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THE CHANGE OF LIQUID STEEL FLOW CONTROL SYSTEM IN THE TUNDISH – MODELLING RESEARCH

ZMIANA SYSTEMU KONTROLI PRZEPŁYWU CIEKŁEJ STALI W KADZI POŚREDNIEJ – BADANIA MODELOWE

The article presents the results of research concerning the change of liquid steel flow and mixing in the T-type tundish. It has been installed in one of polish steel plants. Continuously changing market conditions have forced the change in the range of cast strand. As a consequence the new control system of liquid steel flow had to be applied. Up to now a baffle with notch has played the role of steel flow regulation. It was placed between the inlet and channel zones of a tundish. However such solution was not satisfactory. Therefore, a new flow control equipment was designed – baffles and different constructional variants of turbulence inhibitors. To estimate the efficiency of their functioning and in the same time their influence on the tundish work, modelling research was carried out. The research was also complemented by numerical simulations. The article presents results of such research as well as experimentally and numerically determined RTD curves of mixing (Residence Time Distribution).
Keywords: tundish, continuous casting, physical modelling, numerical modelling

Artykuł przedstawia rezultaty badań dotyczące zmiany przepływu i mieszania się ciekłej stali w kadzi pośredniej typu T. Urządzenie to zainstalowane jest w jednej z polskich stalowni. Zmieniające się warunki rynkowe wymusiły zmianę asortymentu odlewanych wlewków ciągłych, a tym samym wymusiły konieczność zastosowania w kadzi pośredniej nowego systemu regulacji przepływu stali. Dotychczasową zabudowę stanowiła przegroda z otworem przelewowym. Przegroda umieszczona była pomiędzy strefą wlewową i korytową kadzi pośredniej. To rozwiązanie nie spełniało oczekiwań. W związku z tym zaprojektowano nowe urządzenia sterowania przepływem, takie jak: przegrody i różne warianty konstrukcyjne inhibitora turbulencji. W celu oceny zaprojektowanych urządzeń sterowania przepływem i ich wpływu na pracę kadzi pośredniej przeprowadzono badania na modelu fizycznym uzupełniając je o symulacje numeryczne. Artykuł prezentuje wyniki badań modelowych wizualizacji przepływu uzupełnione o krzywe mieszania RTD (Residence Time Distribution).

1. Introduction

Many factors influence the process of obtaining high quality cast strand in continuous casting machine. However, above all there is a need for correct preparation of liquid steel in the casting process in both thermal and metallurgical way [1]. Although, this basic condition does not ensure the expected results taking into account the casting process conducted in specific machine. It is necessary to determine correctly technological parameters of casting for the specific grades of steel considering the characteristic constructive conditions of the applied machine. Tundish belongs to one of the main constructive elements of CC machine that influence the quality of obtained cast strands. In industry many different constructive solutions of a tundish are applied. They are always characterized by the individual geometry, tonnage and amount of outlets [2-10].

The quality of obtained cast strands is significantly influenced by the proper realization of the tundish tasks: homogenization of the liquid steel in its whole volume chemically as well as considering the temperature; ensuring the appropriate conditions of floating the nonmetallic inclusions to the slag; the uniform flow of steel to particular outlets. This concerns both the limitation of defects created during casting and the proper forming of the cast structure during solidification and crystallization. Thus, the most important is to determine the optimal construction and equipment of the tundish working space taking into consideration the flow of liquid steel [5-15]. This is especially important in case of atypical tundishes (T-type, V-type, H-type, L-type and asymmetric tundishes), which have hardly been described in the literature. The research showed that applying flow control device considerably improves hydrodynamic conditions occurring in the tundish. If however the flow control device is placed inadequately, the conditions will deteriorate. The optimization of the tundish working space is usually done using modelling methods [16-18]. Intensive development of these methods, basing on both physical models as well as numerical simulations, gives very good results nowadays.

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This article deals with such an issue. The research was carried out by means of hybrid modelling in which results of physical modelling were complemented by the numerical simulations. 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. Geometrical description of the tundish

A two-strand tundish, which was designed for the continuous casting of slabs intended for small cross-section rolled products, was under the study. It is a typical T-type tundish, which is used in the polish metallurgical industry. Such tundish is symmetrical relative to the transverse plane. Fig. 1 presents the geometry and dimensions of the tundish model at 1:2 scale.

