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INFLUENCE OF MULTIHOLE LADLE SHROUD CONSTRUCTION ON THE LIQUID STEEL FLOW IN THE ONE-STRAND TUNDISH DURING CSC PROCESS

The tundish prevents unsteady flow affecting on the steel cleanness and temperature. The presented article offers a new design of a ladle shroud (LS) with three holes placed in a special dome (separating the steel flow) steeped in a metal bath. Various options of the LS construction were analysed, as well as its positioning in the tundish in relation to its longitudinal axis. The conducted numerical simulations enabled to assess the impact of the designed ladle shroud on the flow of liquid steel through the tundish. The results showed that the best option is to use the LS with two larger holes and one smaller which activates the flow structure and reduces the rate of the liquid steel velocity in the tundish, limiting the flow turbulence.

Keywords: one-strand tundish; ladle shroud; numerical simulation; hydrodynamic conditions; continuous casting process

1. Introduction

The tundish during the continuous steel casting (CSC) functions not only as a flow reactor connecting the steel ladle with the mold, providing a constant flow between the mentioned devices, but also as a vessel that impacts on the behaviour of the liquid steel in the tundish and thereby improves the steel quality. The optimal hydrodynamics in the tundish should be characterised as flow with as little stagnant flow as possible, stimulating flotation of nonmetallic inclusions from the bulk of steel into the tundish powder. The description of hydrodynamic conditions can be made not only on the basis of determining the shares of individual flows resulting from the RTD (Residence Time Distribution) characteristics, but also on the basis of the flow rate of the liquid steel and on the basis of energy of turbulence. The hydrodynamics in the tundish affects: the intensification of mixing, the level of removal of nonmetallic inclusions from the bath or the mass of the continuous slabs with a transient chemical composition during sequential casting. Nonetheless, too intense turbulence may cause undesirable effects, such as entrainment of the tundish powder drops or particles, which will contribute to the steel contamination, which, in turn, will lead to a reduction of its quality. Control of the liquid steel flowing through the tundish is usually accomplished by the use of flow control devices (FCD), including weirs, dams [1-8] and turbulence inhibitors [9-13]. Intensive scientific research popularised the use of trumpet (TLS) [14-15], dissipative (DLS) [16-18] and swirling ladle shrouds (SLS) [19-21] as devices controlling the flow, but the basic feature of these ladle shrouds is that they begin and end with one hole. Several studies have presented an analysis of the impact of modifying the ladle shroud by including a larger number of holes in the shroud, but the obtained results were not sufficiently satisfactory [22-24]. The presented article offers a new design of a ladle shroud placed in a one-strand tundish with three holes placed in a special dome separating the steel flow and steeped in a metal bath. Various options of the structure of the ladle shroud were analysed, as well as the positioning of the ladle shroud in the tundish in relation to its longitudinal axis. The conducted numerical simulations enabled to assess the impact of the designed ladle shroud on the flow of liquid steel through the tundish, taking into account the share of individual types of flows, the degree of mixing of two grades of liquid steel, the average rate of the liquid steel velocity and intensity of liquid steel turbulence in the working volume of the tundish.

2. Characterisation of test facility and mathematical model

The tested object was a one-strand wedge-shaped tundish widening towards the outlet. It was equipped with a low dam

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0.12 m high with two overflow windows measuring 0.14 × 0.05 m placed in front of the stopper rod system (Fig. 1a). Nominal capacity of the tundish was 30 t. Detailed information about one-strand tundish is presented in the paper [25].

For the purpose of analysing the characteristics of liquid steel flow in a one-strand tundish, three planes running parallel to the longitudinal axis of the device were determined. Two of them – A and C planes were distant from the mentioned axis by 0.25 m towards the longer side walls of the tundish, while the B surface covered the longitudinal axis of the tundish. To describe liquid steel flow in tundish pouring zone and powder zone, the authors created additional plane (Plane D) located 0.01 m under the free surface of the tundish, parallel to this surface and plane transverse to the longitudinal axis – plane E, which was perpendicular to the A-C planes and ran through the center of the ladle shroud (Fig. 1a). Circulation zones appearing on planes A-C and E were marked by a rectangle.

The standard ladle shroud CLS (Conventional Ladle Shroud) with a diameter of 0.07 m (base tundish) and three-hole ladle shrouds impact on the liquid steel flow in the tundish were analysed. The modification of the ladle shroud consisted in placing a dome with two cut sides at the lower end of the shroud, with three holes in the base of the dome. The purpose of the holes is to separate the main stream of steel. Construction of special dome provides slag run-off during the sequential casting, so the ladle shroud is not overloaded and there is no risk of its rapture, while this process.

The height of the holes (h) was equal to the wall thickness of the shroud and amounted to 0.03 m, while the height of the entire ladle shroud (H) was 1.2 m. The internal diameter of the main casting pipe was 0.07 m for all considered ladle shrouds. Modified ladle shrouds differed in the diameter of the holes (d1, d2, d3) steeped in liquid steel and in the arrangement of holes in relation to the longitudinal axis of the tundish (Fig. 1b,c). Details about holes diameter in considered ladle shrouds were presented in the TABLE 1. The ladle shrouds from tundish cases 1, 2a and 3 were located on the line of plane B. The design of ladle shroud from tundish case 2b was the same as that of case 2a, but the shroud was located on the line of plane E. In the steel flow simulations, the ladle shroud was immersed 0.1 m below the surface of the metal bath, and the liquid steel flowed into the tundish with a rate equal 35.13 $kg \cdot s^{-1}$.

