Arch. Metall. Mater. **64** (2019), 1, 65-70

DOI: 10.24425/amm.2019.126219

M. WARZECHA*[#], T. MERDER**, P. WARZECHA*, A.M. HUTNY*

HYDRODYNAMIC CONDITIONS OF FLOW IN THE TUNDISH DEPENDING ON SELECTED TECHNOLOGICAL PARAMETERS FOR DIFFERENT STEEL GROUPS

The presented results of investigations are part of a larger study focused on the optimization of the flow and mixing of liquid steel in the industrial tundish of continuous casting machine. The numerical simulations were carried out concern the analysis of hydrodynamic conditions of liquid steel flow in a tundish operating in one of the national steelworks.

Numerical simulations were performed using the commercial code ANSYS Fluent. The research concerns two different speeds of steel casting. In real conditions, these speeds are the most commonly used in the technological process when casting two different groups of steel. As a result of computational fluid dynamics (CFD) calculations, predicted spatial distributions of velocity and liquid steel turbulence fields and residence time distribution (RTD) curves were obtained. The volume fractions of different flows occurring in the tundish were also calculated. The results of the research allowed a detailed analysis of the influence of casting speed on the formation of hydrodynamic conditions prevailing in the reactor.

Keywords: steelmaking, continuous casting, tundish, numerical modelling

1. Introduction

Continuous casting of steel (CC) is currently a widely used production technology of semi-finished steel products. The continuous casting technology was initiated in the 1960s and is constantly being improved and adapted to new market requirements. This method requires constant improvement of quality parameters of the cast billets; moreover, in the case of products made of modern steel grades being introduced to the market they need to be tailored to technological parameters. The manufactured semi-finished products are of various cross-sections that are adjusted to the production of final goods. The steel continuous casting line is one of a key equipment in a modern steelwork.

Continuous casting technology is based on supplying liquid steel from tundish into one or few crystallizers of the CC device and cooling it as long as a fully formed and solidified billet is obtained. A tundish ensures reduction of the ferrostatic pressure of the liquid steel, maintenance of the process continuity (exchange of the main ladle) and – under proper conditions – refining the bath from non-metallic inclusions, as well. Contemporary tundish is defined as a high-temperature flow chemistry reactor in which such processes are implemented that are of significant impact on the level of metallurgical purity of the steel being cast, and this is directly transferred into the quality of final steel products. It is therefore important to identify the nature of liquid steel flow in an industrial tundish under various operating conditions (technological parameters). The obtained information allows for making decision to introduce any change to the system flow control setting in the tundish, which indirectly will have an impact on improving the quality of cast billets.

For the analysis of liquid steel flow and non-metallic inclusions (NMI) in metallurgical aggregates (namely tundish [1-8]) is recently applied the numerical modelling in CFD. This tool enables carrying out simulations of the researched phenomenon in a very short period of time, making it a very convenient and sufficiently precise research tool.

The CFD simulation results presented in the article refer to the analysis of the flow and mixing of steel for the tundish actually used in one of the national steelworks. Calculations are considered for two most commonly used speeds being used in the technological processes of casting steel (that are characteristic for two different steel groups). There was carried out a detailed analysis of their impact on shaping the hydrodynamic conditions in the reactor.

As a result of CFD calculations – predicted spatial distributions of velocity fields and liquid steel turbulences were obtained. RTD curves (of F and E – type) for the analysed cases were also calculated. Based on E curves, the percentage shares of various types of flows arising in the tundish were calculated. Whereas, on the basis of F curves, a range of the transition zone were determined. The presented results are a continuation of research studies described in [9,10].