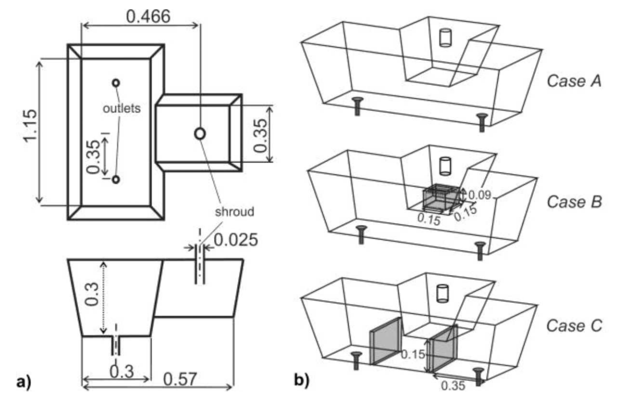

Fig. 1. a) Geometry of the studied industrial tundish, b) proposal of equipping the tundish working zone

In the first stage of the research, the condition of tundish work without the modernization of working zone taking into account the flow and mixing of the liquid steel was diagnosed [13,14,19,20]. It was found that there were unfavorable hydrodynamic conditions causing the improper ratio of the created flow areas (areas of dispersed plug flow, well mixed flow and dead flow).

That is why, further modelling research was conducted. It consisted of the modification of a tundish working zone applying the flow control device. Thus, several equipping variants of this area were worked out. In modelling research different flow control devices were considered such as baffles, baffles with notch and different geometrical variants of turbulence inhibitors [21]. In presented work the analysis was limited to the best solutions of equipping the tundish working zone (Fig. 1b).

3. Methodology of the research

3.1. Physical modelling

Physical model of CC machine was equipped with the model of tundish made from plexiglas at 1:2 scale according to the geometrical criterion of similarity [22, 23]. The flow rate of water in the model was $2.0 \cdot 10^{-4}$ $m^3 \cdot s^{-1}$, which corresponds to casting rate equal 1 $m \cdot min^{-1}$, for the round cast strand $\varphi 200$.

Using physical model the research considering visualization and determining the distribution of tracer concentration was carried out. Such research was based on working out characteristics of RTD (E and F types [24÷26]). As a tracer in the model, water solution of $KMnO_4$ and water solution of NaCl were used.

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 2% NaCl) was opened. The tracer was introduced in such a way during the whole time of measurement. Additionally, introducing another tracer ($KMnO_4$) enabled to conduct research that could describe the way of steel flow and mixing in the tundish. The course of experiment was registered by means of camera systems placed in different planes.

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 of 2% NaCl) was introduced to the system on a one-off basis in the amount of 0.04 m^3.

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

The further problem needed to be solved during the research was to determine the safe steel level in the tundish. It is really important to determine the moment in which swirls near tundish outlets are just being created, because there is a danger of dragging slag to these outlets.

In the first stage water model was filled with water to the level of 0.5 from the nominal level, it means 0.15 m. Then, the kinetics of modelling agent flow was regulated in such a way that the compatibility with conditions of similarity was reached. On the water surface of the granulated foamed polystyrene was thrown. The polystyrene was treated as a tracer for modelling slag particles. After stabilizing the system the feed check valve of tundish water model was closed, so water was not introduced. When the tundish model was emptied a camera registered the whole process. The behaviour of granulated product on the surface of modelling agent was observed.

In the second stage water model was also filled with water to the level of 0.5 from the nominal level. The operations were the same as in the first stage. Here, $KMnO_4$ was pointwise introduced as a tracer on the water surface. When the tundish model was emptied a camera registered the whole process; the existing swirls were observed.

3.2. Numerical modelling

The flow field in the tundish was computed by solving the mass and momentum conservation equation [27] in a boundary fitted coordinate system along with a set of realistic boundary conditions. The flow was treated as steady one neglecting the phenomena occurring during filling and emptying the tundish. The continuity equation was solved in a temporal manner to capture the local variation of the concentration in the tundish. The top surface of the liquid in the tundish was considered to be flat and the slag depth was considered to be insignificant. With these two assumptions the flow field was solved with the help of the equations coming from the k-ε turbulence model [28]. Such model is commonly applied in solving many engineering problems [29,30,31].

Half of the tundish was chosen for the mathematical analysis. Symmetry boundary condition was applied at the symmetry plane, which implies a zero gradient condition for all the variables normal to that plane. The 3D domain of this tundish was divided into 180000 cells, making a finer mesh in the zone of the incoming and outgoing liquid jet in order to visualize better the effects of velocity and turbulence gradients. The walls were set to a no-slip condition, and the turbulent quantities were set from a logarithmic law wall function [32]. A zero shear stress boundary condition was applied to the free surface of the tundish.