TABLE 1

Holes diameters in the modified ladle shrouds used in considered cases of tundish

Tundish case no.	d1 [m]	d2 [m]	d3 [m]
1	0.07	0.11	0.07
2a,b	0.11	0.07	0.11
3	0.11	0.11	0.11

The selection of the test grid was made on the basis of results obtained from two tetrahedral meshes (used in one-strand tundish with CLS) differing to each other in number of elements: approx. 550,000 and 850,000. Determining the impact of the proposed test grids consisted in comparing liquid steel velocities read from three lines carried out as follows: first line was carried out through the center of the ladle shroud from the top of the inlet to the bottom of the tundish, second line located under the end of ladle shroud immersed in metal bath and carried out along the longitudinal axis of the tundish and third line which was carried out through the center of SEN from bottom of the tundish to the outlet. Additionally 8 points were created to compare the average values and standard deviations for liquid steel velocity values read from this points between considered number of iterations (every 10,000 from 10,000 to 150,000, 170,000 and 200,000). Point 1 was located 0.03 m from the tundish bottom, point 2 – at the outlet of the LS, point 3 – 0.03 m under the LS inlet, point 4 – 0.03 m from tundish wall on side of pouring zone,

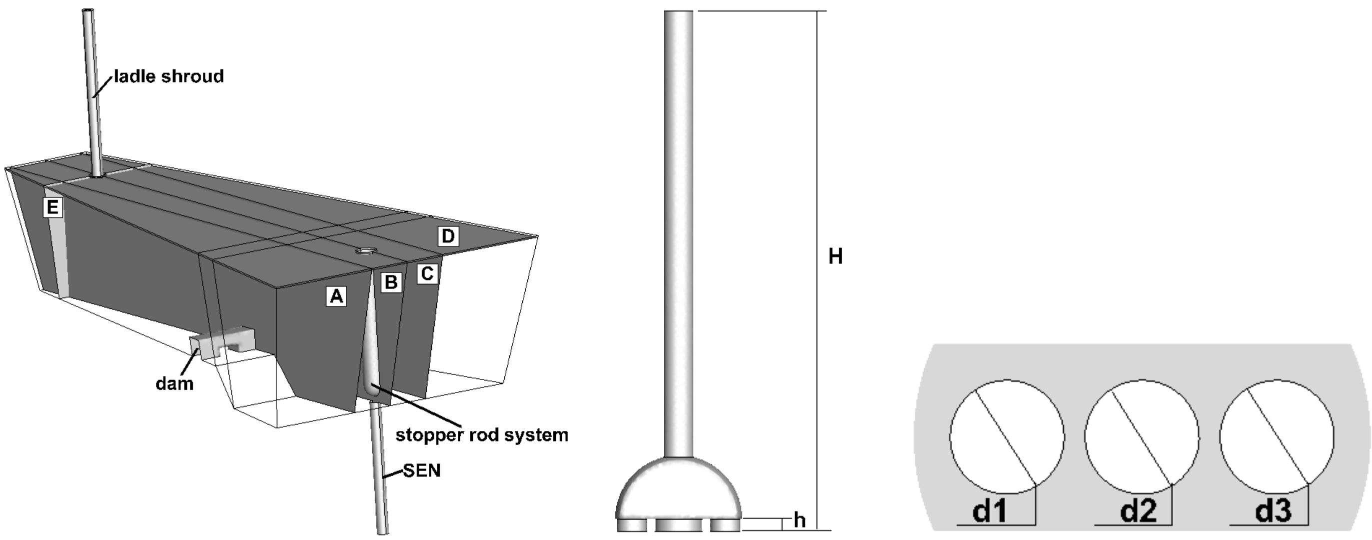

Fig. 1. Virtual model: a) one-strand tundish with analysed planes, b) modified ladle shroud (without external wall) on the example of LS in tundish case no. 1, c) bottom of modified ladle shroud (with external wall) on the example of LS in tundish case no. 3

point 5 – in a feeding stream, point 6 – 0.03 m before stopper rod system, point 7 – located in half of the SEN, point 8 – 0.03 m above the end of the SEN. The results showed similar course of curves (especially at the line coursed along the longitudinal axis (Fig. 2b)) with noticeable differences on the lines located in the ladle shroud and SEN (Fig. 2a,c). Comparing average values of liquid steel velocity for consider meshes in particular points it can be noticed that in most cases this values are similar to each other. Thereafter standard deviation was calculated. Results showed that in points 1, 4, 7 standard deviation in mesh with 850,000 el. is lower, than in mesh with 550,000 el. In points 2 and 3 standard deviation values are very small (less by 3 orders of magnitude) and therefore they are not visible in the chart. In point 8 the standard deviation values for both meshes are nearly the same. This analysis showed that mesh with 850,000 el. is more stable (Fig. 2d).

In order to perform the tests, numerical simulations of the process of continuous casting of steel through a one-strand tundish were conducted. The computer model of the tundish with the ladle shrouds was made in the Gambit 2.4.6 program, while the mesh with averagely 855 thousand tetrahedral elements was made in the Ansys Mesher program. Parameters of the created numerical mesh are as follows: Average Orthogonal Quality – 0.78 and max. skewness – 0.8. The Ansys Fluent 18 program, in which numerical simulations were carried out, bases its solutions on the following equations:

$$\frac{\partial \rho}{\partial t} + \nabla(\rho u) = 0 \tag{1}$$

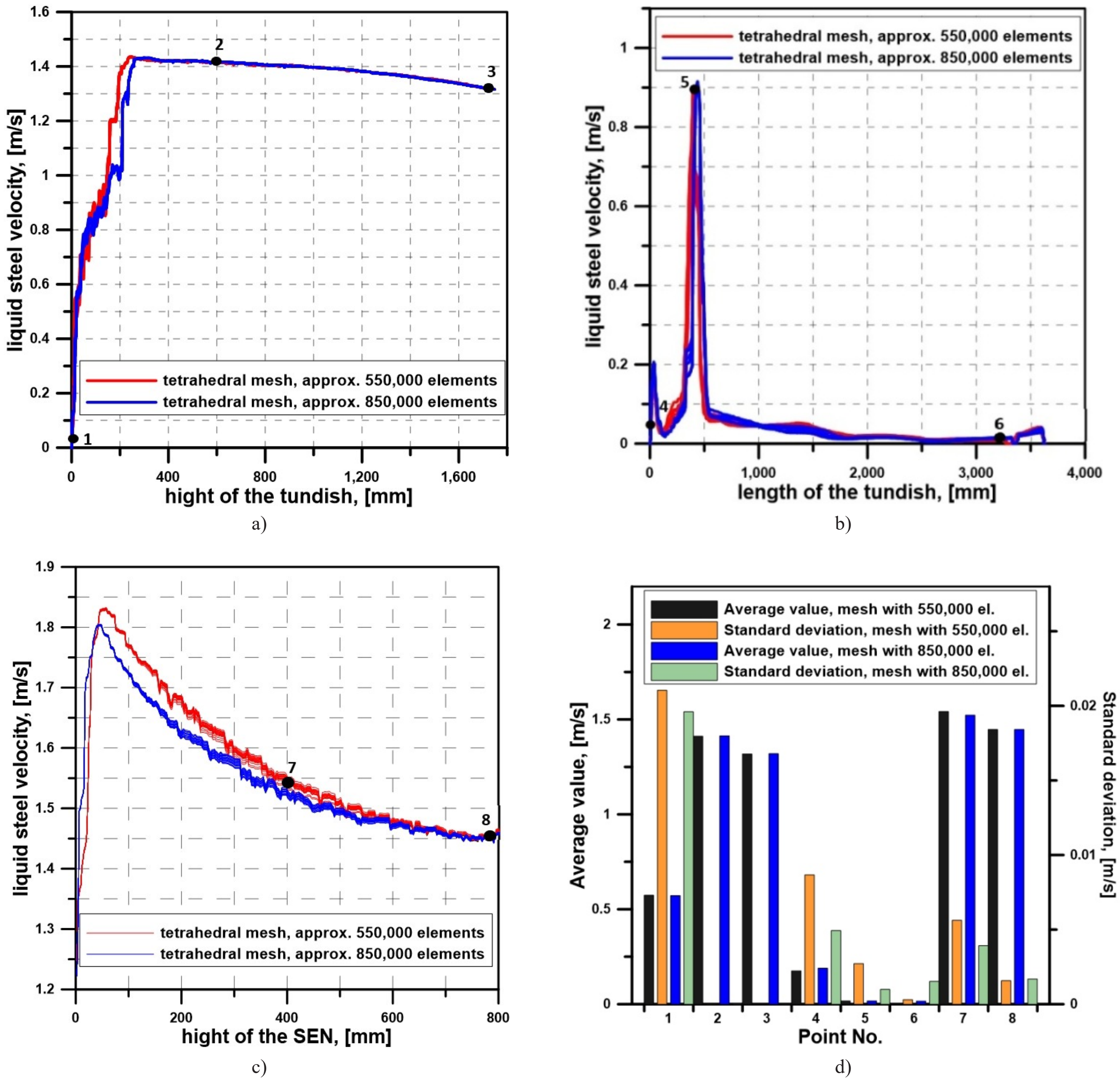

Fig. 2. Impact of two types of mesh on liquid steel velocity values: a) for line carried out through the ladle shroud, b) for line carried out along the tundish, c) for line carried out through the SEN, d) average values of liquid steel velocity and standard deviations for considered points

$$\frac{\partial}{\partial t}(\rho u)+\nabla(\rho u u)=-\nabla p+\nabla\left(\bar{\bar{\tau}}\right)+\rho g \tag{2}$$

$$\bar{\bar{\tau}}=\mu\left[\left(\nabla u+\nabla u^{T}\right)-\frac{2}{3}\nabla u I\right] \tag{3}$$

$$\frac{\partial}{\partial t}(\rho E)+\nabla\left(u(\rho E+p)\right)= =\nabla\left(k_{eff}\nabla T-\sum hJ+\left(\bar{\bar{\tau}}_{eff}\cdot u\right)\right) \tag{4}$$

$$E=h-\frac{p}{\rho}+\frac{u^{2}}{2} \tag{5}$$

$$\frac{\partial C_i}{\partial t}+\nabla\left(-D_i\nabla C_i+C_i u\right)=0 \tag{6}$$

$$\rho=8300-0.7105T \tag{7}$$

Where: t – time, s, ρ – density, $kg\cdot m^{-3}$, u – velocity of the steel flow, $m\cdot s^{-1}$, g – gravitational acceleration, $m\cdot s^{-2}$, p – pressure, Pa, $\bar{\bar{\tau}}$ – stress tensor, Pa, $\bar{\bar{\tau}}_{eff}$ – effective stress tensor, Pa, μ – viscosity, $kg\cdot m^{-1}\cdot s^{-1}$, T – temperature, K, I – unit tensor, E – energy, J, h – enthalpy, J, k_{eff} – effective thermal conductivity, $W\cdot m^{-1}\cdot K^{-1}$, J – diffusion flux, $kg\cdot m^{-2}\cdot s^{-1}$, C_i – concentration of the tracer, $kg\cdot m^{-3}$, D_i – diffusion coefficient of the tracer, $m^{2}\cdot s^{-1}$ [24].

The turbulent motion of liquid steel was described as a result of the usage realizable k-ε model, in which the following constant values were used: C_2 = 1.9, σ_k =1.0, σ_ε = 1.2 [26].

TABLE 2

Liquid steel parameters and initial boundary conditions [26]

Viscosity $[kg\cdot m^{-1}\cdot s^{-1}]$	0.007
Thermal conductivity $[W\cdot m^{-1}\cdot K^{-1}]$	41
Thermal capacity $[J\cdot kg^{-1}\cdot K^{-1}]$	750
Turbulence kinetic energy $[m^{2}\cdot s^{-2}]$	0.0173
Energy of dissipation rate of kinetic energy $[m^{2}\cdot s^{-3}]$	0.06514
Temperature [K]	1823
Velocity at the inlet $[m\cdot s^{-1}]$	1.316

The tests simulated a non-isothermal conditions, which requires the application of the following heat losses: –2600 $W\cdot m^{-2}$ for the walls and bottom of the tundish; –15000 $W\cdot m^{-2}$ for the free surface of liquid steel and –1750 $W\cdot m^{-2}$ for the walls of elements immersed in a liquid steel, i.e. a stopper rod, a dam or a ladle shroud wall. The top wall of the tundish with zero tangential stresses was assumed as the free surface. Liquid steel was casted with 0.015 $m\cdot s^{-1}$ velocity. Slabs dimensions were equal 1.5 × 0.225 m [26].

Flow velocities fields (similarly as turbulence intensity maps) were solved for steady conditions, therefore time was not taken into account. Maps of liquid steel paths and turbulence intensity were took after obtained convergence for calculated flow and temperature fields in the tundish. Then tracer simulation for unsteady conditions was solved. Only RTD curves were calculated consider changes of time. Tundish is one of the reactors, in which fields of liquid steel flow slightly and local fluctuates over the time. The influence of time on liquid steel flow fields has been investigated in the work [26].

