www.czasopisma.pan.pl PAN www.journals.pan.pl

ARCHIVES
of
FOUNDRY ENGINEERING

ISSN (2299-2944)

10.24425/afe.2024.151319

Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences

Numerical and Physical Modeling of Steel Flow Behavior in the Two Strand Tundish During Nonconventional Pouring Conditions

A. Cwudziński [a, *], B. Bul'ko [b], P. Demeter [b]

[a] Czestochowa University of Technology, Faculty of Production Engineering and Materials Technology, Department of Metallurgy and Metals Technology, Poland

[b] Technical University of Košice, Faculty of Materials, Metallurgy and Recycling, Institute of Metallurgy, Slovak Republic

* Corresponding author: E-mail address: adam.cwudzinski@pcz.pl

Received 12.08.2024; accepted in revised form 10.10.2024; available online 31.12.2024

Abstract

Tundish is a flow reactors, hence there is a strong correlation between its flow control devices such as dam, subflux flow controller, gas permeable barrier or advanced ladle shroud equipped, its shape of the internal working volume and the number of outlets visible in the formation of individual hydrodynamic structures. During numerical and physical simulations, the process of continuous steel casting of two slabs with dimensions of 1.15 m × 0.225 m at a speed of 1 m/min was simulated. Two-strand tundish with and without subflux flow controller (SFC) was tested. Off-centered location of subflux flow controller and ladle shroud misalignment in the tundish pouring zone were investigated. Basis on the obtained results the non-standard interaction of the feed stream with the SFC working space revealed the occurrence of a favorable hydrodynamic structure in the tundish working space in the context of limiting the stagnation flow. This is show by the formed hydrodynamic structure consists of vertically circulating streams of liquid steel, effectively eliminating and limiting the impact of reverse streams.

Keywords: Tundish, Subflux flow controller, Ladle shroud, Physical trials, Numerical modelling

1. Introduction

Processes related to achieving a 95% degree of chemical and thermal homogenization and refining of liquid steel are carried out in the ladle at the secondary metallurgy processing station. Then comes the stage of pouring liquid steel in the ladle, tundish and mould system, where the solidification process is initiated. In the process of continuous steel casting, dosing of liquid metal with the lowest possible superheating temperature and with low content of non-metallic inclusions and gases is possible, among others, by using advanced technical and technological solutions in the tundish [1-8]. In the technical aspect, tundishes are characterized by different shapes of the working volume depending on the type, dimensions and number of billets or blooms or slabs cast at the same time. Typically, tundishes are equipped with flow control devices (FCD) to maximize the volume of active flow, maintaining a stable temperature of the liquid steel and supporting the flotation of non-metallic inclusions [9-18]. From the technological point of view, the refractory lining of the working layer of the tundish and the tundish powder covering the surface of the liquid steel should minimize chemical reactions with liquid steel components or liquid steel components with the air atmosphere. At the same time, the selection of the chemical composition of the tundish powder should stimulate the absorption reactions of exogenous non-metallic inclusions. The tundish is a flow reactor, hence there is a strong correlation between its flow control devices (FCDs) equipped, its shape of the internal working volume and the number of outlets visible in the formation of individual hydrodynamic structures [19-24]. Hydrodynamic structures in the tundish working space also evolve when the flow control devices are improperly mounted in the tundish working space or when the ladle shroud is diverted from the vertical [25-26]. Lack of control over this process results in chemical and thermal inhomogeneities in individual strands of the continuous steel casting machine. Moreover, improperly using of FCD occur the local gradients in the velocity of liquid steel, which generating destabilization of the tundish powder i.e. "slag eye". On the other hand, appropriately selected tundish development combined with the asymmetric location of the flow control devices (FCD) in the pouring zone effectively intensifies active flow [27]. In this study, the influence of the displacement of the subflux flow controller and the deviation from the vertical of the ladle shroud in the pouring zone of the tundish was investigated.

2. Methodology

2.1. Tundish

The tested two-strand tundish is an element of a device for continuous casting of slabs (Figure 1). The dimensions of the tundish are described in detail in paper [28]. In the pouring zone of the tundish, a subflux flow controller (SFC) was installed, the dimensions of which are presented in paper [29]. The main dimensions of considered tundish show Table 1. The tests were performed for two variants of tundish with regulation of steel flow to the secondary cooling zone, i.e. with and without a stopper rod system (SRS). Liquid steel flowed into the tundish from the ladle through a ladle shroud with an internal diameter of 0.09 m. The internal diameter of the submerged entry nozzles supplying liquid steel to the moulds was also 0.09 m. The tundish has a characteristic lowering of the bottom in the area of the nozzles with a depth of 0.198 m, the purpose of which is to protect the liquid steel against the slag phase entering it at the final stage of the casting sequence.