The velocity profiles of water at the inlet as well as at the outlets of the tundish were assumed to be uniform through the cross sections, and the other two velocity components were assumed to be zero. Inlet velocity of 1.4 m·s^{-1} water flow rate was set for the incoming jet with a turbulent intensity of 5%. To evaluate the distribution of tracer concentration during the casting process, two types of boundary conditions were set at the inlet:

- at the moment t = 0, a one-off tracer addition was X_{tr} = 0.0002 of mass fraction (Dirac‘s function),
- the tracer concentration was uniform and normalized (C=1) during the whole period of measurement (Heaviside’s function).

The set of governing equations were discredited using the finite volume technique in a computational domain and solved with the help of boundary conditions using commercial CFD package (ANSYSFluent). Water parameters for computations were density (998.2 kg·m^{-3}) and viscosity (0.001 kg·m^{-1}·s^{-1}).

4. Verification of numerical simulation with experiments

Obtained experimental data were confronted with the results coming from numerical simulations [14,19] performed in identical conditions.

To compare results, from numerical simulations with experimental results tracer concentration and time was transformed into dimensionless characteristics. Therefore the appropriate calculations described in [33] were used. The following expression defines the dimensionless time:

$$\Theta = t_{\mathrm{i}} \big/ \tau \tag{1}$$

where theoretical mean residence time is defined in the following form:

$$\tau = V/Q_V \tag{2}$$

whereas real (actual) mean residence time in such form:

$$\mathrm{t_r} = \sum C_{avi} t_i \Big/ \sum C_{avi} (\mathrm{i} = \text{elapsed time}) \tag{3}$$

where: V – volume of the tundish, Q_V – volumetric rate of the flow, C_{avi} – average concentration of the tracer at the outlet, t_i – specified time.

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

$$C_b = (C_t - C_0)/(C_\infty - C_0) \tag{4}$$

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

$$\mathrm{C_b = C_t/C_{av}} \tag{5}$$

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

$$\mathrm{C_{av} = m_{tr}/V} \cdot \rho \tag{6}$$

where: m_{tr} – mass of the tracer, C_t – of the 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.

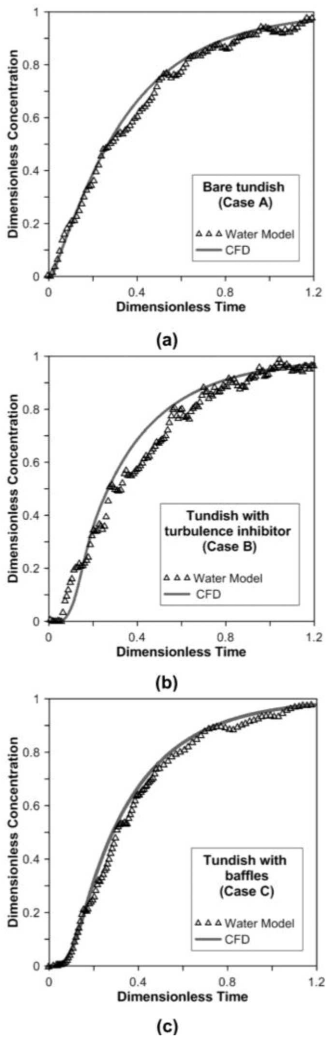

Fig. 2. Results coming from water model and CFD calculations (F-type curve): (a) case A [14], (b) case B [19], (c) case C

Fig. 2 presents dimensionless RTD characteristics of F-type, whereas Fig. 3 shows the dimensionless RTD characteristics of E-type for experimental research and numerical simulations (CFD). For the studied cases the insignificant differences between measured and calculated data were observed. These differences can be seen in the form of curves slip. In the same time the rate of concentration growing is highly compatible. Divergence in experimental and numerical results can come both from simplification of the mathematical model and measuring errors. Basing on comparison presented in Fig. 2 and 3 compatibility was stated between results obtained from experimental model and calculations. Thus, the working out research program has been formulated correctly and can be used in the further research.

