OPTIMIZING OF STEEL FLOW IN THREE-STRAND T-TYPE TUNDISH USING MATHEMATICAL AND PHYSICAL MODELS

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https://doi.org/10.37904/metal.2022.4389

Abstract

The presented research was focused on optimizing the internal equipment of the tundish with respect to residence times between the middle (No. 2) and two lateral casting strands (No. 1 and 3). The different values of residence times of individual strands affect the cleanliness of steel and cause thermal and chemical inhomogeneities. The specific flow given by the shape of the three-strand symmetrical T-type tundish causes the middle casting strand to have a relatively short residence time compared to lateral strands. For this reason, the flow in the tundish was controlled by changing the angle of outlet holes in tundish baffle separating the inlet part of the tundish from its working volume. The research was carried out using computer simulations supported by the results from the SimConT physical model.

Keywords: Tundish, residence time, physical model, CFD simulation, C-curve

1. INTRODUCTION

The tundish residence time, represented by RTD curves, has a significant effect on the cast steel cleanliness [2]. The tundish, including internal furniture, should ensure the thermal and chemical homogeneity of the cast steel for all casting strands. The residence time of the individual strands should also be approximately the same to ensure sufficient time for lower density inclusions to float out. This problem relates in particular to tundishes with an asymmetrically arranged inlet part with respect to individual casting strands. The presented research was performed for a three-strand T-shaped tundish (**Figure 1**) using CFD simulations in Ansys Fluent software along with results from the SimConT physical model [1].

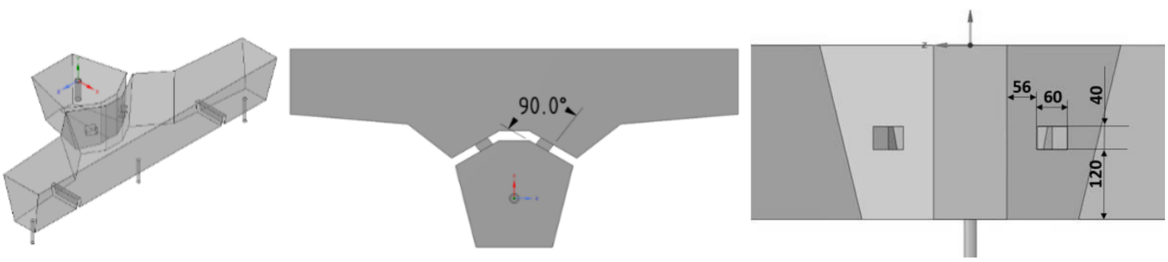

Figure 1 T-shaped three-strand tundish and location of standard 90° outlet holes in the tundish baffle

Based on the C-curve for the standard tundish configuration, it follows that the middle casting strand (No.2) has the shortest residence time. The aim of the research was to achieve approximately the same residence time for all casting strands by deflecting the outlet holes in the tundish baffle, whose standard position is 90° (**Figure 1**).

The implementation of physical simulations on the SimConT model depends on the production of precise model components using 3D printing or CNC technology. For this reason, CFD simulations were performed first [3]. The aim of the CFD simulation was to find the optimal angle of deflection of the outlet holes in tundish baffle. Subsequently, the most suitable configurations from CFD simulations were also simulated on the SimConT physical model.

2. MATHEMATICAL MODELS

Turbulence is caused by the flow around the walls with a viscous fluid and sudden speed differences. This type of flow is composed of large and small vortexes. Big vortexes have energy and break down into smaller vortexes. This process ends with the variance of energy to the heat of the smallest vortexes. The length quantity l [m] and the velocity quantity u [$m.s^{-1}$] characterize turbulent vortexes.

Most of the problems solved in practice have turbulent flow, so that's why a turbulent model is needed.

The time averaging of turbulent quantities (RANS) method is the most widely used method in practice. This method solves the time averaging of the flow values of all sizes of turbulent vortexes. Based on that, the computational requirements are reduced, and the results are sufficiently accurate. This method uses Navier-Stokes equations, averaged according to Reynolds, in which the turbulence model is replaced by velocity fluctuation correlation. By adding additional transport equations, it is possible to simplify the problem, based on different RANS models. Using the Boussinesque hypothesis, turbulent viscosity is introduced for RANS type models $k{-}\varepsilon$, $k{-}\omega$. The use of the RANS method is conditioned by verification with experiments [4], [5].