Table 1.
Dimensions of tundish and subflux flow controller

Tundish	Unit, m	SFC	Unit, m
Upper lenght	7.27	Upper edge of square	0.5
Lower lenght	6.94	Lower edge of square	0.5
Upper width	1.13	Height of square	0.3
Lower width	0.89	Diameter of internal hemisphere	0.45

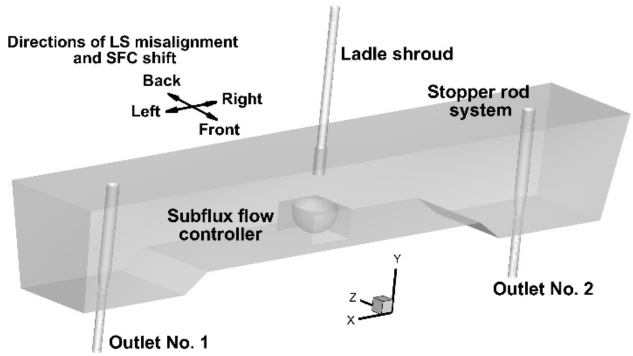


Fig. 1. Two-strand slab tundish with subflux flow controller and stopper rod system

2.2. Casting conditions

During numerical and physical simulations, the process of continuous steel casting of two slabs with dimensions of 1.15 m × 0.225 m at a speed of 1 m/min was simulated. During the tests, the development of the hydrodynamic structure in the tundish without and with SFC was verified. For the tundish variant without flow control devices (FCD), the standard position of the ladle shroud and its tilt towards one of the tundish nozzles by 5° and towards the longitudinal tundish wall by 4° were tested. Then, using SFC, two depths of immersion of the ladle shroud in liquid steel were tested. As standard, the ladle shroud was immersed in liquid steel to a depth of 0.277 m. Additionally, in casting conditions No. 5, the influence of the ladle shroud's immersion depth was tested by increasing its immersion to 0.544 m. At this research stage, the influence of the SFC position relative to the axis of the ladle shroud was also verified. In the third research stage, the angle of deviation from the vertical of the ladle shroud was changed with the standard installation of the SFC. All casting variants are listed in Table 2.

Table 2.
Considered tundish pouring conditions

No. of casting conditions	Type of FCD	Location of SFC	Ladle shroud misalignment
1	none	n/a	n/a
2	none	n/a	5° right
3	none	n/a	4° front
4	SFC	centre	n/a
5	SFC	centre	n/a*
6	SFC	0.15 m back	n/a
7	SFC	0.075 m back	n/a
8	SFC	0.15 m front	n/a
9	SFC	0.075 front	n/a
10	SFC	centre	2° right
11	SFC	centre	5° right
12	SFC	centre	2° left
13	SFC	centre	5° left
14	SFC	centre	4° front
15	SFC	centre	4° back

* deeper immersion in the liquid steel

2.3. Physical water modelling

The physical model made of plexiglass with a nominal capacity of 0.4 m^3 at a scale of 0.33 reflects the actual tundish (Figure 2). Physical modeling was performed in accordance with the criterion of geometric and dynamic similarity, using the dimensionless Froude number as a basis. The water flow rate during laboratory experiments was 36 l/min. During the tests, a marker in the form of a KCl solution was introduced into the water. Then, the change in the degree of water conductivity was recorded at individual outlets of the tundish, obtaining the distribution of tracer concentration as a function of time in the form of a residence time distribution (RTD) curve.

Fig. 2. 0.33 scale water model of two-strand slab tundish

2.4. Numerical modelling

Numerical calculations were performed in the Ansys-Fluent program. The following physicochemical properties of liquid steel were assumed: density as a function of temperature, viscosity 0.007 Pa·s, thermal conductivity 41 W/m·K, heat capacity 750 J/kg·K [29-30]. Liquid steel flowed into the tundish at a velocity of 1.35 m/s. The initial kinetic energy of turbulence was 0.0182 m^2/s^2, and the dissipation energy of the kinetic turbulence energy was 0.0546 m^2/s^3. These values were calculated on the formulas presented by Morales et al. [31-32]. The turbulence model using to predict turbulence phenomena was k-epsilon realizable. The temperature of the liquid steel flowing into the tundish was 1828 K. Computer simulations to validate the numerical model were performed for isothermal conditions, while simulations verifying the evolution of hydrodynamic structures in the tundish were performed for non-isothermal conditions. Therefore, on the walls and bottom of the tundish, heat losses in the form of a heat flux equal to -2600 W/m^2 were assumed, and on the surface reflecting the free surface of liquid steel, the heat flux was equal to -15000 W/m^2 [30, 33-35]. The free surface of liquid steel was reflected by the boundary condition of a wall with zero shear stresses. Simulations were performed for a single-phase system with a constant level of liquid steel in the tundish equal to 1.09 m. Non-isothermal calculations concerned the tundish filled with an average of 46.7 Mg of liquid steel. Hence, the average residence time of liquid steel in the working volume of the tundish was 790 seconds.

The numerical model for the transfer of fluid components in the form of the species model took into account the physico-chemical properties of the tracer. Therefore, in order to eliminate the influence of density on the process of mixing the tracer with liquid steel, a portion of liquid steel numerically isolated in the form of a pulse at the tundish inlet was used as a tracer. The tracer concentration distributions obtained in numerical simulations at the tundish outlets in the form of RTD curves were the basis for the assessment of the hydrodynamic structure. Based on the combined model taking into account the dispersion of plug flow and mass exchange between the zone of active and stagnant flow, the hydrodynamic structure, volume fractions of plug flow, stagnation and ideal mixing were described [36-37]. Thus, the following equations were used during calculations:

$$C_{[-]} = \frac{V_{ls}}{W_m} \cdot C_t \tag{1}$$

$$\theta = \frac{t}{W_{ls}/Q_m} \tag{2}$$

$$\frac{V_s}{V_{ls}} = 1 - \frac{Q_a}{Q} \cdot \theta_c \tag{3}$$

$$\frac{V_p}{V_{ls}} = \frac{\theta_{\min} + \theta_{peak}}{2} \tag{4}$$

$$\frac{V_m}{V_{ls}} = 1 - V_p - V_s \tag{5}$$

where: $C_{[-]}$ - dimensionless concentration of marker, V_{ls} - volume of liquid steel in the tundish, W_m - weight of marker, C_t - temporary concentration of marker, Θ - dimensionless time, , t - time, W_{ls} - weight of liquid steel in the tundish, Q_m - mass flow rate, V_s - volume of stagnant region in the tundish, V_p - volume of plug region in the tundish, V_m - volume of mixing region in the tundish, Q - total volumetric flow rate through the tundish, Q_a - volumetric flow rate through the active region of a tundish, Θ_c - dimensionless average mean residence time up to Θ=2, Θ_{min} - dimensionless time of first appearance of marker, Θ_{peak} - dimensionless time of maximum concentration of marker.