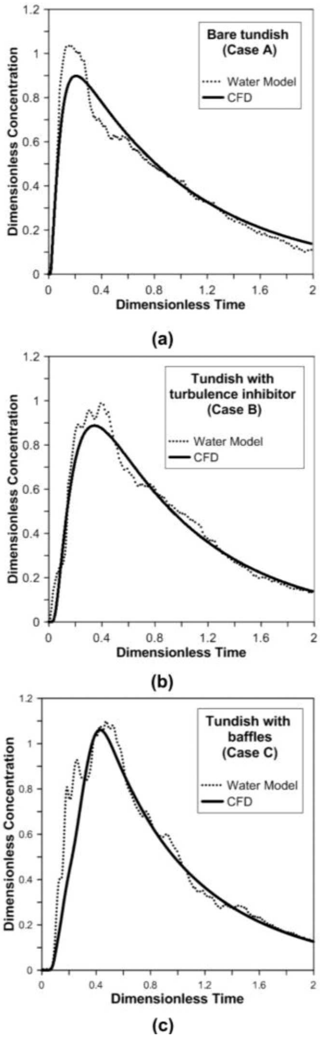

Fig. 3. Results coming from water model and CFD calculations (E-type curve): (a) case A, (b) case B, (c) case C

Obtained RTD characteristics contain cumulated information about hydrodynamic conditions of steel flow through tundish. They enable to estimate quality of the objects considering steel mixing and possibilities of intensifying the refining processes.

5. Research results and discussion

Results of physical modeling - optimization of steel flow through tundish. Applying $KMnO_4$ tracer in the model, kinetics of steel flow and mixing was registered. Every variant of experiment was conducted for the same conditions of tundish work. Fig. 4 to 6 show chosen results of tracer propagation during the test appropriately for cases A to C. The course of experiments was registered in two planes: central and side. Above the model, a mirror was placed to observe additionally what happened in the tank on the surface.

It was found that in case A (bare tundish – Fig. 4) there was insufficient size of well mixed flow area. This area has a big impact on the quality of obtained cast strand due to the fact that during their run the steel refining process (impurities float to slag) occurs. Thus, it should be expected that cast strand in this variant cannot obtain required quality. Further flow of modelling agent has circulative character. Tracer propagates in the direction of water surface and at the headwall falls down creating right circulation (movement of a liquid is in conformity with clockwise direction – view from left side of tundish water model). It was also found that there was dangerously low kinetics of modelling agent mixing in the area of model back walls. This phenomenon can cause the creation of dead zones in this area of a real tundish.

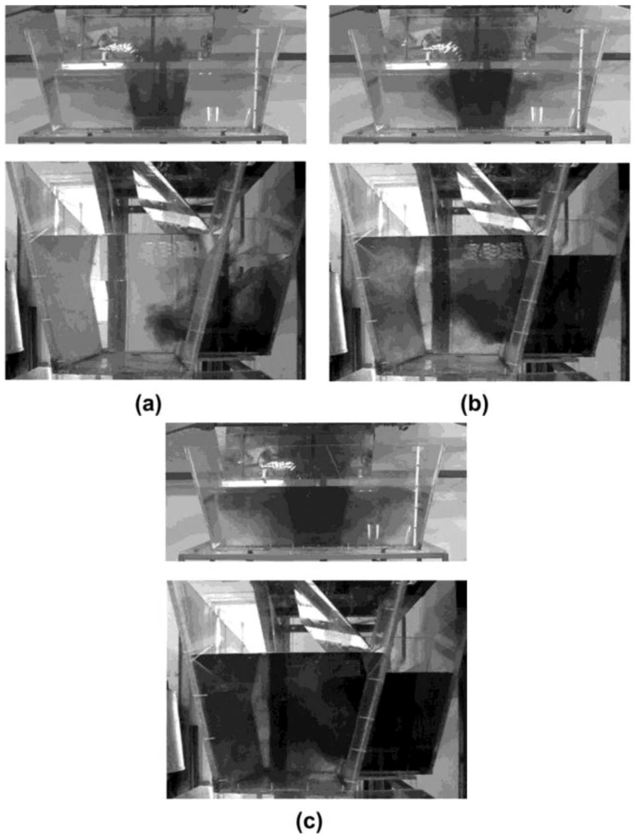

Fig. 4. Tracer propagation in tundish model (case A) after the time: (a) 10s, (b) 30s, (c) 60s

Kinetics of flow for case B (Fig. 5) – working area was equipped with turbulence inhibitor - comparing to case A is weaker. Extension of tracer resident time in a tundish was observed. However, in the area of well mixed flow the very favourable character of water flow was seen. Mixing was sufficient and there was no strong mixing of raising jet with the water surface layer. Turned up upper walls cause that there is additional rotational movement of modelling agent in the area of well mixed flow. This can influence the increase of steel refining intensity in a real object. Further flow of modelling agent through a tundish model has a required character of dispersed plug flow. However, the kinetics of mixing (likewise in other studied variants) in the area of the model back walls was not sufficient.