The assumption of the Boussinesque hypothesis is that the shear stress tensor can be replaced by Newton's relation (1). An example of this relation for simplified two-dimensional flow is expressed by the equation

$$\tau = \eta \frac{du}{dy} \tag{1}$$

where τ - shear stress (Pa)

η - dynamic viscosity ($Pa.s^{-1}$)

u - velocity ($m.s^{-1}$)

Investigated models

One of the most used turbulence models is the K-ε model, which uses two special transport equations representing the turbulent properties of the flow. The first transport quantity is the kinetic energy of turbulence - k, which determines the energy of turbulence. The second is the turbulence variance - ε, which determines the extent of turbulence.

Using the standard K-ε model, the flow is assumed to be fully turbulent, and the effect of molecular viscosity is negligible. This model is used at high Reynolds numbers. The disadvantage of using the model is under conditions such as large strand curves, vortexes, rotations, strand breaks and low Reynolds numbers.

Turbulent viscosity is calculated from the relationship (2):

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \tag{2}$$

where C_μ - model constant

k - kinetic energy of turbulence ($m^2.s^{-2}$)

ε - kinetic energy variance ($m^2.s^{-3}$)

The RNG k-ε model (Renormalization group method - RNG) is actually an extension of the standard k-ε model in that it includes the effects of vortexes on turbulence and thus has a wider use in different types of flow.

The latest model is the Realizable $k{-}\varepsilon$ model. Compared to the standard model, it contains two important changes like a different formulation of turbulent viscosity and a modified transport equation for ε. The Realizable model, like the RNG, also brings flow enhancements with large strand curves, vortexes, and rotations.

C_μ is not a constant in this model, but is calculated from the relation (3)

$$C_\mu = \frac{1}{A_0 + A_s \frac{kU^*}{\varepsilon}} \tag{3}$$

where $U^* = \sqrt{S_{ij}S_{ij} + \widetilde{\Omega_{ij}}\widetilde{\Omega_{ij}}}$; $\widetilde{\Omega_{ij}} = \Omega_{ij} - 2\varepsilon_{ijk}\omega_k$; $\Omega_{ij} = \overline{\Omega_{ij}} - \varepsilon_{ijk}\omega_k$

$S_{ij} = \frac{1}{2}\left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j}\right)$ - strain rate tensor (s^{-1})

$A_0 -$ value constant 4,04

A_s - constant

where $\overline{\Omega_{ij}}$ - the mean value of the vortex tensor (s^{-1}) displayed in a moving speed reference system ω_k

$\Omega_{ij} -$ vortex tensor (s^{-1})

$\varepsilon_{ijk}\omega_k$ - non-physical turbulent viscosity

The model k-ω belongs to two-equation models as well as the model k-ε. Both solve two additional differential equations. We know two types for this model, namely Standard and SST (Shear Stress Transport).

The Standard K-ω model better predicts negative pressure drop, boundary layers and tear flows. This model is unsuitable for free flows. In the area of the walls, k-ω is very accurate, but away from the walls, its accuracy decreases. [7]

Empirical model K-ω Standard solves the transport equations of the kinetic energy of turbulence *k* and the specific energy variance *ω ~ ε/k*.

Turbulent viscosity is calculated according to the relationship (4)

$$\mu_t = \alpha^* \frac{\rho k}{\omega} \tag{4}$$

where α^* - the coefficient reduces the intensity of the turbulent viscosity

The k-ω SST model combines robustness and accuracy near the wall with the k-ε model, which is suitable further away from the walls. This model is more advantageous for several types of flow than Standard k-ω.

Turbulent viscosity is calculated according to the relationship (5)

$$\mu_t = \frac{\rho k}{\omega} \frac{1}{max\left[\frac{1}{\alpha^*}, \frac{SF_2}{\alpha_1 \omega}\right]} \tag{5}$$

where S - user-specified source members

a - inverse effective Prandtl numbers

F - internal volume force ($N.m^{-3}$) [7]

The most represented results of c-curves and values of min. a max. residence times for a T-shaped three-strand tundish were obtained using a two-equation turbulent Realizable $k-\varepsilon$ model.