3. Results and discussions

3.1. Model validation

In the first research stage, the correctness of the representation of hydrodynamic conditions by the numerical model was verified by performing laboratory experiments using water. Figure 3 shows the residence time curves of liquid steel in the tundish for both outlets. The presented data show that in a tundish with SFC, the flow in relation to the feed zone is almost symmetrical. Average values reflecting the change in salt concentration in water as a function of time for both tundish outlets were plotted on the obtained numerically hydrodynamic system. The shape of the curves from numerical and physical simulations is quite similar. However, the quantitative analysis of the value of the plug flow volume showed a difference of 3.8%. Hence, based on qualitative analysis (shape of curves) and quantitative analysis (share of plug flow), the effectiveness of the numerical model in assessing hydrodynamic phenomena in the tundish is sufficient.

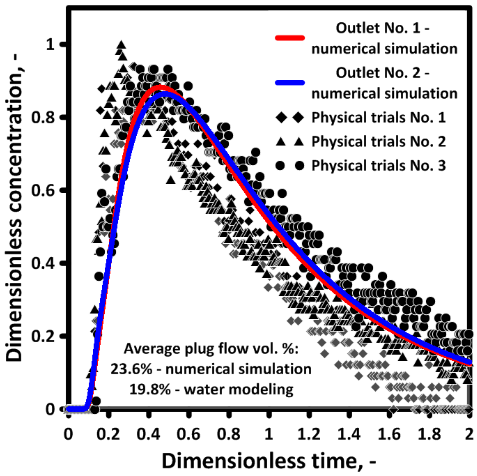


Fig. 3. Residence time distribution of liquid steel and water in the tundish - comparison of numerical and physical results

3.2. Numerical results – active flow contribution

Based on the results from computer simulations regarding the tracer distribution as a function of time, the volume share of plug flow (Figures 4, 6 and 8) and stagnation flow (Figures 5, 7 and 8) in the overall flow structure developing in the tundish was calculated. In Figures 4-8, the results refer to both tundish outlets and two variants of steel flow regulation to the primary cooling zone. In a tundish without FCD, the average share of plug flow at the level of 10% and stagnation flow at the level of 34% indicates the need to look for solutions that activate more than 1/3 of the volume of liquid steel (Figure 4). Moreover, the occurrence of tilting of the ladle shroud, especially towards one of the outlets, significantly introduces asymmetry in the flow structure, resulting in an 80% increase in the share of stagnant flow in the area of one of the outlets (Figure 5). However, the tilt relative to the longitudinal tundish wall does not significantly disturb the symmetry of the liquid steel flow in relation to the pouring zone, but maintains the share of stagnant flow in over 1/3 of the liquid steel bulk (Figure 5). Installing the proposed SFC in the tundish in the pouring zone does not significantly increase the share of plug flow in the tundish to an average value of 12.5% (Figure 4). However, still over 30% of the flow is stagnant (Figure 5). This situation is not improved by deeper immersion of the ladle shroud in the liquid steel. With a 100% increase in the immersion depth, an asymmetry in the flow structure of approximately 4% in the volume of the stagnant flow is highlighted (Figure 5). The macroscopic condition of the hydrodynamic system is not significantly influenced by casting with or without a stopper rod system. In the second stage of the research, the impact of shifting the SFC relative to the axis of the ladle shroud towards one of the longitudinal tundish walls was assessed.

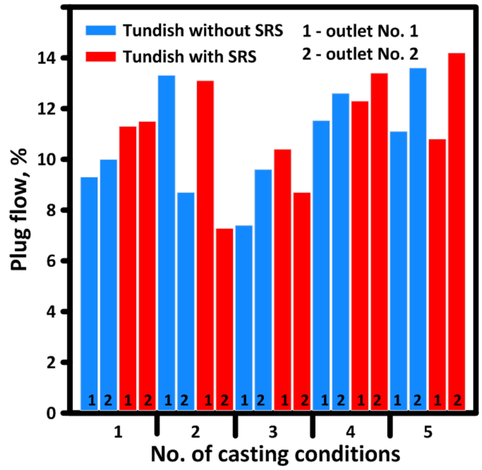


Fig. 4. Plug flow in the bare tundish and tundish with subflux flow controller

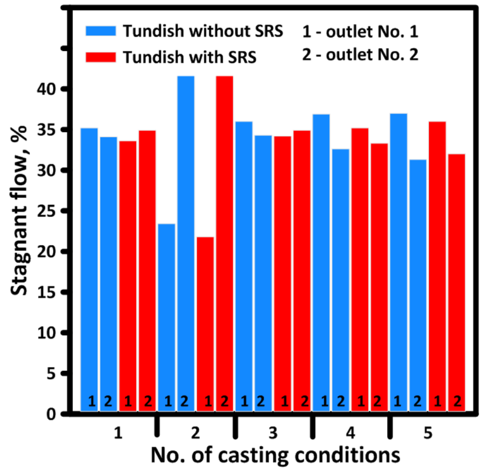


Fig. 5. Stagnant flow in the bare tundish and tundish with subflux flow controller

Figures 6 and 7 show the impact of the SFC shift on the volume fractions of plug flow and stagnation flow. Moving the SFC towards one of the tundish walls reduces the volume fraction of the plug flow. However, a decrease of almost 50% occurs in the case of a significant shift of the SCT by 0.15 m compared to the variant in which the longitudinal axis of the ladle shroud and the SFC coincide. The structure modification is not significantly influenced by the direction of shift of the subflux flow controller, but only by the value of the length of the section describing the shift distance. In the context of the formation of stagnation flow and the analyzed influence of the position of the SFC relative to the ladle shroud, an additional deactivation of the hydrodynamic structure is observed.