Fig. 6 presents results of the research for case C – working area is equipped with the baffles placed parallelly to the side walls of the channel part of the tundish model. Creating the extensive area of well mixed is characteristic for this variant.

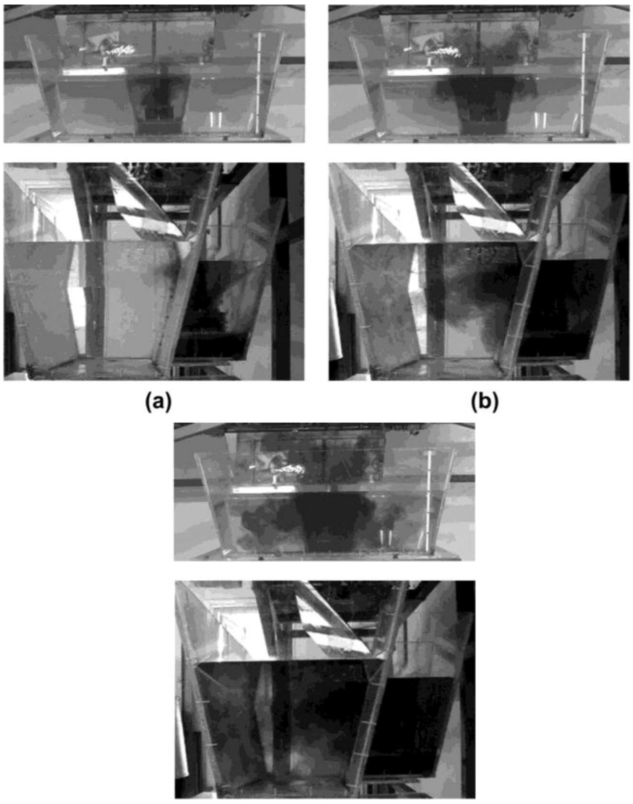

Fig. 5. Tracer propagation in tundish model (case B) after the time: (a) 10s, (b) 30s, (c) 60s

flow. Kinetics of mixing is the highest in the zone of immersed inlet and is diminishing with the movement of liquid in the direction of front tundish wall. Baffles limit possibilities of creating undesirable circulative flow, in the same time directing the modelling liquid jet into the surface favour obtaining required dispersed plug flow in the channel part of a tundish model. It provides the needed contact of flowing steel with slag in real conditions and as a consequence good conditions for steel refining.

To sum up, applying flow control devices in working area of tundish caused expected profitable changes in the kinetics of flow. Installing such devices leads to creating desirable ratio between the area of well mixed flow and the area of dispersed plug flow. It also caused elongation of tracer resident time in the tundish (time that is necessary for a tracer to get to outlets), which influenced the process of forming the transient area (creating favourable conditions for sequence casting). Applying flow control devices, and especially turbulence inhibitor, the volume of dead areas decreased; however it was not possible to eliminate them totally. Places which were particularly susceptible to this problem were areas near back tundish wall (near the liquid surface).

