The Analysis of the Conditions of Flow in the Tundish Performed by a Numerical and Physical Method

T. Merder[1], J. Jowsa[2], A. M. Hutny[2], J. Pieprzyca[1], M. Warzecha[2]
[1]Silesian University of Technology, Institute of Metals Technology, Krasinskiego 8, 40-019 Katowice, Poland, [2] Czestochowa University of Technology, Department of Metals Extraction and Recirculation, Al. Armii Krajowej 19, 42-201 Czestochowa, Poland
*Corresponding author: tomaszmerder@polsl.pl

Abstract: Studies of the liquid metal movement (hydrodynamic) in a real object (tundish) are substantially precluded due to the objective difficulties (high temperature and the size of metallurgical equipment), compared to their execution by the use of physical and numerical modeling. In presented study, two test methods for analyzing the flow and mixing of the liquid steel in the tundish were used. The calculation of fluid flow through the tundish was carried out using the COMSOL Multiphysics program.

Conducted experimental measurements and numerical calculations enable to estimate the steel flow field. The research was implemented by the RTD characteristics. Basing on such characteristics the percentage participation of dead volume flow, dispersed plug volume flow and well-mixed volume flow was calculated.

Obtained results enable to evaluate in details the working conditions of the investigated object.

Keywords: numerical modeling, physical modeling, tundish, RTD characteristics.

1. Introduction

Following the Electric Furnace and Secondary Metallurgy units, the implementation of a modern CC machine ensures a compact and effective steel production process. However the increasing demands for higher metallurgical quality standards involve new technological solutions, in particularly to eliminate previous imperfection of the continuous casting process. Among these solutions, the tundish has ability to play a great role as an active metallurgical reactor. That is why we need a better knowledge about the physical chemistry processes which are occurring in the tundish.

There exist various construction types of the tundish, following the metallurgical demands and assumed level and grades of production [1-5]. Given priorities decide not only about the tundish construction type but also about other issues like the nominal tundish capacity, the number and sections of moulds, the casting time, the length of casting sequence, etc… To compare various construction types at the same capacity, a good knowledge of the “working zone” of the tundish is necessary, which needs a good knowledge of the hydrodynamics of the liquid steel flow.

The working zone of the tundish is characterized by the following constructive parameters: shape, dimensions, capacity. The equipment of the working zone with flow control devices (FCD) is also very important. Such devices like baffles, dams, notches [4,6] or turbulence inhibitors [1,3,7] are used. Their role is to give appropriate direction to the liquid steel flow in the tundish.

Analysis of the flow and mixing way of liquid steel in the tundish in industrial conditions is very difficult, and the observation of the phenomena of interest – impossible. A very good solution to this problem is to use the modelling techniques.

This article deals with such an issue. The research was carried out by means of hybrid modelling in which results of numerical simulations were complemented by the physical modelling. Simultaneously such method allows to verify the obtained results according to the rule which says about the truth of the convergent results of research obtained by different methods.

2. Description of the plant and the conditions of numerical computations

Two-strand tundish with a nominal capacity of 60 t was studied. The tundish is symmetrical with respect to the central cross-section (through the steel pouring gate axis). A scheme of the tundish is shown in Figure 1, while the dimensions of the commercial tundish and its model at the scale of 1:4 are given in Table 1.

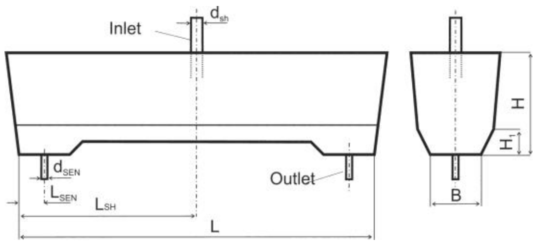

Figure 1. Scheme of the tundish shape and its size.

Table 1: Dimensions of the 60-t tundish and the water model (at the 1:4 scale)

	Symbol	Unit	Tundish	
			Scale 1:1	Water model scale 1:4
Volume of tundish at filling level H	V	m^3	8.55	0.13
Tundish length	L	m	7.600	1.900
SEN position	L_{SEN}	m	0.400	0.100
Shroud position	L_{SH}	m	3.800	0.950
Tundish width	B	m	0.720	0.180
Filling level	H	m	1.200	0.300
	H_1	m	0.440	0.110
Shroud diameter	d_{SH}	m	0.110	0.030
SEN diameter	d_{SEN}	m	0.040	0.010

The simulation of the liquid steel flow in the tundish during the continuous casting process is a complex hydrodynamic problem. An appropriate mathematical model (describing this process) should take into account several characteristics of such flows.