The share of stagnation flow in the overall hydrodynamic structure in casting variants Nos. 6-9 increases to almost 40%.

Due to the fact that the difference in the hydrodynamic system in a tundish with or without a stopper rod system is almost identical, Figure 8 shows the results only for the tundish equipped with a stopper rod system.

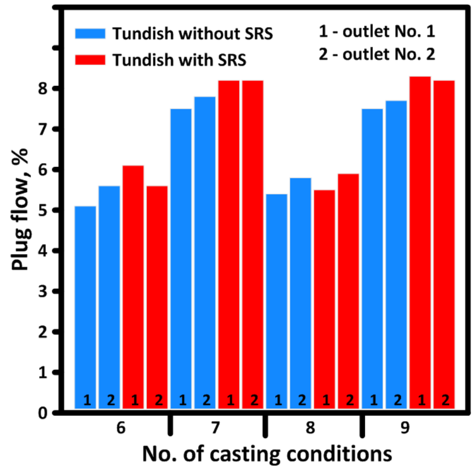


Fig. 6. Influence of SFC shift on plug flow

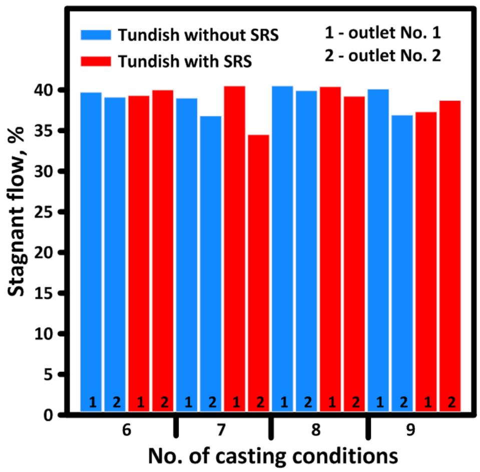


Fig. 7. Influence of SFC shift on stagnant flow

Figure 8 shows the results regarding the impact of tilting the ladle shroud towards one of the outlets with the correct installation of the SFC. Compared to the standard, correct location of the ladle shroud in relation to the SFC, at a tilt of 5° there is an average increase in the share of plug flow by 40%. However, the asymmetry in the distribution of plug flow in relation to both outlets of the tundish amounts to 1.5% on average. It is also worth noting that the share of stagnation flow decreased to an average value of 27%. A significant asymmetry occurs at a smaller value of the tilt angle. When the ladle shroud is tilted towards outlet nozzle no. 2, the difference in the share of plug flow for both outlets exceeds 100%. If the ladle shroud is tilted by an angle of 4° towards one of the longitudinal walls, the required symmetry of the hydrodynamic structure in relation to the pouring zone is maintained. However, the share of stagnation flow reaches a value close to 40%, while the share of plug flow drops to an average value of 6.5%.