---

* CZESTOCHOWA UNIVERSITY OF TECHNOLOGY, DEPARTMENT OF METALS EXTRACTION AND RECIRCULATION, AL. ARMII KRAJOWEJ 19, CZESTOCHOWA, POLAND

** SILESIAN UNIVERSITY OF TECHNOLOGY, FACULTY OF MATERIALS ENGINEERING AND METALLURGY, UL. KRASIŃSKIEGO 8, KATOWICE, POLAND

[#] Corresponding author: warzecha@wip.pcz.pl

2. Object of the research study

Under this research study a tundish of CC equipment is analysed (with its nominal capacity of 22 Mg), working in one of the national steelworks. This is a tundish with channel type induction heating. It is used for casting billets intended for rolled products with small cross-sections. Figure 1 indicates geometry of the tundish with its main dimensions and characteristic dimensions of the turbulence inhibitor. The turbulence inhibitor is standard tundish equipment.

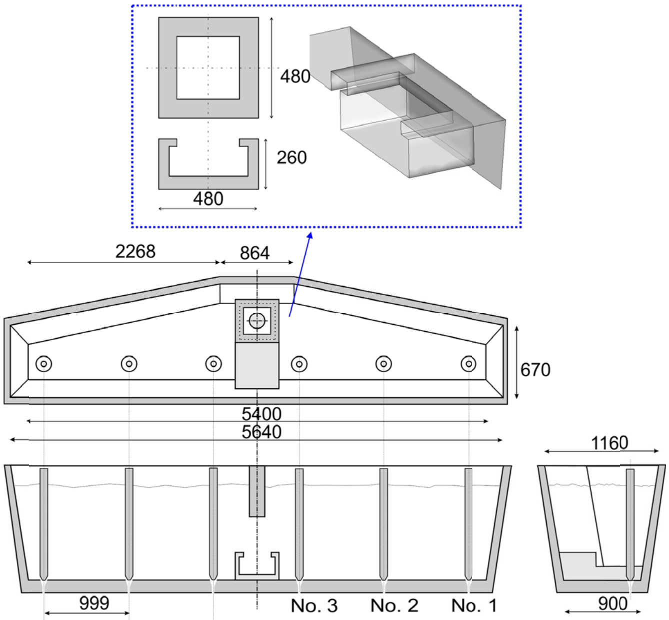

Fig. 1. Scheme of the tundish

TABLE 1

Process parameters and its related conditions of steel flow in the tundish

Steel group	Steel grade	Billet cross-section	The average linear speed of continuous casting	Speed by inlet	Mean theoretical residence time
		mm	m×min^{-1}	m×s^{-1}	s
A	A1 A2 A3 A4	130×130	2.7	0.98	719
B	B1 B2 B3	160×160	1.9	1.1	675

Two speeds of casting steel using CC equipment were subject of the analysis (see Table 1). These speeds are characteristic, as they are most commonly used in the technological process when casting the analysed grades of steel. These grades belong to two steel groups: (A) for cold drawing and/or rolling, cold heading, and (B) for cold extrusion. In steels code A, the carbon content is in the range of <0.41:0.73>, while in steel code B of <0.19:0.29>.

3. Research methodology

Numerical simulations were performed by using the ANSYS Fluent commercial code [11]. The working area of the object was mapped in the ANSYS SpaceClaim Direct Modeler preprocessor [12]. The flow field is normally turbulent in the most regions of continuous casting tundish. The mathematical model [13,14] describing the flow of steel in the tundish includes differential equations of the momentum and energy, as well as, an equation describing the turbulent flow structure of liquid steel in the tundish. For turbulence modeling, there was used a semiempiric two-valued k-e model proposed by Lauder and Spalding [15], being commonly used for problem analysis in engineering.

In order to solve a system of differential equations, proper initial and boundry conditions were adopted. Subject of the analysis is a spatial and symmetric system, due to the fact that the geometry of the tundish is symmetrical in reference to the plane passing through the axis of the pouring opening (shroud). At the edge of the system corresponding to the pouring opening, the liquid steel inflow speed was assumed depending on the case (Table 1) and temperature (Table 2) with a turbulence intensity of 5%. The flow rate of the stream outcomming from the tundish is based on the mass balance. The applied boundary conditions were described in details elsewhere [10].