Half of the tundish was chosen for the mathematical analysis. The 3-D domain of this tundish is divided into 160000 cells, making a finer mesh in the zone of the incoming and outgoing liquid jet in order to visualize in more details the effects of velocity, turbulence gradients. The geometry of the object (tundish) was imported to the COMSOL program in the form of IGS file.

The walls are considered with no slip condition for the fluid flow. The upper surface is assumed as a free surface with zero shear stresses. The standard wall function is used to calculate the value of a node near a solid wall.

The inlet nozzle has velocity inlet boundary condition with 1.15 m/s water flow rate. At inlet nozzle the mean vertical velocity is assumed to be uniform through its cross section and other two perpendicular velocities are assumed to be zero. Turbulence intensity at inlet is specified as 5%. At the outlet boundary condition “Pressure” was fixed as 0 Pa.

„Turbulent Flow, k-ε” model was choosen to calculate flow of incompressible medium (water) at the room temperature (ρ = 998 kg/m^3, μ = 0.001Pa·s)

The set of partial differential equations is solved with the help of the above boundary conditions numerically in a finite volume technique using the education version of the CFD software COMSOL Multiphysics.

Two-stages numerical procedure „Segregated” was used to solve the equations. In the first stage (Segregated Step 1) the equations of „Velocity Field and Pressure” were solved, whereas in the second stage (Segregated Step 2) the equations of ”Turbulent Kinetic Energy and Turbulent Dissipation Rate”.

Calculations „Study 1” were conducted in the transient state „Time Dependent Procedure” till reaching the process time t=360 s.

Velocity fields at steady state were first calculated and later they were employed to solve the mass transfer equation „Study 2”. Thus, the model “Transport of Diluted Species” was applied in conditions „Time Dependent”. Calculations were carrie out through 2000s assuming: „Initial values concentration” c_0 = 0 mol/m^3, diffusion coefficient = D_c =1e-9 m^2/s. At the „Inflow” the following conditions were fixed depending on the curves type:

- for F curve, c =1mol/m^3 (is injected through inflow for the during whole measurement time),
- for E curve, $c=c_e \cdot \exp[-(t-3)^2]$, where c_e= 1mol/m^3, t – time in s.

In calculations „Study 2” equations of „Turbulent Flow, k-ε” model were not solved, whereas the „values of variables not solved” were taken from „Study 1” for time t=360s.

A criterion for convergence was set to be less than 10^{-6} on all variables and computations were carried out until the relative sum of residuals on all variables all fell bellow the fixed value. For the Transport of Diluted Species model, the solution was considered converged when the residual for concentration species was below $1 \cdot 10^{-6}$.

Fig. 2 shows the view of object assumed to calculations and the calculation mesh.

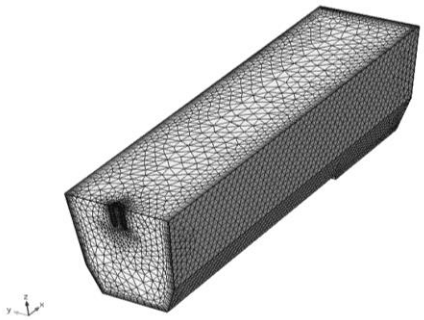

Figure 2. Computational mesh set at walls of the tundish.

3. Physical Modeling

Studies were carried out on the physical model of the CSC plant. It is a segmented water model and was constructed according to the conditions of the theory of similarity. Figure 3 shows the test stand.

Figure 3. The test stand of CSC plant water model.

In the studies of hydrodynamic and isothermal flows in the CSC plant it is not necessary to take into account the thermal and chemical effects, and therefore the similarity of the model to the actual facility is achieved through the geometrical, dynamic and kinetic similarity. In order to meet the above conditions, methods described in the theory of similarity were employed in designing the physical model. For the dimensional analysis of steel flow and its mixing, the Navier-Stokes and stream continuity equations were used. On their basis and also considering the Buckingham equation, similarity criteria in the form of criterial numbers were determined.

Physical model of CC machine was equipped with the model of tundish made from plexiglas at the scale 1:4. The flow rate of water in the model was $5.2\cdot10^{-4}$ $m^3\cdot s^{-1}$, which corresponds to casting rate equal 1.3 $m\cdot min^{-1}$.

Using physical model the research was carried out considering the distribution of tracer concentration. Such research was based on working out characteristics of RTD (E and F types). Water solution of NaCl was used as a tracer in the model.

To identify F-type curve, the method of step input function (Heaviside) on the inlet was applied. When the assumed level of water in the tundish water model was reached and the flow was stabilized according to working out conditions of similarity, the tank with clear water was closed and then the tank with a tracer (water solution of NaCl) was opened. The tracer was introduced in such a way during the whole time of measurement.