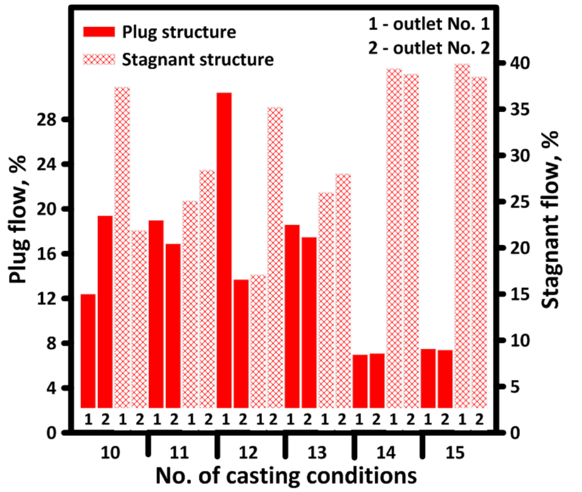


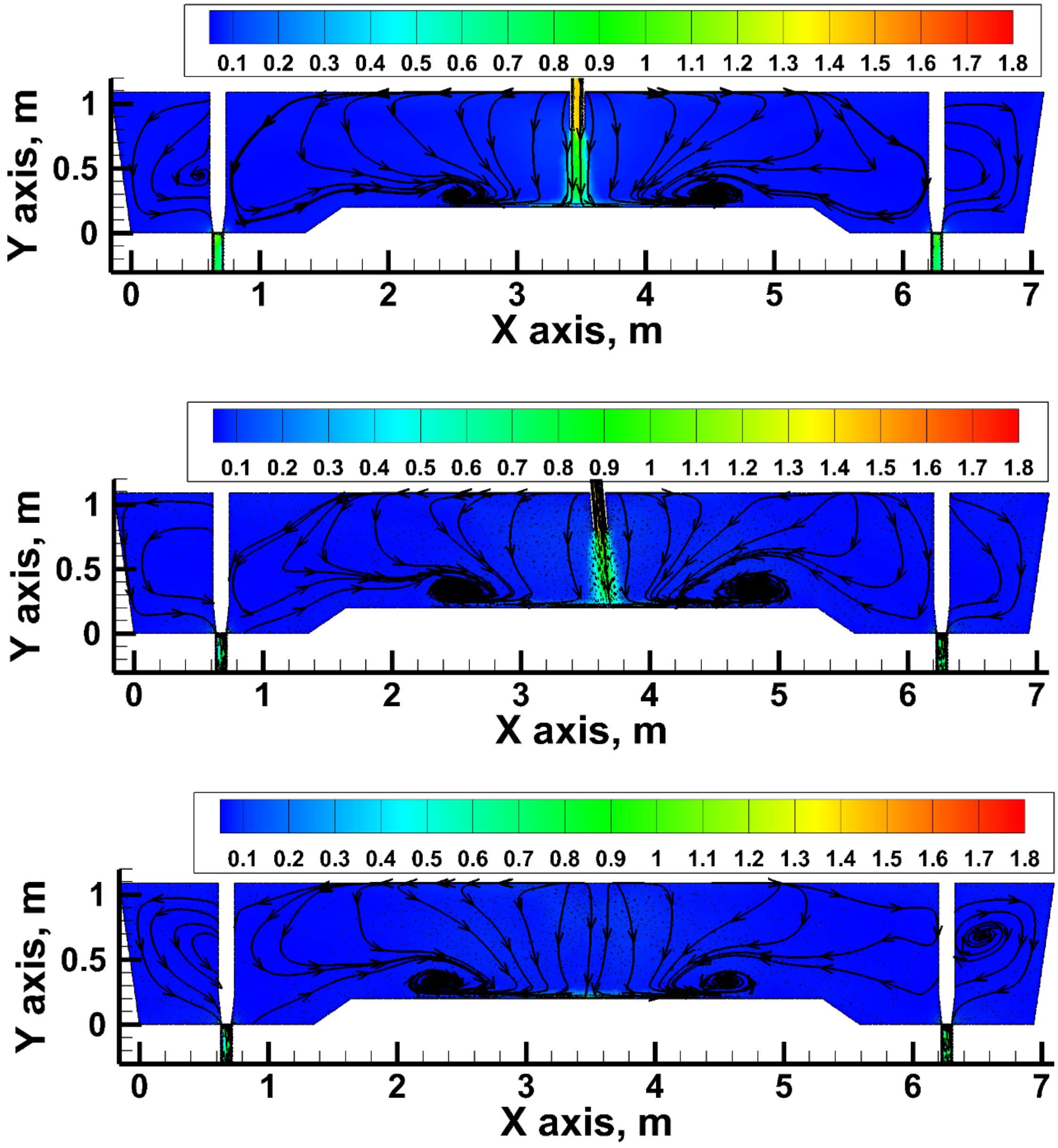
Fig. 8. Influence of ladle shroud misalignment on plug and stagnant flow in the tundish with SRS

The presented data show that the average share of the ideal mixing flow in the tundish with or without SFC, under various conditions of pouring the tundish, is at an average level of 54%. However, in a tundish without SFC, when the ladle shroud tilts towards outlet nozzle no. 2, there is a drop of over 35%.

The occurrence of non-standard pouring conditions of the tundish during the casting sequence generally adversely disturbs the hydrodynamic system. However, the hydrodynamic structure diagnosed with the asymmetrical position of the ladle shroud in relation to the SFC, activating additional areas of the tundish working space, is an alternative to searching for new advanced non-standard technological solutions in tundishes.

3.3. Numerical results – liquid steel flow paths

In order to more precisely verify the mutual interactions of the stream feeding the tundish with the working surface of the tundish bottom or the SFC, Figures 9-11 show the distribution of liquid steel flow directions on the central longitudinal plane located in the pouring and stopper rod system zones. In the absence of SFC, in the pouring zone in the central part of the tundish, a vertical flow of liquid steel can be seen descending towards the bottom. At the bottom of the tundish, horizontal reverse flow is visible. As a result of the contact of the reverse and feed streams at the bottom of the tundish, two areas of steel recirculation are created (Figure 9a). If the ladle shroud is tilted towards outlet No. 2, the area of liquid steel recirculation located at its bottom moves closer to the lowered bottom zone, thus shortening the flow path of reverse streams flowing from outlet No. 2. If the ladle shroud is tilted towards the front longitudinal wall, there are no obvious modifications in the flow directions of liquid steel. In the tundish variant without SFC, the average flow velocity of liquid steel in the tundish is 0.039 m/s and remains at the same level also in the variants with a ladle shroud deviated from the vertical.



a)

b)

c)

Fig. 9. Tundish without SFC: a) standard location of LS, b) misalignment of LS (right side tilt - 5°), c) misalignment of LS (front side tilt - 4°)

Figure 10a shows the hydrodynamic system in a tundish with the SFC. The controller changes the hydrodynamic structure in the central part of the tundish to a strictly horizontal flow. The feed streams are directed towards the free surface of the liquid steel, hence there is no interaction at the bottom with the reverse streams flowing from the stopper rod system zone. Moving the SFC by 0.15 m towards the longitudinal wall initiates two distinct areas of horizontal recirculation between the tundish pouring zone and the stopper rod system zones (Figures 10b). The hydrodynamic system undergoes a complex modification in the central part of the tundish when the SFC is moved by 0.075 m. In this case, microrecirculation areas are created in the hydrodynamic structure located at the free surface of the liquid steel and in the immediate vicinity of the stopper rods (Figure 10c). If SFC is used in the pouring zone and the correct location of the ladle shroud in relation to the flow control device, the average velocity of liquid steel in the tundish is reduced by over 30% compared to the tundish without FCD. However, moving the controller by 0.15 m and 0.075 m causes an increase in the average flow velocity by 0.007 m/s and a decrease in the velocity by 0.004 m/s, respectively, in relation to the flow velocity of liquid steel in a tundish without SFC.