In order to determine the trace concentration distribution in steel during the casing process, based on which the residence time distribution (RTD) curves were determined, calculations for nonstationary conditions were performed. Time step of 0.01 s with approximately 20 iterations in each time step was employed to generate the RTD curve.

The target for calculation grid consisted of 360,000 control volumes concentrated in the vicinity of the opening, where the steel is being poured into the tundish and at the outlets of the tundish. The problem was solved numerically by using the finite volume method in the three-dimensional (3D) area.

All numerical simulations were carried out with the use of double-precision solver (3ddp) and the second-order spatial discretization scheme. For describing the pressure-velocity coupling, the SIMPLEC algorithm was select-ed. The mathematical simulations were run on an INTEL CORE i7 processor computer.

The physical properties of liquid steel are shown in Table 2.

TABLE 2

Thermo-physical data for CDF calculations (liquid steel)

Steel group	Viscosity	Thermal conductivity	Density	Temperature
	kg×m^{-1}×s^{-1}	W×m^{-1}×K^{-1}	kg×m^{-3}	K
A	0.00438	39.57	6842	1783
B	0.0045	40.96	6973.5	1804

The temperature of the liquid steel was determined based on measurements carried out under industrial conditions. The temperature was measured in a tundish, the given value is the average value for the analyzed melts. Thermo-physical properties of liquid steel, needed for numerical calculations, were determined using the chemical compositions of the analyzed steel grades according to the relationships given in literature [16,17].

4. Calculation results

In order to receive greater transparency, when comparing the presented results, the object was divided by two characteristic planes. The first vertical plane passes through the inlet of the tundish (A plane), while the second vertical plane goes through the outlets of the tundish (B plane). Due to the fact that the system (tundish) is symmetric, explicitly a half of the object (outlets N^{o} 1, 2 and 3) was subject to the analysis.

Figures 2 and 3 presents the forecasted flow of steel for the analysed cases.

The state of liquid steel motion in the researched tundish was complemented by flow turbulence characteristics. For this purpose, spatial distributions of the kinetic energy of turbulences (*k*) of liquid steel were generated – through the shroud (plane A) and through the outlets (plane B) Image of these characteristics is presented in Figs. 4 and 5.

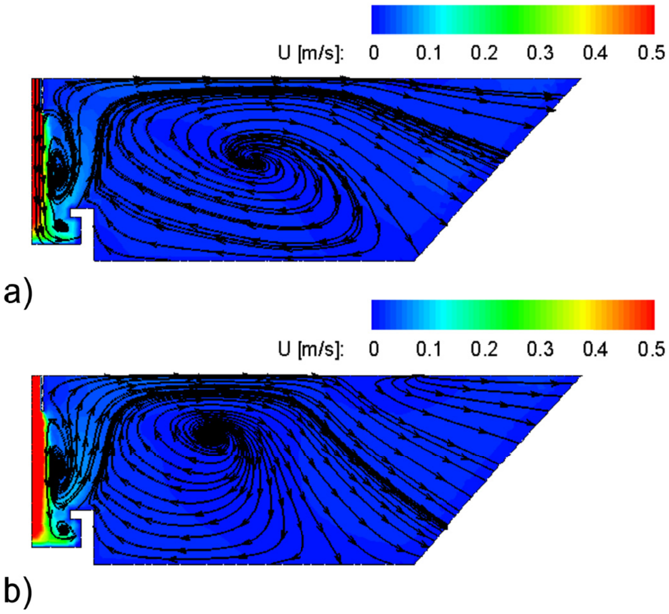

Fig. 2. Maps showing contours of speeds with marked current lines presented in plane A for steel casting speeds of: a) 0.98 m×s^{-1}; b) 1.1 m×s^{-1} [10]