To identify E-type curve, a method of impulse input function (Dirac) on the outlet was applied. When the assumed level of water in the tundish water model was reached and the flow was stabilized according to working out conditions of similarity, the tracer (water solution NaCl) was introduced to the system on a one-off basis in the amount of $1.0\cdot10^{-4}$ m^3.

In both cases using conductometers the change of tracer concentration (NaCl) was registered continuously, right behind the outlets from the tundish model.

4. Results and Discussion

4.1 Tracer concentrations

The forecasted variations in the dimensionless tracer concentrations is shown in Figure 4. Four variants (after 100, 300, 500 and 800 seconds) are presented.

It can be seen in Figure 4 that the tracers moves in the steel primarily due to the forced convection resulting from the flow in the plant under examination. Tracer in the tundish is gone up at the bottom of the tundish. That means that the main stream of fluid goes directly to the outlet nozzle without having any interaction with the rest of the fluid in the tundish.

The characteristics of tracer distribution give the knowledge abort the transient zone during the sequence casting of different grades of steel. However, they do not replace information necessary for the multidimensional estimation of tundishes. For such aim quantitative characteristics like RTD curves F type are used.

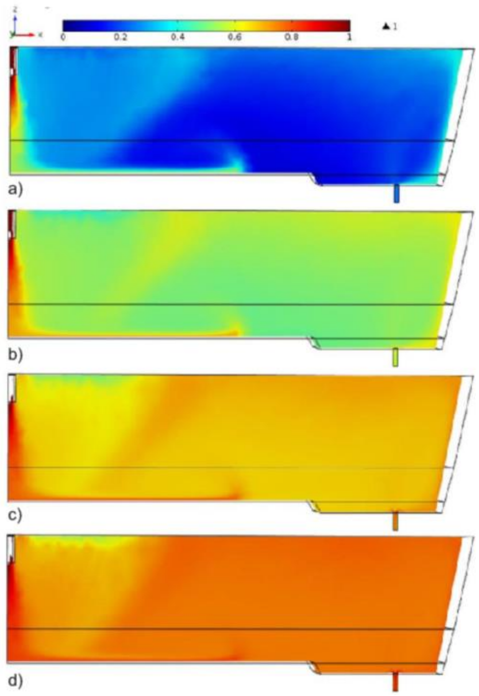

Figure 4. Isoconcentration lines of the tracer at – a) 100 s, b) 300s, c) 500s, d) 800s.

4.2 RTD characteristics

Obtained experimental data were confronted with the results coming from numerical simulations performed in the identical conditions.

To compare results from numerical simulations with experimental results tracer concentration was transformed into dimensionless characteristics. Therefore the appropriate calculations described in [4] were used.

To define the dimensionless tracer concentration for F-type curve such an equation can be used:

$$C_b = (C_t - C_0)/(C_\infty - C_0) \quad (1)$$

whereas to define this concentration for E-type curve the equation in the following form:

$$\mathrm{C_b = C_t/C_{av}} \quad (2)$$

where mean tracer concentration in conditions of ideal mixing is given in the form:

$$\mathrm{C_{av} = m_{tr}/V \cdot \rho} \quad (3)$$

where: m_{tr} - mass of the tracer, C_t – tracer concentration at time t, C_{av} – average concentration of the tracer in case of ideal mixing, C_∞ – end concentration of the tracer, C_o – starting concentration of the tracer.

Figure 5 shows mixing curve (F –type) for the tundish outlet (CFD and physical model).

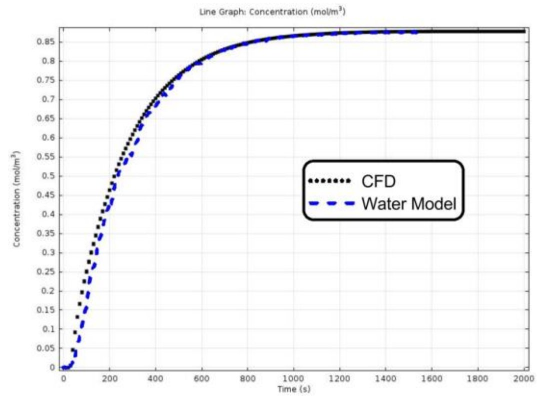

Figure 5. Mixing time characteristics from water model and CFD calculations.

Basing on the comparison presented on the Figure 5 it can be claimed that there is good qualitative compatibility of water model results with the numerical ones. For the analyzed variants the slight difference between the experimental and calculated data is observed. Such differences can be seen as a transfer of curves. The rate of concentration growing is, however, in good agreement.

