_t - turbulent diffusion coefficient,
g_i - gravitational acceleration,
C_i - concentration of the tracer,
u_i - velocity components,
ρ - specific density,
μ_{eff} - effective coefficient of viscosity,
T - time.

To solve the differential equation system, it is necessary to assume suitable initial and boundary conditions, corresponding to the industrial process conditions. The boundary conditions used in computations are shown in Figure 2.

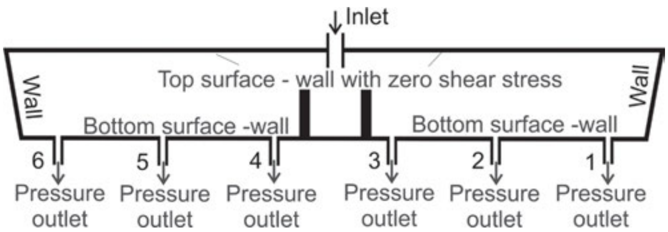

Fig.2. Boundary conditions set for numerical simulations

5. Residence Time Distribution (RTD) analysis

RTD curves contain cumulated information about the hydrodynamic conditions of steel flow through the tundish. They allow to estimate the quality of the object taking into account the mixing of steel and possibility of intensification of the refining processes. According to the theory of flows in the open reactors, the proper characteristics for the estimation of the flow through the tundish are curves E and F-type [5,15].

F-type curves are the source of information about the kinetics of mixing steel in the tundish. They can be obtained by means of determining the time constant τ and T_0 (Fig. 3).

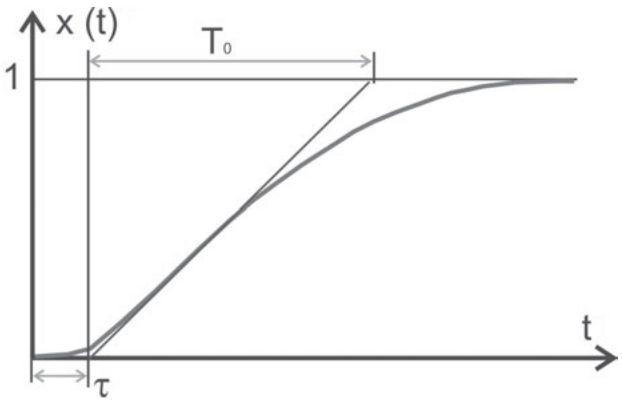

Fig. 3. Typical step response of the inertial system with the delay – it characterizes the steel mixing in the tundish

The time constant τ determines the time after which the marker achieves the tundish outlet. So, this constant allows to evaluate the size of the intensive mixing zone. The time constant T_0 is used to characterize the system inertia that means the intensity of steel mixing in tundish. Basing on this constant the time after which the marker reaches the needed concentration can be determined.

The results obtained with numerical model were confronted with data from experiment done on the industrial plant. The F-curves give information about the tracer concentration changes at individual strand. The results let to verify numerical model and answer if it properly describe the nature of the phenomena occurring in the real facility. To validate the model, collected experimental data were compared as mixing characteristics. To perform the direct comparison of the results, transformation of Mn concentration in steel to the concentration of a tracer in a model has been made. The tracer element concentration was converted into dimensionless characteristics using the following relationship:

$$C_b = \left(C_t - C_o\right) / \left(C_\infty - C_o\right) \qquad (3)$$

where:

C_b - dimensionless concentration,
C_o - initial concentration of the tracer,
C_t - tracer concentration at time t,
C_μ - final concentration of the tracer.

The results of dimensionless manganese concentration changes in investigated steel grades at specific SEN, for experimental measurements and numerical simulations, are shown in Fig. 4.

Based on the results comparison shown in Fig. 4, one can see good agreement between numerical calculations and experimental data. For the studied variants a slight difference can be observed between the measured and calculated data. These differences are seen as a curves shift. However, the rate of concentration rise is highly compatible. The discrepancies between experimental data and results of numerical simulations may come both from a mathematical model simplifications and measurement errors.