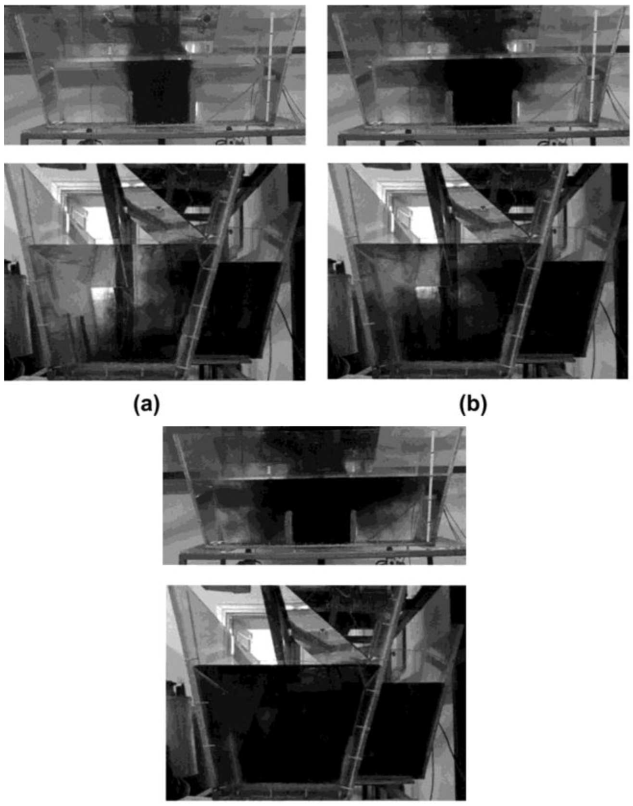

Fig. 6. Tracer propagation in tundish model (case C) after the time: (a) 10s, (b) 30s, (c) 60s

Results of physical modelling – determining the safe level of steel in the tundish. The next stage of the research relied on determining the safe level of steel in the tundish. Moment, in which swirls start to create (considering the possibility of dragging slag into them) in tundish, was indicated. Fig. 7 presents exemplary results of experiments carried out for case A, analogical measurements were conducted for case B and case C.

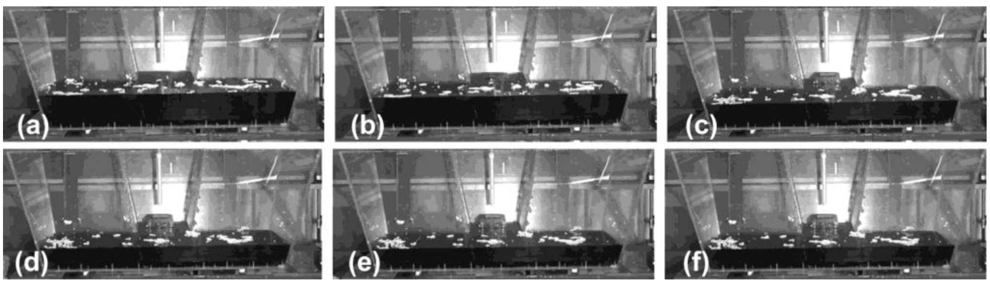

Fig. 7. Modelling research of slag dragging into outlets at the level of filling the tundish model equal: (a) 0.0123 m, (b) 0.0119 m, (c) 0.0107 m, (d) 0.0101 m, (e) 0.0098 m, (f) 0.0096 m

It was found that circulative movement of modelling agent was created near the outlets at the level of water filling equaled 0.125 m (Fig. 7a). With decreasing water surface in the tundish, kinetics of such movement was increasing. At the level of filling 0.098 m (Fig. 7e) distinct and strong circulation of tracer at outlet plane was registered. Considering the big difference in density material of the tracer and modelling agent, there was no sucking of granulated product to the outlet. Therefore, it should be expected that in real conditions (after calculating the model scale) level of tundish filling with steel below 0.24 m can cause dragging the slag into outlet. To verify the above mentioned observations the complementary research was conducted. On the water surface water solution of $KMnO_4$ as a tracer was introduced poinwise and then creation of swirls were observed. Fig. 8 shows creation of swirl and slag dragging into the outlet at the dangerous level of tundish filling (determined in the first stage of research).

Fig. 8 presents the swirls creation in the area of tundish outlet when the filling was at the level between 0.013 to 0.006 m. From the level 0.009 to 0.006 the distinct swirl with meniscus was observed. Fig. 9 shows such phenomenon.

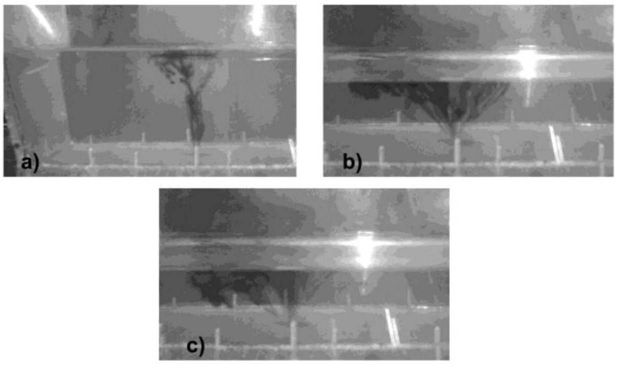

Fig. 8. Visualization of swirls creation in the area of tundish model outlet (case A) at the filling level of the model equaled: (a) 0.013 m, (b) 0.0075 m, (c) 0.006 m