The presented characteristic is used for evaluation of the steel mixing conditions in the tundish. On its basis, the transient zone can be evaluated. This is done by defining the range as determined from the differences of the times necessary for obtaining concentrations at the assumed levels (the dimensionless concentration range) of the concentration forecast for a given steel grade. Transient zone ranges at a dimensionless concentration level of 0.2÷0.8 were considered. The values of transient zone range for respective outlet are given in Table 2.

Table 2: Kinetics of steel mixing in the range of 0.2 to 0.8 of the maximum concentration.

Parametr	The transient zone [s]	
	CFD	Water model
0.2÷0.8	521.5	505.5

Divergences (Table 2) in obtained experimental and numerical results can be the result of simplifications of the mathematical model and the measuring error.

Numerical simulation of flows was done in order to draw E-type curves. The following boundary condition for the inlet was applied: the impulse change of the tracer concentration (Dirac impulse). The changes of tracer concentration during the casting process were registered at the outlets of the tundish.

Figure 6 presents non-dimensional residence time characteristics (the E-type curve) for the tundish under examination. It can be seen agreement between results from physical research (water model) with CFD calculations.

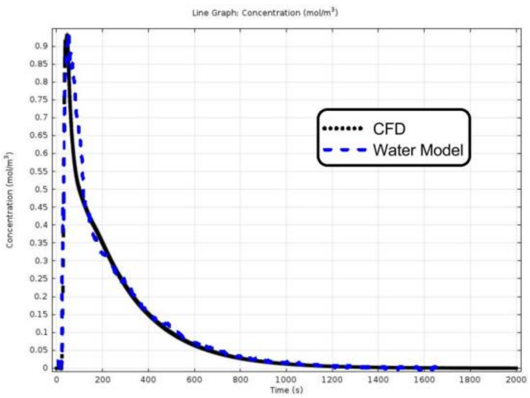

Figure 6. Residence time distribution characteristics (E-type) for the tundish.

Short minimum residence times and low peak concentrations are observed. That suggests that in the studied tundish the considerable participation of well-mixed flow is, whereas the small participation of plug flow.

When the evaluation of the flow character in the industrial tundish is done (especially their usability in the refining process) the relation to the ideal reactors is made, that means reactor with only one kind of flow. Such evaluation is mainly qualitative, however it allows to obtain very quickly information about the hydrodynamic condition occurring in the examined object.

5. Conclusions

Applying the CFD techniques and physical modeling to modeling the flow of steel in tundish is effective way of replacing the expensive and difficult industrial experimental research that are used to diagnose the work of the tundish and to optimize its construction.

The carried out research gave important information about the working condition of industrial tundish. The analysis of obtained results showed that in the examined tundish are unfavorable phenomena taking into account the mixing and the steel flow. They are caused by the characteristic channel geometry of the working zone of the tundish.

Obtained results shows that there is necessity to modify the interior of the tundish (equipping with the devices of controlling the flow) to reduce the range of transient zone. Such modernization should be preceded by the series of modeling research both numerical and physical.

6. References

1. R.D. Morales, M. Diaz, J. Palafox-Ramos, S. Lopez-Ramirez, J.J Barreto, Modelling steel flow in a three-strand tundish using turbulence inhibitor, *Steel Research Int.*, **72**, 11-15 (2001)
2. R. Schwarze, F. Obermeier, J.Hantusch, A. Franke, D. Janke, Mathematical modeling of flows and discrete phase behavior in a V-shaped tundish, *Steel Research Int.*, **72**, 215-220 (2001)
3. T. Merder, J. Pieprzyca, Optimization of two-strand industrial tundish work with use of turbulence inhibitors: Numerical Modelling, *Steel Research Int.*, **83**, 1029-1038 (2012)
4. T. Merder, M. Warzecha**,** Optimization of a six strand CC tundish: industrial measurements and numerical investigation of the tundish modifications, *Metallurgical and Materials Transactions B*, **43**, 856-868 (2012)
5. M. Warzecha, T. Merder, P. Warzecha: CFD modelling of non-metallic inclusions removal process in the T-type tundish, *J. Achiev. Mater. Manuf. Eng.*, **55,** 590-595 (2012)
6. Q. Yuan, B. Zhao, S.P. Vanka, B.G. Thomas, Study of computational issues in simulation of transient flow in continuous casting, *Steel Research Int.*, **76**, 33-43 (2005)
7. A. Cwudzinski, Simulation of the liquid steel alloying process in a one-strand tundish with different addition positions and flow control devices, *Metallurgical Research & Technology*, **112**, 308-315 (2015)

7. Acknowledgements

The scientific work was funded by NCN, project No 2013/09/B/ST8/00143.