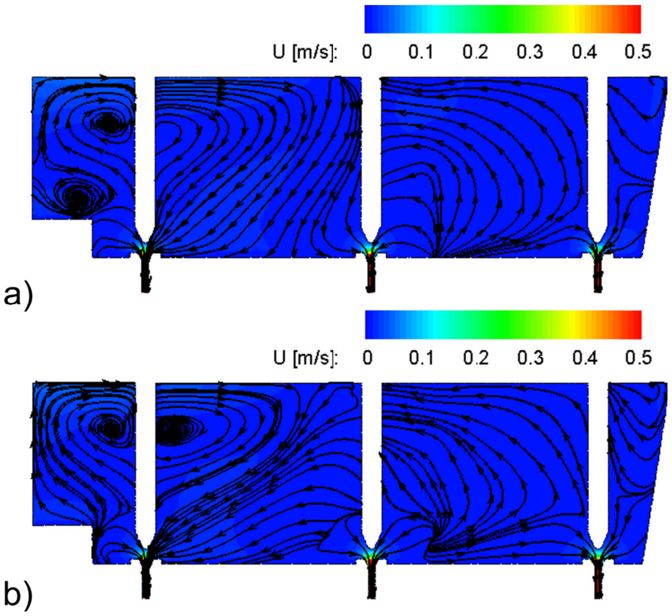

Fig. 3. Maps showing contours of speeds with marked stream lines presented in plane B for steel casting speeds of: a) 0.98 m×s^{-1}; b) 1.1 m×s^{-1} [10]

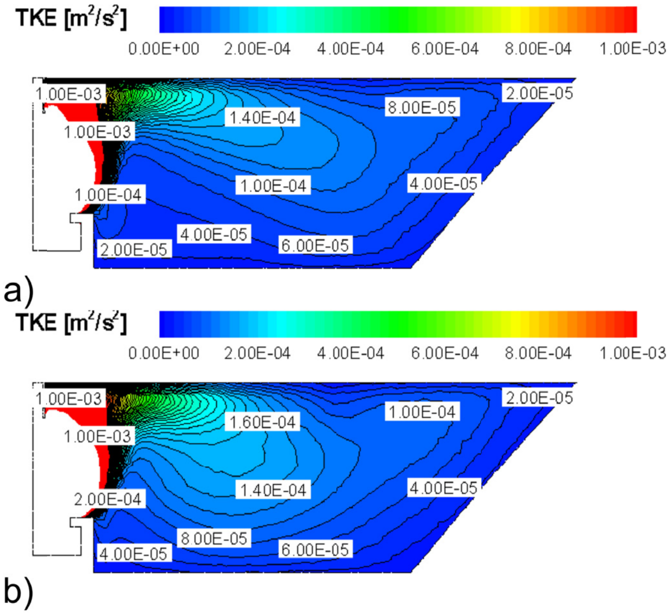

Fig. 4. Maps showing contours of kinetic energy turbulences presented in plane A for steel casting speeds of: a) 0.98 m×s^{-1}; b) 1.1 m×s^{-1} [10]

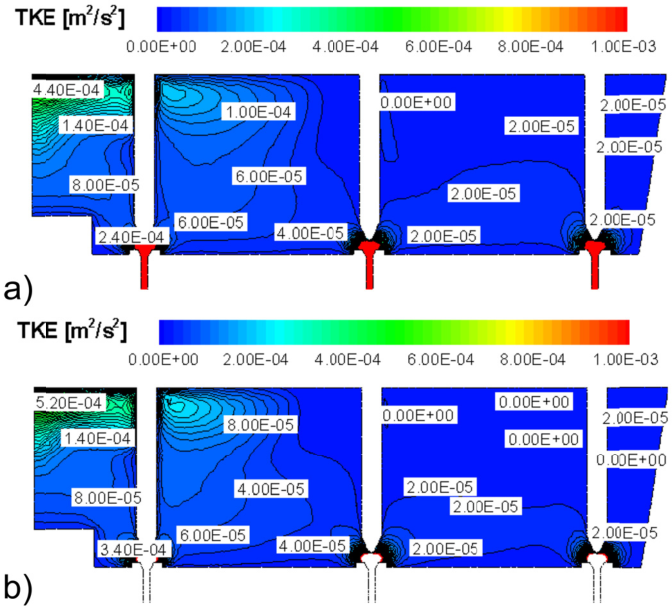

Fig. 5. Maps showing contours of kinetic energy turbulences presented in plane B for steel casting speeds of: a) 0.98 m×s^{-1}; b) 1.1 m×s^{-1} [10]