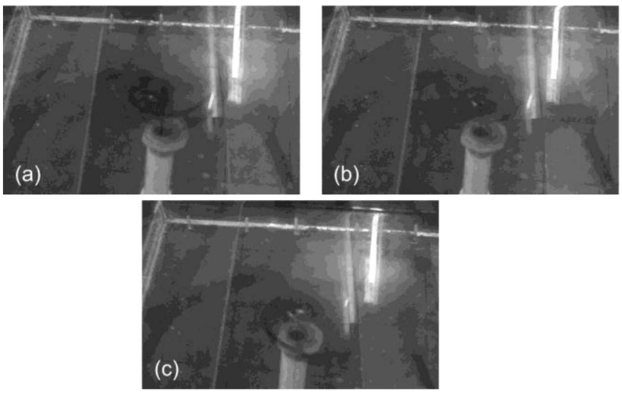

Fig. 9. Creation of swirl meniscus at the modelling agent surface dragging slag at the filling level of the model equaled: (a) 0.009 m, (b) 0.0075 m, (c) 0.006 m

Experiments confirmed conclusions coming from the research obtained in the first stage that steel casting in industrial conditions should be avoided when the level of steel filling is below 0.24 m. In those conditions it is highly possible to drag slag into continuous casting mould. Considering the scale of the model it was calculated that at the level of steel filling equaled 0.12 m, the mass of liquid steel in real object was 0.85 Mg for case A and case B. Whereas, for case C even if this filling level is also 0.12 m the mass of liquid steel in the real object will be 1.2 Mg due to baffles. To conclude, in industrial conditions to avoid danger of slag dragging from tundish to continuous casting mould, the process should be conducted in such a way that the steel mass in tundish is no lower than 1÷1.3 Mg.

Numerical modelling – RTD curves. As a result of numerical calculations for steady conditions, the velocity field distribution and turbulence field for studied cases were obtained [14,19]. To draw RTD curves (Residence Time Distribution) [30] the numerical simulations were made for the earlier determined velocity field assuming unsteady conditions.

RTD curves F-type. As a consequence of calculations characteristics of mixing time (F-type curve) for studied cases were obtained. To compare them directly, they were presented graphically in dimensionless form (Fig. 2). The difference was found between curves (Fig. 2) for case A (bare tundish) and suggested variants of equipping tundish working area (case B and case C). This was caused by the shape of the flow in the area of outlet and a connection with baffles and turbulence inhibitor, which bring about disturbance of the steel flow and mixing. For bare tundish applied in steel plant (case A) the contribution of dispersed plug flow is quite small comparing with suggested variant of equipping the working zone of tundish (case B and case C). In all studied cases the contribution of well mixed flow is dominant. Thus, evaluating the tundish work from hydrodynamic point of view it can be stated that its work is principally correct and enables to sequence casting of different grades of steel. However, this estimation is only qualitative. F-type curves also enable to estimate kinetics of steel mixing in the examined tundish quantitatively. Table 1 presents comparison of values characterizing the kinetics of steel mixing (water model and industrial tundish) in studied object. To count over values obtained for tundish model the following relationship was used [23]:

$$t_{ip} = t' \Big/ \sqrt{S_L} \tag{7}$$

where: S_L – dimensional scale of model, t' – time in water model.

As a comparable range, the time interval Δt was determined, needed to obtain 20% and 80% of maximum concentration (Table 1). The lower values of Δt, the better conditions of mixing.

TABLE 1

Kinetics of steel mixing (transient zone) in the studied cases

Tundish configuration	Kinetics of steel mixing Δt, s		Mass of cast steel, Mg
	Water model, scale 1:2	Scale 1:1	
Bare tundish (case A)	313.5	443.5	3.50
Tundish with turbulence inhibitor (case B)	255.5	361.3	2.87
Tundish with baffles (case C)	256.0	362.0	2.88

Kinetics of steel mixing in tundish model equipped in suggested flow control devices is much better. Presented results prove that bare tundish is not the optimal installation for the casting process. If the value Δt for a given tundish is known, the mass of cast steel can be estimated without any problem, especially if it differs in chemical composition and materials properties forecasted for planned grade of steel. Comparing obtained masses of cast strand (Table 1) it was found that these masses slightly differ for bare tundish (case A) and for baffle and turbulence inhibitor (case B and C). This difference is 0.7 Mg on one strand of CC machine in favour of proposed tundish equipping. If calculating it to the mass of one melt (20 Mg) it constitutes 7% of cast steel.