3. PHYSICAL MODEL

The SimConT laboratory is a part of the Laboratory for Simulation of Flow Processes (LSPP) at the Faculty of Materials, Metallurgy and Recycling, TU of Košice. [1] The SimConT laboratory has been designed to utilize the long-term experience of faculty members and scientists according to the following requirements:

- Simatic®-based, fully automatic regulation of the water level and all volumetric flow rates in the tundish.
- Easy access to the tundish equipment to facilitate service and maintenance, and future upgrades.
- Flow measurement in steady state (C-curves).
- Flow measurement in transient conditions (F-curves).
- Flow measurement in non-standard, limiting states (e.g., one- or two-strand casting, low steel level with vortex formation, shroud deviation - misalignment and others).
- Evaluation of flow patterns using colorimetric and conductivity methods.

C-curves measurement method was selected to compare the influence of angle in outlet holes in tundish baffle on steel flow in a tundish. A C-curve is one of the most important tundish parameters in terms of steel flow quality. It describes the residence time for any given tundish configuration. The residence time is the overall time of a steel particle “spends” in the tundish or, more technically, the time between entering the tundish via the ladle shroud and leaving it via one of the exit ports (submerged entry nozzles), C-curves are measured in steady state, i.e., with constant water level in the tundish (input flow rate = output flow rate). [8-12]

During the measurements it was empirically found that the optimal quantity of tracer in terms of the working range of conductivity probes is 150 ml. In general, three measurements are performed for each set of tundish configurations and casting conditions.

4. RESULTS AND EXPERIMENTS

Defining CFD simulation conditions

The computational network was created with a tetrahedral core and a prismatic boundary layer. With this type of computer network, the best controlled quality was achieved based on the SKEWNESS and ORTHOGONAL algorithms. The mathematical model of the tundish was modeled as a non-stationary process, for the possibility of analysis of C-curves. The non-stationary model shows the state of the system in individual time periods corresponding to the set time step. The time step was 0.1 s.

The boundary conditions of the model were defined on the basis of the analysis of the physical water model SimConT on a scale of 1: 2. (Boundary conditions are physical quantities defined at the boundaries of the computational area, which express the physical nature of the modeled process).

The main boundary condition on the inlet side was the mass flow of water into the water model, which was set as a constant (the value did not change over time). Tracer injection into the model was defined through a time-dependent function that was included in the water mass flow. The injection time was 6 seconds in an amount of 150 ml. On the output side of the model, the boundary condition Outflow was set, which redistributes the mass flow to several places as the water model has 3 outputs. The walls of the model were defined by the boundary condition Wall, which presents the fixed walls of the computational domain.

As mentioned above, the simulations were performed using Navier-Stokes equations, averaged according to Reynolds, in which it is necessary to replace the correlations of velocity fluctuations with a turbulence model. Specifically, the Realizable k-model was used. For time-dependent tasks, URANS (Unsteady-RANS) methods are used, which assume a time scale many times smaller. These models are able to capture instabilities, such as vortex release, but are not able to capture turbulent instabilities. They solve the calculation by a sequence of stationary phenomena.

Parameters entered in the solver:

- Non-stationary calculation
- The effect of gravity in the z-axis is considered = - 9.81 m.s^{-2}
- Model - Realizable k - ε
- Material - water
- Boundary conditions - inlet as Mass Flow Rate
- Solution method - (Simple), Initialization - (from all zones)
- Shear friction on the walls - not considered
- Number of iterations - 50 with a time step of 600 per 1 second

Optimization of the tundish furniture

The aim of optimizing of the tundish furniture by changing the angles of the holes in the tundish baffle is to minimize the differences in residence time between 2nd (middle), 1st and 3rd (lateral) casting strands while respecting the requirement to eliminate excessive wear of tundish working lining at the slag line area caused by dynamic steel flow in the inlet section [13,14,15]. All the simulations above are compared with the standard (currently used) configuration of the tundish - marked as the standard configuration 0 °. To better understand the effect of the deflection of the holes in the tundish baffle, the velocity profile of the flow in the selected virtual line was monitored. The beginning of the line was from the wall of the tundish and at the height of the axis of the hole in the tundish baffle (**Figure 2**). The line was 140 mm from the bottom, the length of the line is 750 mm and the distance from the holes is 110 mm. The line runs from the wall to the opposite front wall.