The obtained three-dimensional distributions of velocity fields, kinetic turbulence energy of the liquid steel and mark concentration in the working space of the tundish are the source of significant knowledge on the steel casting conditions. However, these characteristics do not determine directly whether the identified state of steel flows in the tundish is proper for instance for mixing processes (sequential casting of various steel grades) or removing NMI. Relevant results in these cases are obtained by using macroscopic RTD characteristics (E and F curves), referring to the basic series of flow reactor tests [18].

Figure 6 presents RTD characteristics of F type for the analysed cases. Values of the dimensionless marker concentration were obtained directly from CFD calculations. Whereas dimensionless time was calculated based on expressions described in [10]. Average time of stay for the tested theoretical variants are provided in Table 1.

The curves of type F shown in Fig. 6, despite the fact that they are suitable for quality analysis of flows, at the same time, they are no so sensitive in quantitative assessment of contributions of flow types occurring in tundishes. More adequate for this assessment are RTD characteristics of E type (see Fig 7).

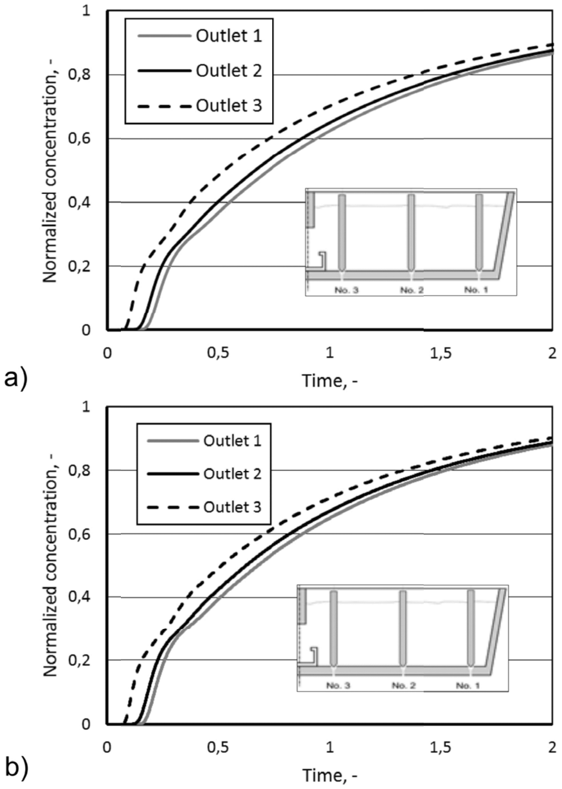

Fig. 6. RTD characteristics of F type: a) 0.98 m×s^{-1}; b) 1.1 m×s^{-1} [10]