The increase in active flow in the working volume of the tundish diagnosed using residence time curves should be reflected in the modification of the flow directions of liquid steel in the tundish. Figure 11a confirms the occurrence of a different hydrodynamic system in relation to the tundish without and with SFC in the pouring zone. In variant of casting conditions No. 10, on the side of outlet number 2, there was a significant reduction in the share of stagnation flow and an increase in the share of plug flow. In this variant, it can be seen that on the side of outlet nozzle No. 2 in the tundish, in the central part, a hydrodynamic system rising in the vertical direction is activated (Figure 11a).

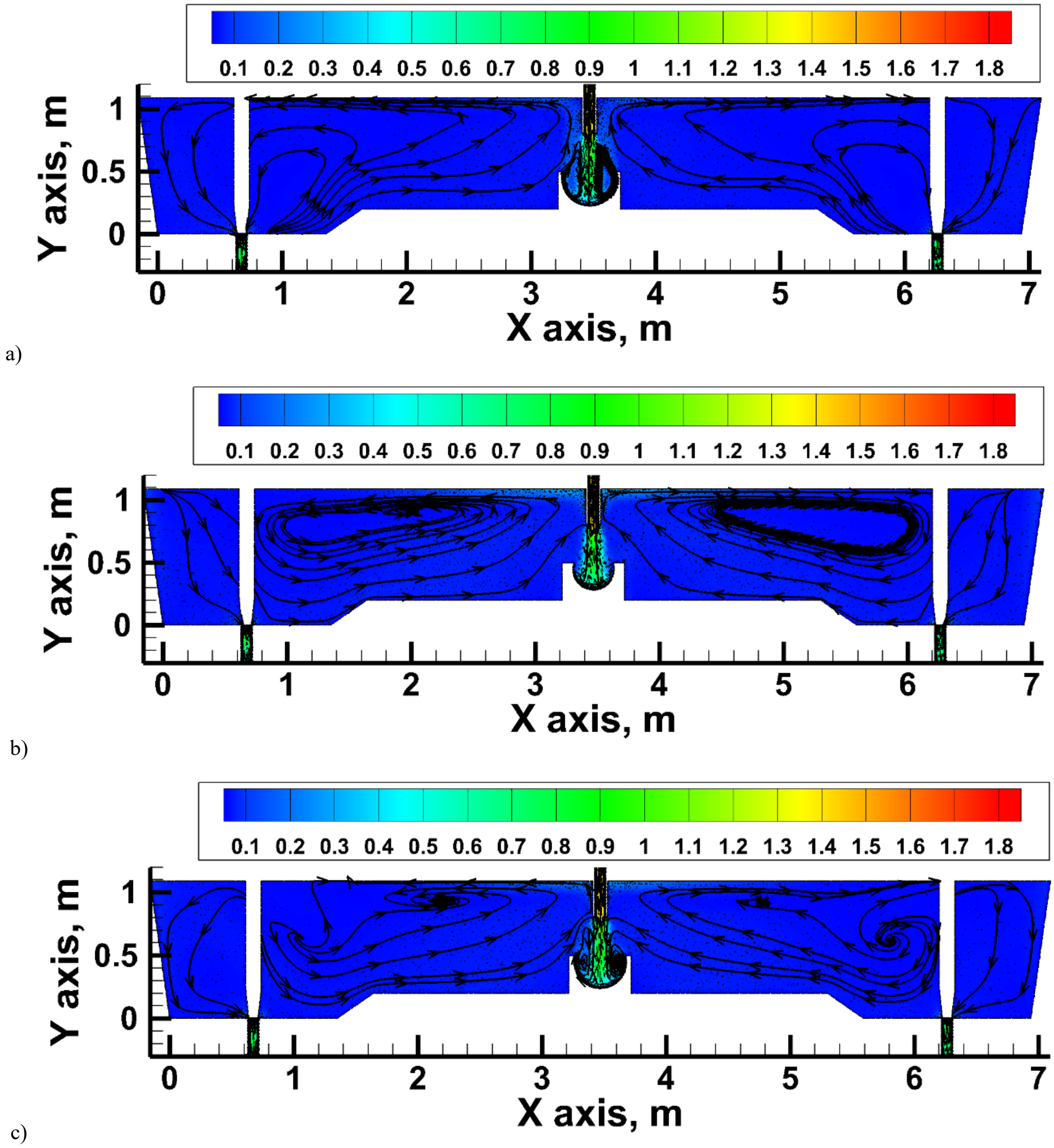
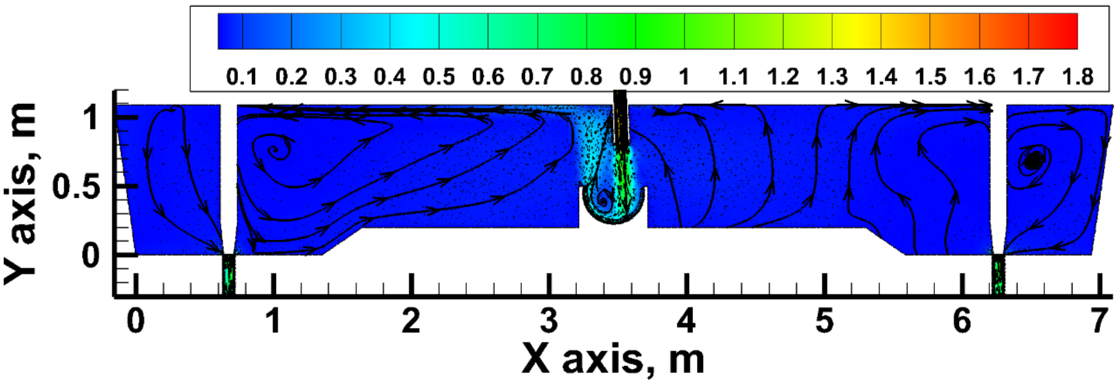