In order to determine the share of individual volumes of liquid steel flow and the degree of mixing of two different grades of steel cast successively, the User Defined Scalars (UDS) function was used, thanks to which it was possible to track the marker put into the tundish from the ladle shroud to the nozzle. Based on the analysis of the change of marker concentration as a function of casting time, RTD curves of F and E type were lined out. Based on the obtained curves, the share of individual flow zones in the tundish was calculated. The purpose of usage F-curve is to find solution of modified ladle shroud which will reduce transition zone between two different grades of liquid steel during sequential casting, what's affect on reducing weight of casted slab with mixed chemical composition. The transition zone time was calculated on the basis of the F curve of the dimensionless concentration range within 0.2÷0.8 [25]. Presented numerical model has been validated by industrial and physical trials in the previous work of co-author [26-27]. To assess the share of active and stagnant flow, the combined model was used [28-29]:

$$\Theta=\frac{t}{\bar{t}} \tag{8}$$

$$\frac{Q_a}{Q}=\sum_{\theta=0}^{2}C_i\Delta\theta \tag{9}$$

$$\overline{\theta_c}=\frac{\sum_{\theta=0}^{2}C_i\theta_i}{\sum_{\theta=0}^{2}C_i} \tag{10}$$

In the combined model stagnant flow consist slowly moving fluid between stagnant and active zone.

$$\frac{V_s}{V}=1-\frac{Q_a}{Q}\overline{Q_c} \tag{11}$$

Dispersed plug flow in which all fluid elements have equal residence times in the tundish can be described by expression:

$$\frac{V_p}{V}=\frac{\left(\theta_{\min}+\theta_{\max}\right)}{2} \tag{12}$$

Well-mixed flow in definition ensures the uniform mixing condition in a tundish and can be calculated by equation:

$$\frac{V_m}{V}=1-\frac{V_s}{V}-\frac{V_p}{V} \tag{13}$$

Where: Θ – dimensionless time [-], t – time [s], $\bar{t}$ – the average residence time of the liquid steel in the tundish [s], Q_a – flow in the active region [-], Q – total volumetric flow rate [-], $\overline{\theta_c}$ – mean time of the C-curve [-] , (V_s/V) – stagnant volume fraction [-], (V_p/V) – plug volume fraction [-], (V_m/V) – well-mixed volume fraction [-], $\theta_{\min}$ – dimensionless time of the lowest marker concentration [-], $\theta_{\max}$ – dimensionless time of the highest marker concentration [-].

RTD curve type F, based on Equation 14, was created to determine impact of modified ladle shroud on the duration of transition zone.

$$F = \frac{C_t - C_0}{C_\infty - C_0} \tag{14}$$

Where: C_t – temporary concentration of chemical element [wt %], C_0 – initial concentration of chemical element [wt %], C_∞ – final concentration of chemical element [wt %].

The performed numerical simulations also enabled to determine the average velocity of the liquid steel in the tundish and to determine the maximum Reynolds number (max. height of the tundish – 0.92 m), which defines the intensity of turbulence characterising a given flow [30].

$$\mathrm{Re} = \frac{\rho L u_{av}}{\mu} \tag{15}$$

Where: ρ – density of liquid steel, $\mathrm{kg \cdot m^{-3}}$, L – liquid steel depth in the tundish, m, u_{av} – average velocity of liquid steel in the tundish, $\mathrm{m \cdot s^{-1}}$.

Turbulence intensity was described by following equation:

$$I = \frac{\sqrt{\frac{2}{3} \cdot k}}{u} \tag{16}$$

Where: k – kinetic energy, $\mathrm{m^2 \cdot s^{-2}}$.

3. Results and discussion

An analysis of the impact of the modified ladle shroud on the behaviour of the liquid steel was presented on plane E (Fig. 3). It can be seen that base tundish and tundish cases 1, 2a and 3 show a large flow symmetry on both sides of the feeding stream (Fig. 3a-d). However, tundish case 2b shows a clear lack of flow symmetry in the mentioned plane (Fig. 3e). The analysis of liquid steel velocity showed that its values in the pouring zone under the free surface are similar to each other (Fig. 3a-e). In all tundish cases it can be seen that liquid steel under the ladle shroud is reducing its value. The lowest velocity values are occurring between walls and pouring stream. The most symmetrical velocity distribution can be noticed in tundish cases 1, 2a and 3 (Fig. 3b-d). The legend of the liquid steel velocity values is attached to the Fig. 3 and is describing velocity fields on planes A-E in Figs. 3-5.

By analysing the flow of liquid steel through the tundish on plane A, several circulation zones occurring in the tested options can be noticed. The greatest circulation occurs in the stopper rod zone in each case (Plane A, rectangle 3 Fig. 4a,c-e and rectangle 2 Fig. 4b). Horizontal circulation occurs at the bottom of the tundish, near the pouring stream from the central side of the device (Plane A, rectangle 2 Fig. 4a,c,e and rectangle 1 Fig. 4b,d). The smallest area of this circulation occurs in tundish case 1 (Plane A, Fig. 4b). In tundish case 3, a slight longitudinal circulation is created under the free surface of the metal bath at the height of the low overflow dam (Plane A, rectangle 2 Fig. 4d). In base tundish and in tundish cases 2a and 2b, an elliptical circulation can also be noticed at the ladle shroud from the side of the tundish center (Plane A, rectangle 1 Fig. 4a,c,e). The tundish with the ladle shroud with smaller central hole is marked by the smallest number of circulation zones (Plane A, Fig. 4b). On the C plane, as on the A plane, the greatest circulation occurs in the stopper rod zone and in each of the cases it covers more than half of the tundish height (Plane C, rectangle 3 Fig. 4b, rectangle 4 Fig. 4a,d-e, rectangle 5 Fig. 4c). In each tundish case there is also a longitudinal circulation area at the bottom of the tundish (Plane C, rectangle 2 Fig. 4a-e). In tundishes with CLS and modified ladle shrouds liquid steel recirculations appear near the ladle shroud (in tundish case 3 circulation is shifted towards the center of the device) (Plane A, rectangle 2 and Plane C, rectangle 3 Fig. 4d). The circulation located at the height of the low overflow dam in tundish with ladle shroud with three holes measuring 0.11 m occurs on both planes but on the plane C it is closer to the second circulation under the free surface (Plane A and C, rectangle 2 Fig. 4d). Plane C in all tundish cases is characterised by higher amount of circulations than in the plane A (Fig. 4). Analysis of liquid steel velocity fields in all tundish cases showed that higher velocity values appear in pouring zone and reach 0.26 m/s near the short wall located close to the pouring stream. It can be seen that the liquid steel reaches lower values in the area of the center of the tundish to the stopper rod zone in the middle of the volume of the device (values in the range 0.027-0.005 m/s).