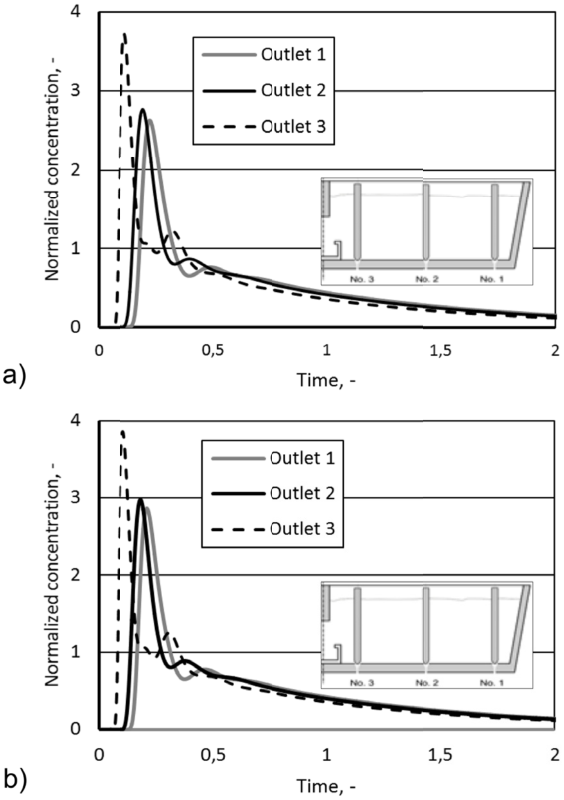

Fig. 7. RTD characteristics of E type: a) 0.98 m×s^{-1}; b) 1.1 m×s^{-1} [10]

5. Flow characteristic analysis

When analysing the forecasted flow of steel (see Figs. 2 and 3) there can be seen that in the tundish are being formed two areas, namely: by-inlet, limited by flow modifier (turbulence inhibitor), and out-of-inlet. They are clearly characterized by a separate structure of the liquid steel motion. In the by-inlet area, circulation (with a significant share of ascending component) is visible, which can promote the interphase separation of the NMI.

In outside zone of the by-inlet area (Fig. 3), a high share of falling flows can be marked (in particular in the area between inlets No. 3 and No. 2). This type of flow does not assist the process of raising the non-metallic inclusions into the slag phase. On the contrary, it can cause incineration of NMI into crystallizers of the CC equipment.

In this part of the tundish can also be found areas characterized by a significant slowdowns of the liquid steel flow, which occur at the end of the tundish and in the vortex centres.

Significant speeds of liquid steel are being noted at the interphase of the liquid steel-slag, and this can cause the situation of pumping the slag into the liquid steel. This in turn promotes formation of endogenous non-metallic inclusions. It may also expose the mirror of liquid metal.

Distributions of the kinetic energy of turbulences complements the presented liquid steel motion state in the tundish. Distributions of the kinetic energy of turbulences clearly show the behaviour of the liquid steel in the tundish (Figs. 4 and 5). It is visible how the liquid steel in the tundish flows out in the direction of its walls and in the vicinity of the outlet No. 3, located closest to the by-inlet zone. This may be disturb by local flow of the steel and cause disturbances in casting the steel into the crystallizer co-working with this outlet. A significant increase of turbulences is being also noted at the surface of the inter-phase liquid steel-slag, in the inlet zone. Such a system is not conducive to the removal of inclusions, and it can even cause pumping the slag into the liquid steel and formation of exogenous NMI.

By analysing curves of type F (Fig. 6), varied times of reaching the marker into the particular outlets (for both variants being considered) is visible. The shortest time is recorded for the nozzle of outlet No. 3 (in the closest proximity to the supplying stream). Whereas, for the other outlets No. 1 and 2, the times are much longer. Under industrial conditions, such state can cause disturbances in particular pipes of the CC equipment during the sequential casting process of different steel grades. It can also cause delivering to the outlet No. 3 portions of liquid steel with much higher temperature.

Marker arrival times to particular outlets for the analysed variants are slightly shorter for variant B. Small differences can be also marked in the trend of curve increments for both cases. However, the characteristic of their course is very similar.

The presented curves also indicated that the share of flow with well (perfect) mixing in both of the analysed cases are also dominant.

By analysing the E curves (Fig. 7) and undertaking additional calculations, the macroscopic character of the flow in the tested object can be assessed. In tundish, three areas of liquid steel flow can be distinguished, namely: the zone of perfect mixing, where the flow is turbulent and the steel is completely mixed, plug flow zone in which the liquid steel flows in a stabilized manner and the dead (stagnation) zone in which the steel bath flow is insignificant.

By assessing the correctness of refining the liquid steel in the tundish, it is crucial to determine shares of individual flows. The dead zone in tundish adversely affects the gravitational removal of non-metallic inclusions (inflow NMI) and temperature distribution of the steel. The plug flow zone favours the free inflow of NMI from steel. Whereas, in the intensive mixing zone intensive phenomena of coagulation and coalescence occur and this greatly facilitates the free outflow of non-metallic inclusions into the slag phase.