Fig. 10. Tundish with SFC: a) standard location of SFC, b) shift of SFC (0.15 m to back), c) shift of SFC (0.075 m to back)

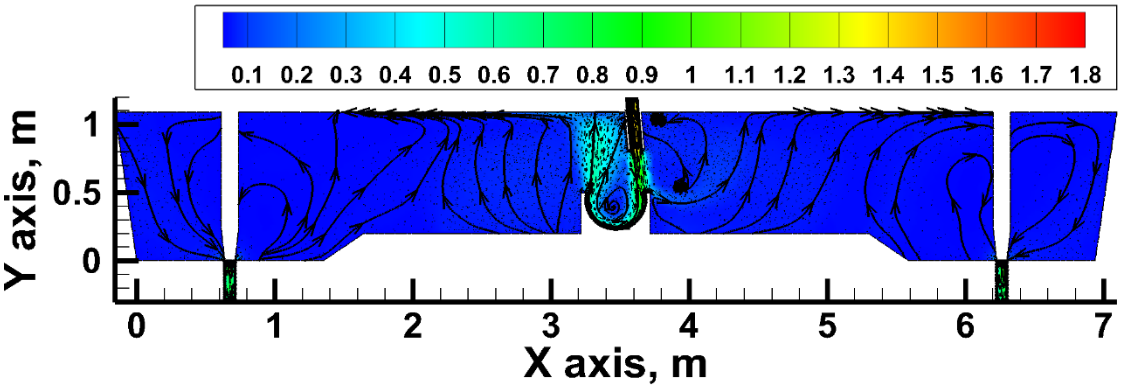
However, on the side of outlet nozzle No. 1, the recirculation of steel in a horizontal arrangement with returning reverse streams resembles that for a tundish with SFC and a correctly located ladle shroud. With further tilting of the ladle shroud, not only a reduction in the stagnation flow share was achieved, but also relative hydrodynamic symmetry for both outlets (Figure 11b). In this case, the position of the ladle shroud relative to the SFC, a vertical upward movement is observed on both sides of the SFC. In both casting conditions variants of the ladle shroud tilt, the average velocity of liquid steel was 0.031 m/s and 0.035 m/s at a tilt of 2° and 5°, respectively.

The average velocity of liquid steel increased to 0.042 m/s with the ladle shroud tilted by 4° towards the longitudinal tundish wall, and the horizontal recirculation structure of liquid steel between the pouring zone and the stopper rod system zones is similar to that formed as a result of shifting the SFC by 0.15 m (Figure 11c and 10b).

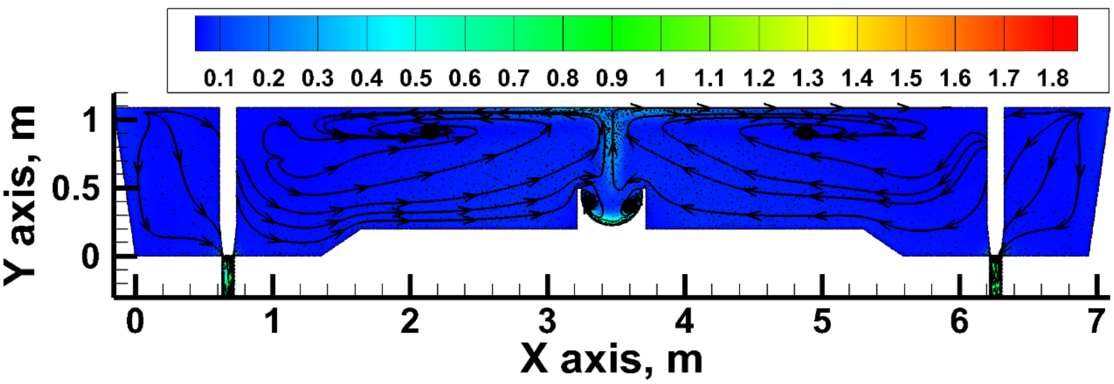
In order to further verify the behavior of the hydrodynamic system on a macro scale, flow paths of all liquid steel streams, including feeding, reverse and recirculating streams, were generated. Figure 12 shows cognitively important variants of pouring the tundish during the casting sequence. Similarly to the tundish without SFC, moving the ladle shroud by 5° towards tundish outlet No. 2 resulted in the initiation of vertical recirculation in the central part of the tundish (Figure 12a and 12b). In the variant of pouring the tundish, with SFC, which is advantageous in terms of active flow volume, the range of reverse flows is practically limited to the area of stopper rod systems. Moreover, although vertical recirculation occurs in both pouring variants, in the SFC tundish the recirculation movement has the opposite direction, which causes the streams of liquid steel to fall at the longitudinal walls of the tundish.



a)