Curves presenting RANS results are smooth, which is an effect of description of the flow field by this method. This is not the case for LES results. The best fit between measurements and calculations is found for SEN's No. 3 and 4 which are the closest to the shroud. For this tundish outlets a high oscillations in tracer concentration is also observed for LES method. The reason for that could be higher – than in the other nozzles area – level of turbulence.

Presented characteristics give also a qualitative idea about the influence of hydrodynamic conditions occurring in the tundish on the kinetics of mixing in the liquid steel. A different time (τ) has been found at which the tracer reached different SEN's, which affects the quality of continuously cast ingots. Considering the rate of rise curves one may also see the significant differences for individual outlet. This fact indicates that the tundish does not work properly with sequential casting of steel.

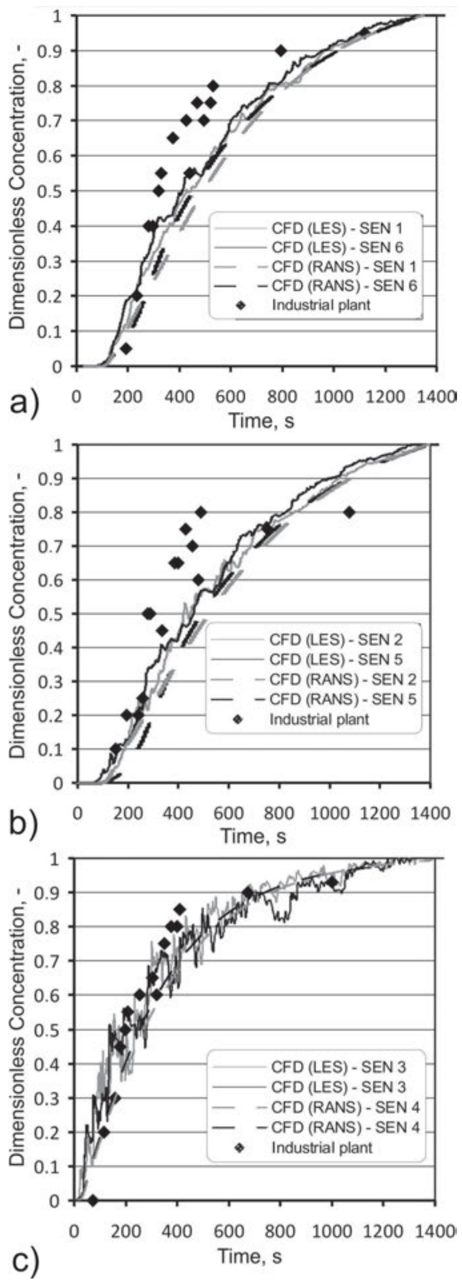

Fig. 4. Dimensionless tracer (Mn) concentration distribution in steel for CFD (RANS and LES) simulation and experimental data for: a) SEN's 1 and 6, b) SEN's 2 and 5, c) SEN's 3 and 4

6. Summary

During numerical modeling, the choice of an appropriate model to solve the turbulence has a huge impact on the representation of the fluid flow structure in the analyzed test facilities. So far, the overwhelming number of numerical simulations (analysis of the liquid steel flow in tundishes) was carried out using RANS method (Reynolds-averaged Navier-Stokes equations). However, the rapid development of numerical methods and computational units allow to carry out numerical simulation of the flows in metallurgical aggregates with the use of LES method.

Presented results of numerical simulations with the use of LES and RANS methods show high qualitative agreement between experimental data and numerical calculations. Obtained numerical values are very similar (for both compiled methods), but, according to a review of the available literature, the use of LES method should give a better approximation of the trajectory of non-metallic inclusions and thus to improve the analysis of the distribution and separation of inclusions in the test object.

It should be noted that the use of LES method and hence increase the accuracy of the turbulent flow description requires large computational power and long computational time.

Acknowledgements

Acknowledgements to the National Centre for Research and Development for financial support (project No PBS2/A5/32/2013). This research was also supported in part by PL-Grid Infrastructure.

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Received: 20 October 2014.