RTD curves E-type. Fig. 10 presents characteristics of dimensionless concentration and time for analyzed cases. After qualitative analysis (Fig. 10) of obtained curves it can be stated that the kind of applied flow control device influences the change of steel flow character. Earlier mentioned advantages of equipping the working zone of tundish and its role in getting optimal conditions of steel casting are also confirmed. It is also worth mentioning that equipped flow control devices eliminate the danger of steel "short flow". It is advantageous because such phenomenon does not favour floating nonmetallic inclusions.

Applying mathematical relationships (8 to 10) basing on the obtained E-type RTD curves the participations of flow (dispersed plug flow volume (V_{dp}), well mixed flow volume (V_m) and dead flow volume (V_d)) [10] were calculated for the analyzed cases. Table 2 presents obtained results.

$$V_d = 1 - \dot{V}_a / \dot{V} \Theta_c \tag{8}$$

$$V_{dp} = \frac{\left(\Theta_{\min} + \Theta_{peak}\right)}{2} \tag{9}$$

$$V_m = 1 - V_d - V_{dp} \tag{10}$$

$$\frac{\dot{V}_a}{\dot{V}} = \sum_{\Theta=0}^{2} C_i \Delta\Theta \tag{11}$$

$$\Theta_c = \sum_{\Theta=0}^{2} C_i \Delta\Theta \Big/ \sum_{\Theta=0}^{2} C_i \tag{12}$$

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

It was found that the increase of dispersed plug flow for case B and C could be observed (Table 2). The biggest increase is in case B and equals 0.259. It is expected effect of tundish working area modification, because the increase of dispersed plug flow is favourable to floating nonmetallic inclusions.

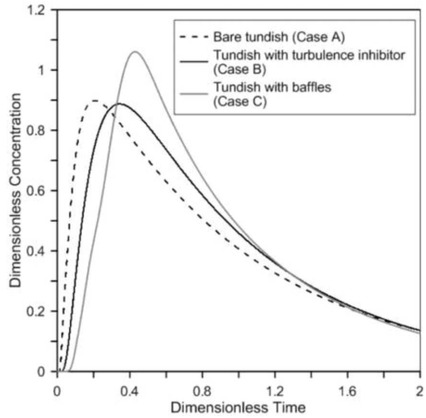

Fig. 10. Residence time characteristics (E-type curves) for the studied tundish equipping

TABLE 2

Calculated contributions of flow for the studied cases

Tundish configuration	Volume fraction		
	Dispersed plug flow (V_{dp})	Well mixed flow(V_m)	Dead flow (V_d)
Bare tundish (case A)	0.188	0.456	0.356
Tundish with turbulence inhibitor (case B)	0.259	0.439	0.302
Tundish with baffles (case C)	0.221	0.502	0.277

Applying flow control devices (baffles and turbulence inhibitor) has insignificant effect on the contribution of well mixed flow. The average contribution was 0.468 for analyzed cases. Presented values of particular flow fractions show that applying baffles or turbulence inhibitor decreases the fraction of dead flow. In case of bare tundish this fraction is the biggest (0.356). The smallest fraction of such flow (0.277) is for case C (tundish with baffles). It is also worth mentioning that optimal tundish should be characterized by well mixing of steel, should have possibly big area of dispersed plug flow and the smallest possible fraction of dead zones. Analyzing results in Table 2 it was found that installing appropriate flow control devices (baffles or turbulence inhibitor) in studied tundish is advisable. Applying such equipment allows to obtain correct ratio of flow volume (dispersed plug and well mixed) with the simultaneous minimization of dead flow. This will definitely influence metallurgical quality of cast strands and will stabilize the process of steel continuous casting.

6. Conclusions

Analysis of obtained results coming from both physical modelling and numerical simulations enables to draw the following conclusions:

- In industrial tundish (case A) the unfavourable hydrodynamic conditions of steel flow and mixing are found, it influences the quality of obtained cast strand.

- Applying flow control devices beneficially effects process of forming the ratio of particular friction of flows (Table 2), and as a consequence shortens the transient zone (Table 1).
- From hydrodynamic point of view using turbulence inhibitor (case B) or baffles (case C) gives almost the same results. Choosing the most proper flow control device can be done using analysis of technical possibilities of its installing and durability and also economic effects of steel CC process.
- The optimal device, considering technical and technological possibilities of the device, seems to be the turbulence inhibitor (case B).

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