It was found that the velocity profile when the holes are deflected by 8 ° has a flat course, without a significant maximum. Deflection of holes from the perpendicular axis, causes that there is a higher flow velocity on the line, based on which it is possible to predict that the inflowing steel will reach the lateral outlets of the tundish a little earlier, so it is expected that the residence time for casting strand No.2 will be extended (**Figure 3**).

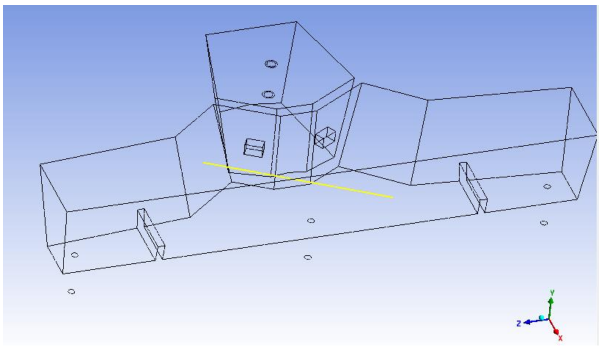

Figure 2 Geometry of the tundish with a standard impact plate with a marked virtual line on which the flow velocity was monitored

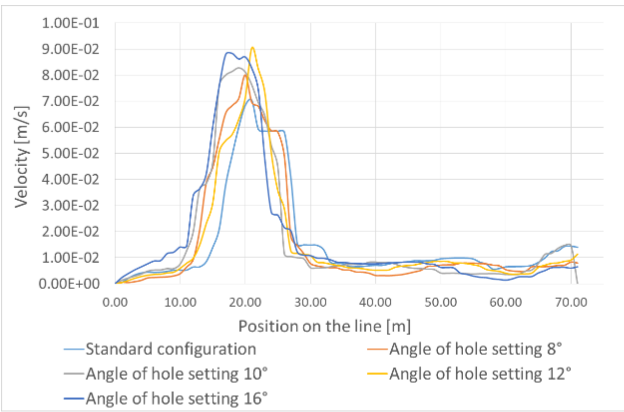

Figure 3 Velocity profile along the virtual line

With the intention of extending the residence time of casting strand No.2, several CFD simulations were performed with different deflections of the holes in the tundish baffle at angles of 8 °, 10 °, 12 ° and 16 ° from their original perpendicular axis. Based on the results of these simulations, 2 variants (8 ° and 10 °) were selected, which were simulated using a physical model.

In the **Table 1** the residence time values for the individual configurations measured on the water model with calculated results of the residence time from the CFD simulations are compared.

Table 1 Minimal and maximal residence time values for monitored configurations

	Angle of hole setting	Residence time [s]					
		Strand No.3		Strand No.2		Strand No.1	
		T_{min}	T_{max}	T_{min}	T_{max}	T_{min}	T_{max}
Water model	**0°**	35.4	180.6	22.7	157.3	53.2	248.6
	8°	41.8	247.7	24.8	129.7	42.1	245.5
	10°	48.7	219	25	116.8	48.3	224.7
CFD model	**0°**	40	210	20	120	50	250
	8°	42	209	25	129	42	239
	10°	57	227	32	117	55	247

5. CONCLUSION

A comparison of the results of C-curves and residence time in the realized CFD simulations with the results of the SimConT physical model indicate that the selected mathematical turbulent model Realizable $k-\varepsilon$, including the setting of boundary conditions, correlates and is relevant. The results of the simulations show that the deflection of the holes in the tundish baffle has a positive effect on the homogenization of the residence time of the tundish within the individual casting strands 1 to 3. The proposed deflection of the holes by 10 ° shows the best results in terms of minimum residence time. For these reasons, tundish baffle with deflected holes were recommended for testing in real casting conditions.

ACKNOWLEDGEMENTS

This research was funded by [VEGA MŠ SR a SAV] grant number [1/0212/21].

REFERENCES

[1] BUĽKO, B., DEMETER, P. *Laboratory of simulation of flow processes*. Technical University of Košice Institute of Metallurgy. [online]. 2022. [viewed: 2022-03-24]. Available from: https://ohaz.umet.fmmr.tuke.sk/lspp/index_en.html.