Applying mathematical relationship (1-3) basing on the obtained RTD curves of E-type the participations of flow (dispersed plug flow volume, well mixed flow volume and dead flow volume) [19-21] were calculated for the analysed cases. Table 3 presents obtained results.

$$V_d = 1 - \frac{\dot{V}_a}{\dot{V}} \Theta_{av} \tag{1}$$

$$V_{dp} = \frac{\left(\Theta_{\min} + \Theta_{peak}\right)}{2} \tag{2}$$

$$V_{im} = 1 - V_d - V_{dp} \tag{3}$$

where: V_{dp} – dispersed plug flow volume, V_{im} – well mixed flow volume, V_d – dead flow volume, θ_{av} – dimensionless mean residence time up to $\theta = 2$, $\theta_{\min}$ – minimal dimensionless time, θ_{peak} – peak dimensionless time, $\dot{V}_a$ – volumetric rate of flow trough the active region of the tundish, $\dot{V}$ – total volumetric flow rate trough a tundish.

For outlet No. 3 very unfavourable conditions are observed. During obtained results analysis, it can be stated that for the outflow No. 3 (located closest to the tundish feed stream) there is the highest share of dead flow and the lowest plug flow in comparison to other outflows.

The presented data also show that by increasing the speed of casting, the percentage of dead flow reduces, and the perfect mixing flow for all outflows increases. This indicates more favourable refining conditions for liquid steel during casting of the steel code B. Nevertheless, the worst conditions are observed for the outlet nozzle No. 3.

TABLE 3

Volume fraction of flow in tundish

Volume Fraction %	Steel group A				Steel group B			
	Outlet No.			Average	Outlet No.			Average
	1	2	3		1	2	3	
Dead (V_d)	32	34	42	*36*	30	33	41	*35*
Dispersed Plug (V_{dp})	17	14	8	*13*	16	14	8	*12*
Well-Mixed (V_{im})	51	52	50	*51*	54	53	51	*53*

For comparison of the analysed cases, the perfect mixing to dead flow ratio V_{im}/V_d and the plug flow to dead flow ratio V_{dp}/V_d were determined (Table 4). The V_{im}/V_d coefficient is an indicator of the well mixed area found in the tundish; its share suggests improved thermal and chemical homogenization in the tundish. The V_{dp}/V_d coefficient is an index of inactive region; its share suggests that in the given area, there are conditions favouring the flotation of NMI [22].

The data presented in Table 4 confirm previously noticed observations that the most unfavourable parameters are also for the outlet No. 3. It can be observed for both steel grades, and thus, speeds of casting. The best parameters – in terms of non-metallic inclusions removal- are noted for the outlet No.1, whereas they are slightly worse for the outlet No. 2.

TABLE 4

List of calculated coefficients V_{im}/V_d and V_t/V_d

Parameter	Steel group A			Steel group A		
	Outlet No.			Outlet No.		
	1	2	3	1	2	3
V_{im}/V_d	1.59	1.53	1.19	1.80	1.61	1.24
V_{dp}/V_d	0.53	0.41	0.19	0.53	0.42	0.20

6. Summary and statements

Since the research tests of the liquid steel motion (flow hydrodynamics) on a real object are basically excluded, so the solution to this problem was determined by using modelling technique. It was decided to use numerical modelling based on the developed mathematical model. This method, thanks to advanced CFD programs and constantly increasing computers' computing power, gives the possibility of solving very complex problems.

These test results are part of a larger study of optimizing the flow and mixing of liquid steel in a real tundish of a continuous steel casting device.