The flow on the B plane in the illustrated cases is similar to each other. The main difference is in the largeness of circulation that occurs between the overflow stream and the closer short wall of the device. It covers the largest area in base tundish case and tundish with turned ladle shroud (Plane B, rectangle 1 Fig. 5a and e). In the middle of the tundish bottom, an elliptical circulation can also be seen, reaching below the half of the tundish (Plane B, rectangle 2 Fig. 5a-e). It covers the largest area in tundish case 2b (Plane B, rectangle 2 Fig. 5e). Comparing velocity maps from planes A and C to plane B it is also shown that liquid steel velocities are higher in the pouring zone. It can be seen that the feeding stream achieves velocity on a level around 0.5 m/s near to the bottom of the device. In tundish cases 1, 2a and 3 the area of slower flowing liquid steel moves towards the bottom of the device (Plane B, Fig. 5b-d). The greatest area of slower flowing fluid can be noticed in tundish case 3 (Plane B, Fig. 5d).

To investigate the effect of liquid steel behaviour on slag entrapment the additional plane D has been made. It can be noticed that 0.01 m under the free surface liquid steel velocity is similar in all tundishes and changes to a small extend (Plane D, Fig. 5a-e). The least symmetrical liquid steel velocity distribution can be seen in tundish case 2b (Plane D, Fig. 5e). The highest velocity on plane D occurs in the pouring zone and doesn't exceed 0.1332 m/s. The Authors of works [31-34] indicated that the critical liquid steel velocity, which causes slag emulsification, depends on the parameters of the slag and its value is within the range 0.3-0.5 m/s. It can be seen that obtained in the presented work values are significantly lower than above mentioned values.

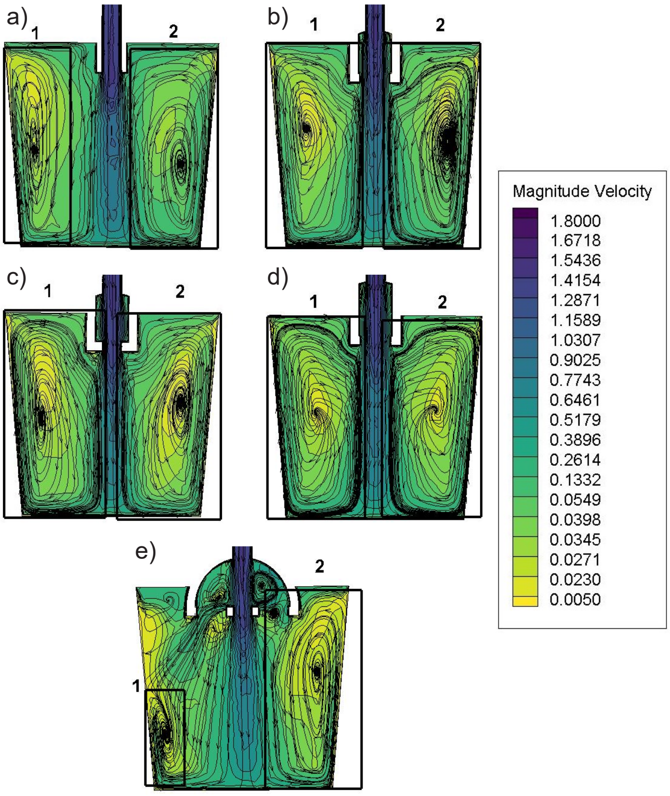

Fig. 3. Liquid steel paths and fields of liquid steel velocity for the plane E for steady conditions: a) base tundish with CLS, b) tundish case No. 1, c) tundish case No. 2a, d) tundish case No. 3, e) tundish case No. 2b

However, local zones of possible vortexes formation occur in tundish with CLS and tundish cases 1, 3 and 2b that can affect on slag behaviour (Plane D, Fig. 5a-b,d-e).

The analysis of the share of individual flows of liquid steel in a one-strand tundish showed that the largest share of stagnant flow, at the level of approx. 34.5%, appears in tundish with modified ladle shroud in tundish case 2b. An improvement in the value of the share of stagnant flow in relation to the base tundish was noted in tundish case 2a, for which less than 30.0% of this flow was obtained. A share of a similar value was obtained in tundish cases 1 and 3- the results fluctuate around 32.6-33.0% and they are higher by over 1.0% than the share obtained in base tundish with conventional ladle shroud. By analysing the plug flow share, the highest percentage share can be seen in tundish case 2b – it amounts around 11.7% (where the θ_{min} was about 0.0004 and θ_{max} was about 0.23) and it is almost 3% higher than for tundish with CLS (where the θ_{min} was about 0.0009 and θ_{max} was about 0.18). In tundish case 1 θ_{min} is close to the value from tundish with CLS and is equal to 0.0009, but θ_{max} is 0.19. In tundish case 2a the values of θ_{min} and θ_{max} are equal, respectively, 0.002 and 0.21 and for tundish case 3 – 0.0005 and 0.19. The value of the plug flow share in all tundish cases with ladle shroud located on the line of plane B is slightly higher than when using a CLS (Fig. 6a,b), however, the difference is not significant. The biggest difference in the obtained results can be noticed in the share of the well-mixed flow. In all tundish cases with