[2] TKADLEČKOVÁ, M. Numerical Modelling in Steel Metallurgy. *Metals*. 2021, vol. 11, no.6, p. 885. Available from: https://doi.org/10.3390/met11060885.

[3] TKADLEČKOVÁ, M., WALEK J., MICHALEK, K., HUCZALA, T. Numerical Analysis of RTD Curves and Inclusions Removal in a Multi-Strand Asymmetric Tundish with Different Configuration of Impact Pad. *Metals*. 2020, vol. 10, pp. 885. Available from: https://doi.org/10.3390/met10070849.

[4] URUBA, V. *Turbulence*. ČVUT v Praze, Fakulta strojní. [online]. 2009. [viewed: 2009-04-27]. Available from: http://www2.it.cas.cz/~uruba/docs/Aero/Turbulence_45.pdf

[5] VLČEK, P. *Modelování turbulentního proudění*. České Vysoké Učení Technické v Praze. [online]. 2018. [viewed: 31-03-2020]. Available from: http://chps.fsid.cvut.cz/pt/2013/pdf/3509.pdf.

[6] MICHALEK, K., GRYC, K., TKADLEČKOVÁ, M., MORÁVKA, J. *Modelování a vizualizace metalurgických procesu*. Ostrava: VŠB, 2013, pp. 118.

[7] BLEJCHAŘ, T. *Turbulence Modelování proudění - CFX*. Ostrava: Vysoká škola báňská - Technická univerzita Ostrava. 2010, pp.263.

[8] BRAUN, A., WARZECHA, M., PFEIFER, H. Numerical and Physical Modeling of Steel Flow in a Two-Strand Tundish for Different Casting Conditions. *Metal. and Mater. Trans. B*. 2010, vol. 41, no. 3, pp. 549-559. ISSN 1073-5615.

[9] CHATTOPADHYAY, K., ISAC, M., GUTHRIE, R.I.L. Physical and mathematical modelling of steelmaking tundish operations: A review of the last decade (1999-2009). *ISIJ International*. 2010, vol. 50, pp. 331-348. ISSN 0915-1559.

[10] MICHALEK, K., GRYC, K., SOCHA, L., TKADLEČKOVÁ, M., SATERNUS, M., PIEPRZYCA, J., MERDER, T., PINDOR, L. Physical modelling of tundish slag entrainment under various technological conditions. *Archives of Metallurgy and Materials*. 2017, vol. 62, pp. 1467-1471. Available from: https://doi.org/10.1515/amm-2017-0227.

[11] MICHALEK, K., GRYC, K., SOCHA, L., TKADLEČKOVÁ, M., SATERNUS, M., PIEPRZYCA, J., MERDER, T., PINDOR, L. Study of tundish slag entrainment using physical modelling. *Arch. Metall. Mater*. 2016, vol. 61, no. 1, pp. 257-260.

[12] TKADLEČKOVÁ, M., VÁLEK, L., SOCHA, L., SATERNUS, M., PIEPRZYCA, J., MERDER, T., MICHALEK, K., KOVÁČ, M. Study of solidification of continuously cast steel round billets using numerical modelling. *Arch. Metall. Mater.* 2016, vol. 61, no. 1, pp. 221-226.

[13] ODEHNAL, J., SOCHA, L., GRYC, K., ŠURAL, R., BULÍN J., STRAKA, J. Influence of Refining on Achieving Low Oxygen Contents at Production of Special Steels for Energetic Industry. In *METAL 2018: 27th International Conference on Metallurgy and Materials*. Ostrava: TANGER, 2018, pp. 93-101.

[14] SOCHA, L., VODÁREK, V., MICHALEK, K., FRANCOVÁ, H., GRYC, K., TKADLEČKOVÁ, M., VÁLEK, L. Study of Macro-Segregations in a Continuously Cast Billet. *Materiali in Tehnologije.* 2017, vol. 51, no. 2, pp. 237-241.

[15] GRYC, K., STROUHALOVÁ, M., SMETANA, B., SOCHA, L., MICHALEK, K. Influence of Direct Thermal Analysis Experimental Conditions on Determination of the High Temperature Phase Transformation Temperatures. *Archives of Metallurgy and Materials.* 2015, vol. 60, no 4, pp. 2867-2871.