On the basis of CFD simulations, the following conclusions can be stated:

- Certain hydrodynamic conditions of flow in the tested tundish are characteristic for this type of reactor, so its operation conditions do not raise major objections.
- Characteristics of liquid steel flow in tundish for both analysed steel groups (of the considered speed) are very similar.
- Specific area of flow are formed appropriately and provide safe and undisturbed steel casting process.
- However, some remarks can be evoked by the relation of the volume of the laminar flow area to turbulent flow ratio, and this can be the reason for some disturbances in the area of the outlet No. 3, and insufficient refining capacity of the pipe zone.

Results obtained at this stage of the research study will significantly enrich the information available, enabling the decision to be made in order to change the previously used flow control system in industrial tundish of the continuous steel casting equipment.

Acknowledgements

To the National Centre for Research and Development for financial support (project No PBS2/A5/32/2013).

REFERENCES

[1] K. Chattopadhyay, M. Isac, R.I.L. Guthrie, ISIJ Int. **51**, 4, 573-580 (2011).

[2] K. Raghavendra, S. Sarkara, S.K. Ajmania, M.B. Denysa, M.K. Singh, Applied Mathematical Modelling **37**, 9, 6284-6300 (2013).

[3] A. Cwudziński, Ironmaking & Steelmaking **42**, 2, 132-138 (2014).

[4] R. Schwarze, D. Haubold, C. Kratzsch, Ironmaking and Steelmaking **42**, 2, 148-153 (2015).

[5] P. Warzecha, M. Warzecha, T. Merder, Metalurgija - Journal for Theory and Practice in Metellurgy **54**, 3, 462-464 (2015).

[6] S. Chatterjee, K. Chattopadhyay, ISIJ Int. **55**, 7, 1416-1424 (2015).

[7] A. Mabentsela, G. Akdogan, S. Bradshaw, J. S. Afr. Inst. Min. Metall. **117**, 5, 469-483 (2017).

[8] M. Warzecha, T. Merder, P. Warzecha, G. Stradomski, ISIJ Int. **53**, 11, 1983-1992 (2013).

[9] T. Merder, M. Warzecha, J. Pieprzyca P. Warzecha, S. Garncarek, Assessment of changes in casting speed at operated tundish during casting of a high carbon steels, 46th International October Conference on Mining and Metallurgy, Bor Lake, Serbia, 35-39 (2014).

[10] P. Warzecha, A.M. Hutny, M. Warzecha, T. Merder, Archives of Metallurgy and Materials **61**, 4, 2071- 2078, (2016).

[11] ANSYS Fluent, User's guide, version 14.5, Fluent Inc.

[12] ANSYS SpaceClaim Direct Modeler – User's guide, Canonsburg, USA (2013).

[13] J.F. Wendt, Computational fluid dynamics, Springer-Verlag, Germany (1996).

[14] J.M. Kay, R.M. Nedderman, Fluid mechanics and transfer processes. Cambridge University Press, Great Britain (1985).

[15] B.E. Launder, D.B. Spalding, Computer Methods in Applied Mechanics and Engineering **3**, 269-289 (1974).

[16] T. Iida, R.I.L. Guthrie, The physical properties of liquid metals, Clarendon Press, Oxford, United Kingdom (1988).

[17] E. Kawai, Y. Shiraishi, Handbook of physico-chemical properties at high temperatures, The Iron and Steel Institute of Japan, Tokyo (1988).

[18] J. Szekely, O.J. Ilegbusi, The physical and Mathematical Modeling of tundish operations, Springer-Verlag, USA (1989).

[19] C.Y. Wen, L.T. Fan, Models for flow systems and chemical reactions, Dekker, New York (1975).

[20] S.P. Ferro, R.J. Principe, M.B. Goldschmit, Metall. Mater. Trans. B **6**, 32, 1185-1193 (2001).

[21] K. Chattopadhyay, M. Isac, R.I.L. Gutrie, ISIJ Int. **52**, 11, 2026-2035 (2012).

[22] L.G. Demedices, R.D. Morales, S. Lopez-Ramirez, J.J. Barreto, J. Palafox, Steel Research Int. **72**, 10, 346-352, (2001).