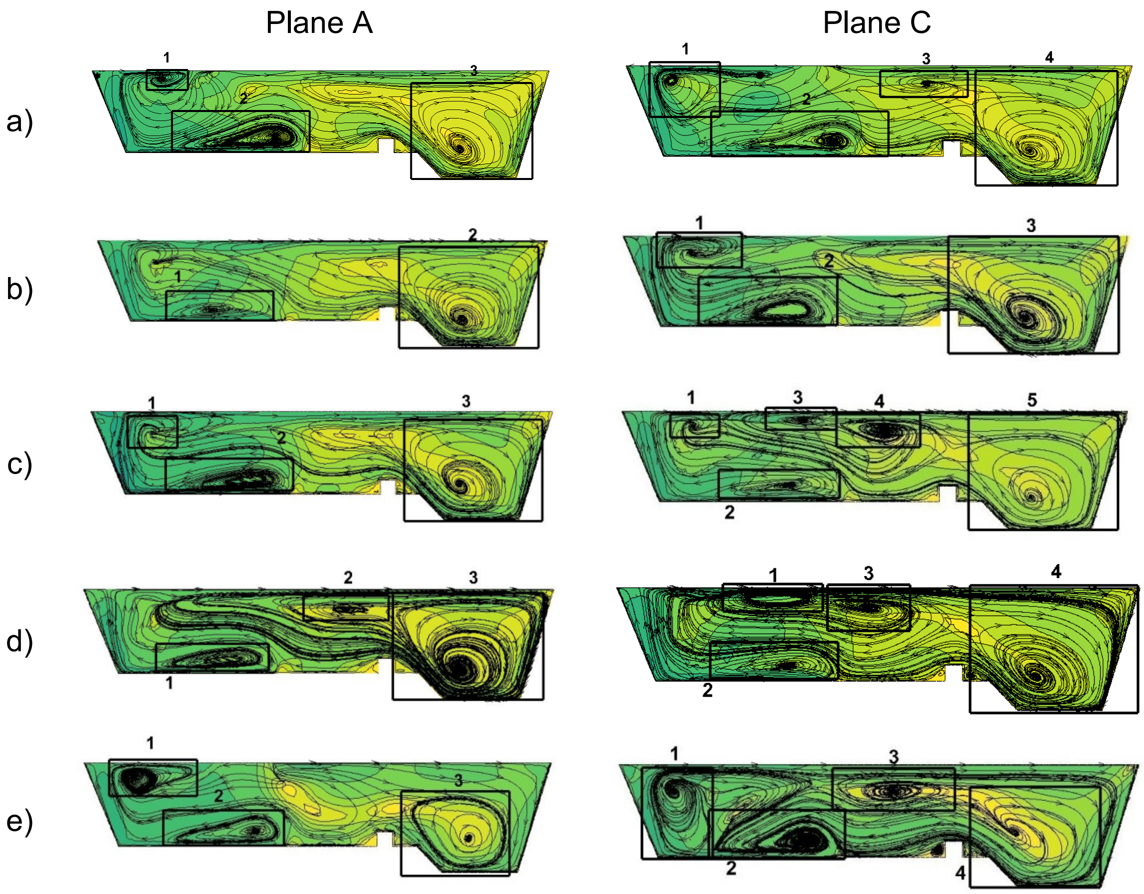

Fig. 4. Liquid steel paths and fields of liquid steel velocity for planes A and C for steady conditions: a) base tundish with CLS, b) tundish case No. 1, c) tundish case No. 2a, d) tundish case No. 3, e) tundish case No. 2b

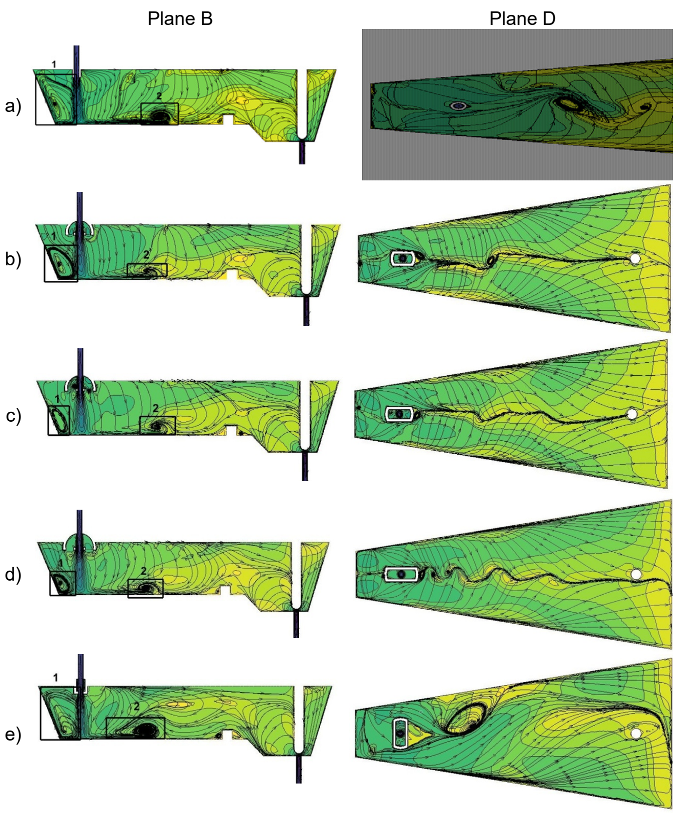

Fig. 5. Liquid steel paths and fields of liquid steel velocity for the plane B and D for steady conditions: a) base tundish with CLS, b) tundish case No. 1, c) tundish case No. 2a, d) tundish case No. 3, e) tundish case No. 2b

modified ladle shrouds share of well-mixed flow is lower than in base tundish. The highest difference can be noted in tundish case 2b were the share is smaller by almost 6.0%. In tundish case 3, the share of this type of flow is at similar level, while in tundish case 1 is higher by over 2.0% (Fig. 6b).

As part of the analysis of the impact of individual modifications of the ladle shroud on the characteristics of the liquid steel flow through a one-strand tundish, the length of the mixing zone occurring during sequential casting of two steel grades of different chemical composition was also determined. The application of modified ladle shroud in tundish case 2a enabled to reduce the duration of the transition zone by 20 seconds compared to tundish with CLS. The longest duration of the mixing zone occurs in tundish case 1 and amounts to 759 seconds. The duration of the mixing zone is related to casting of slabs with a transient chemical composition. According to the obtained duration of the mixing zone, the smallest weight of the slab with a transient chemical composition is in tundish case 2a – 25,445 kg, and the largest is in tundish case 1 – 26,935 kg. This is 713 kg less (for tundish case 2a) and 777 kg more (for tundish case 1) compared to the base tundish, in which the weight of the slab was 26,158 kg (Fig. 6c,d).

In the base tundish with conventional ladle shroud, the most intense turbulences appear in the place of the overflow stream, its contact with the bottom of the tundish and in the lower part of the closer short wall (Fig. 7a). In tundish case 1, the greatest turbulence intensity appears at the point of the impact of overflow stream on the tundish bottom at the height of the central hole with a diameter of 0.11 m at the shroud bottom. As it moves away from the overflow stream towards the center of the tundish, the intensity of turbulence decreases. Lower intensity turbulence occurs above 1/3 of the tundish height (Fig. 7b). In the tundish with the applied ladle shroud with center hole smaller, the highest turbulence intensity occurs in the area of the overflow stream and at the bottom of the device. The farther away from the overflow stream and the closer to the surface of the free metal bath, the turbulence becomes less intense (Fig. 7c). In tundish case 3, similarly to tundish case 1, the highest turbulence intensity occurs in the area of the overflow stream, however, compared to tundish case 2a, higher intensity of turbulence can also be noted in the upper part of the tundish (Fig. 7b,d). In a tundish with the ladle shroud perpendicular to the longitudinal axis of the tundish, the intensity of turbulence increases with the descending of the overflow stream, and the intensity of turbulence from the center of the tundish is very irregular (Fig. 7e). In all tundish cases, turbulence intensity in the range of 0.108 to 0.152 occurs between the overflow stream and the closer short wall of the device. By analysing the modification of the ladle shroud, it can be noticed that the most intense turbulence occurs in the modified part of the ladle shroud with center hole smaller, applied on the line of plane B (Fig. 7a-e). Application of the modified ladle shrouds causes an increase of turbulence intensity in the feeding stream. The greatest increase in its value occurs in tundish case 3. However, in tundish cases 1, 2a and 2b it decreases its value towards the center of the device. The impact of holes diameter on turbulence intensity in tundish is seen in tundish case 2b, where the central hole with 0.07 m diameter directs liquid steel perpendicular to the tundish bottom, reducing dispersion of feeding stream. Therefore the turbulence intensity is irregular in its range on the central side of tundish (Fig. 7e).

The analysis of the average flow rate of liquid steel in the entire volume of a one-strand tundish showed that its highest values – over 0.038 $m \cdot s^{-1}$ – occur in tundish with CLS and in tundish cases 1 and 3. The lowest average rate value occurs in tundish with ladle shroud located on the line of plane D and amounts to ~0.034 $m \cdot s^{-1}$. At the same time, the highest value of the max. Reynolds number, less than 37,000, appears in tundish case 1, while the lowest value appears in tundish case 2b and amounts to ~32,795 (Fig. 8).

As mentioned earlier treating ladle shroud as a flow control device which has an effect on liquid steel behaviour is one of the subjects on which scientists' attention is focused. Finding the right ladle shroud is a complex task, which consists of, among others, determination of share of individual flows, liquid steel impact on slag layer, impact of pouring stream on tundish refractory lining, nonmetallic inclusions removal, temperature distribution in tundish or calculating of the transition zone and the mass of the slab with mixed chemical composition [14-20,22-24,35].

The aim of the Authors was to find a new construction of ladle shroud which could completely replace another flow control

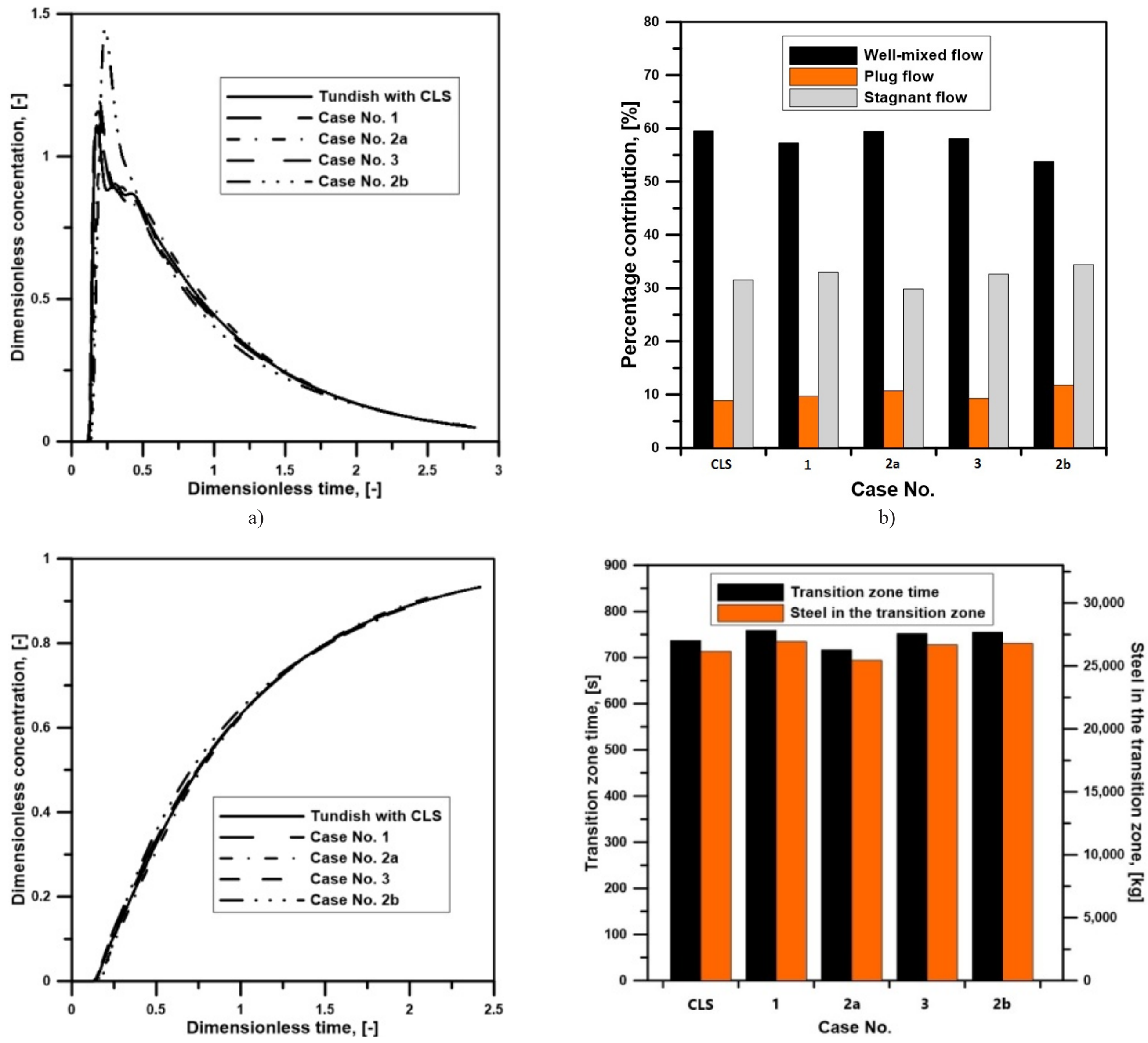

Fig. 6. Tundish hydrodynamics: a) RTD curve- type E, b) flow zones for considered tundish cases, c) RTD curve- type F, d) slab weight and casting duration in considered tundish cases

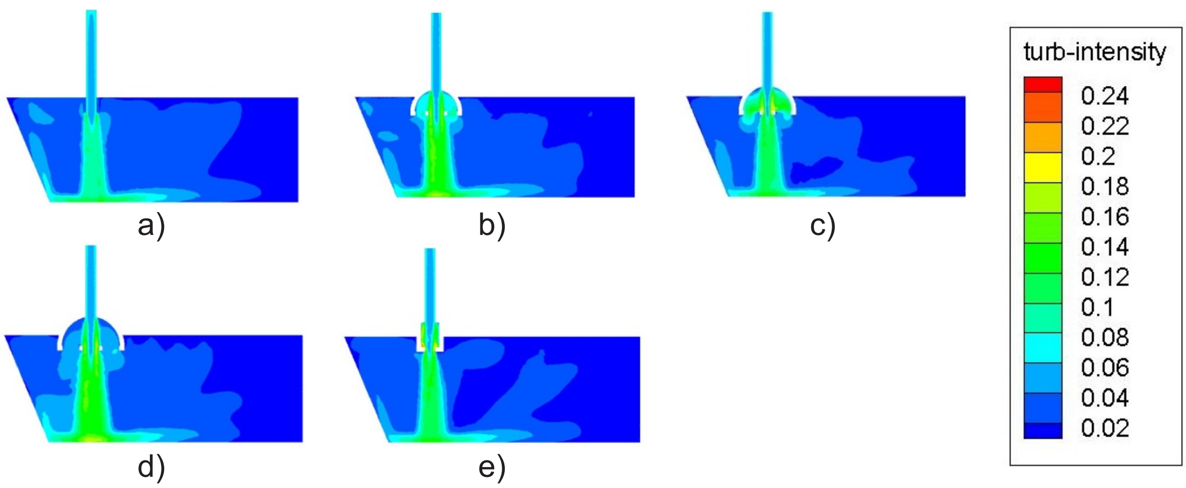

Fig. 7. Turbulent intensity maps for the plane B for the impact zone for steady conditions: a) base tundish with CLS, b) tundish case No. 1, c) tundish case No. 2a, d) tundish case No. 3, e) tundish case No. 2b

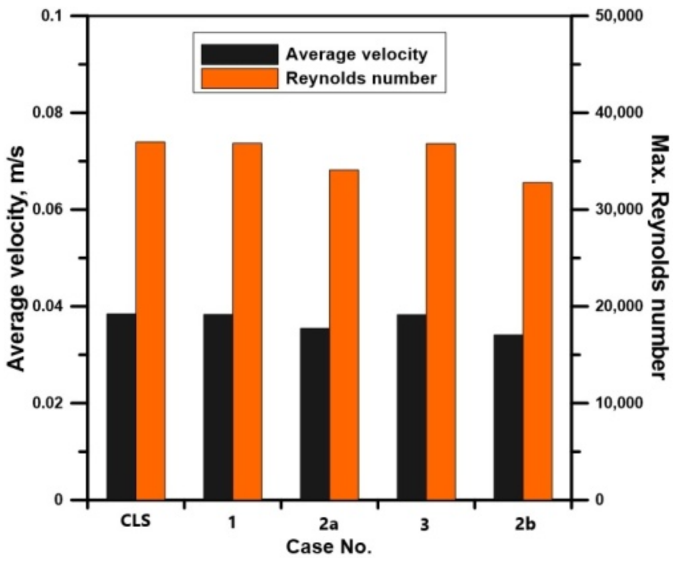

Fig. 8. Average liquid steel velocity in the bulk of liquid steel and max. Reynolds number for considered tundish cases

devices as impact pads, weirs or dams. In science journals some works showed the effect of the modified ladle shrouds on tundish hydrodynamics. Morales-Higa et. All. [16] showed that usage of modified ladle shroud which is dispersing the feeding stream (DLS) instead CLS in bare tundish decreases stagnant volume and increases plug volume share. They stated that it is possible to use only DLS without any flow control devices. Solorio-Diaz et all. [17] indicated that although usage of turbulence inhibitor and dam supports inclusion removal, the best option is to use SLS without FCD, which is able to handle different mass flow rates of liquid steel.

In this papers Authors proposed to use new modifications of the ladle shroud without appliance any control devices. Analysed factors which were the diameters of the holes located in the dome, as well as the method of setting the ladle shroud in relation to the longitudinal axis of the tundish.

Some researchers [14,17,19] studied new ladle shroud impact on turbulence intensity and velocity in pouring zone and in volume of the tundish. It is favorable to reduce its value to avoid destruction of refractory lining protecting tundish walls. In the basis of studies it was noted that the appropriate construction of LS reduces turbulence intensity. Comparing to mentioned works, proposed multihole ladle shrouds designed by Authors of this work, showed positive effect on the properties mentioned above.

It was also shown by Bartosiewicz and Cwudziński [35] that it is possible to reduce mass of transition slab by usage only modified ladle shroud without any fluid control devices. In the following work also noted reduction of slab mass in transition zone.

Analysis of the velocity distribution of liquid steel made it possible to assess the risk of slag entrainment by liquid steel. Based on obtained results, it was proved that the use of new ladle shrouds doesn't contribute to the slag entrainment into the tundish.

On the basis of the conducted test the Authors stated that there is one modification which decreases stagnant volume and decreases also slab with transient chemical composition during sequential casting. In the tundish cases 2a and 2b analysis of the Reynolds number indicated a decrease in its value. It is also shown that none of the modification doesn't negatively affects on slag layer.

4. Conclusion

On the basis of the conducted research, it was found that:

1) A symmetrical flow of liquid steel in the pouring zone of the tundish is possible only when the considered ladle shrouds are set parallel to the longitudinal axis of the tundish.
2) The use of a modified ladle shroud, in which the central opening has a diameter smaller than the diameter of the side openings (tundish case 2a), increases the intensity of turbulence inside the ladle shroud volume, while increasing the diameter of all the ladle shroud holes immersed in the liquid steel increases the turbulence intensity in a larger area around the overflow stream.
3) The use of modified ladle shroud with 0.07 m diameter central hole is the most advantageous in terms of reducing the stagnation area. A significant increase in the share of mentioned area occurs as a result of the application of the same ladle shroud but in the transversal position.
4) Only the use of ladle shroud with 0.07 m diameter center hole which is located in parallel with tundish longitudinal axis reduces the mass of the slab with a transient chemical composition during sequential casting.
5) The best solution is to use modified ladle shroud from tundish case 2a because it activates the flow structure and reduces the rate of the liquid steel velocity in the tundish, limiting the flow turbulence.

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