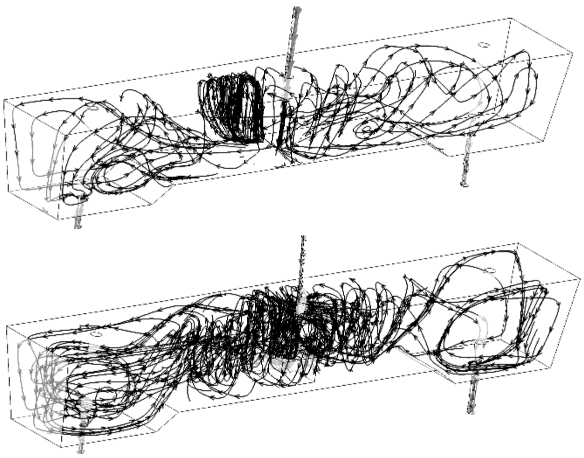


b)



c)

Fig. 11. Tundish with SFC: a) misalignment of LS (right side tilt - 2°), b) misalignment of LS (right side tilt - 5°), c) misalignment of LS (front side tilt - 4°)



a)

b)

Fig.12. Liquid steel path lines in tundish working volume: a) bare tundish, b) tundish with SFC and ladle shroud misalignment (right side tilt - 5°)

4. Conclusions

The computer simulations and laboratory experiments performed allowed the following conclusions to be formulated.

In the analyzed two-strand tundish without SFC, the tilt of the ladle shroud towards one of the tundish outlets significantly contributes to the asymmetry of the hydrodynamic system, causing a decrease and increase in the share of stagnation flow by over 5% for outlet nozzle 1 and 2, respectively.

Both in the tundish without and with SFC, the tilt of the ladle shroud towards one of the longitudinal tundish walls does not cause asymmetric flow of liquid steel in the working space of the tundish.

Changing the position of the SFC towards one of the longitudinal tundish walls does not affect the asymmetry of steel flow and ensures similar casting conditions at both outlets of the tundish. However, moving the SFC e.g. by 0.15 m causes an almost 50% decrease in the share of plug flow compared to the standard location of SFC and ladle shroud.

The non-standard interaction of the feed stream with the SFC working space revealed the occurrence of a favorable hydrodynamic structure in the tundish working space in the context of limiting the stagnation flow. The formed hydrodynamic structure consists of vertically circulating streams of liquid steel, effectively eliminating and limiting the impact of reverse streams. Hence, the next stage of research will be to develop a technology for pouring a two-strand tundish that will effectively limit the range of reverse flow impact and activate stagnation flow zones. For this purpose unique flow control device will be created and tested in the considered tundish.

Acknowledgements

This research was funded by the Ministry of Science and Higher Education Republic of Poland, as Statutory Researches of Czestochowa University of Technology, grant number BS/PB-200-301/2023 and BS/PB-200-301/2024.

This research work was performed under the project APVV-21-0396 was financially supported by APVV and grant project 1/0199/24 and was financially supported by the VEGA agency of the Ministry of Education, Science, Research and Sport of the Slovak Republic and the Slovak Academy of Sciences.

References

[1] Li, Y., Wu, C., Xie, X., Chen, L., Chen, J., Jang, X. & Ma, X. (2022). Numerical simulation and application of tundish cover argon blowing for a two-strand slab continuous casting machine. *Metals*. 12(11), 1801, 1-12. https://doi.org/10.3390/met12111801.

[2] Liu, J., Zhou, P., Zuo, X., Wu, D. & Wu, D. (2022). Optimization of the liquid steel flow behavior in the tundish through water model experiment, numerical simulation and industrial trial. *Metals*. 12(9), 1480, 1-13. https://doi.org/10.3390/met12091480.

[3] Wang, K., Tie, Z., Cai, S., Wang, H., Tang, H. & Zhang, J. (2023). Flow control to a t-shaped five-strand tundish for its overall enhanced metallurgical effects with an approachable identical products quality. *ISIJ International*. 63(8), 1351-1359. https://doi.org/10.2355/isijinternational.ISIJINT-2023-008.

[4] Huang, W., Chang, S., Zou, Z., Song, H., Qu, Y., Shao, L. & Li. B. (2022). Removal of inclusions using swirling flow in a single-strand tundish. *ISIJ International*. 62(7), 1439-1449. https://doi.org/10.2355/isijinternational.ISIJINT-2021-600.

[5] Yang, B., Deng, A., Li, Y. & Wang, E. (2022). Exploration of the relationship between the electromagnetic field and the hydrodynamic phenomenon in a channel type induction heating tundish using a validated model. *ISIJ International*. 62(4), 677-688. https://doi.org/10.2355/isijinternational.ISIJINT-2021-018.

[6] Zhang, J., Liu, Q., Yang, S., Chen, Z., Li, J. & Jiang, Z. (2019). Advances in ladle shroud as a functional device in tundish metallurgy: a review. *ISIJ International*. 59(7), 1167-1177. https://doi.org/10.2355/isijinternational.ISIJINT-2019-044.

[7] Zepeda-Diaz, F.A., Garcia-Hernandez, S., de Barreto, J. & Gutierrez, J. (2019). Mathematical modelling of the effects of transient phenomena on steel cleanness during tundish transfer practices. *ISIJ International*. 59(1), 51-59. https://doi.org/10.2355/isijinternational.ISIJINT-2018-527.

[8] Ni, P., Jonsson, L.T.I., Ersson M. & Jönsson P.G. (2017). Application of a swirling flow producer in a conventional tundish during continuous casting of steel. *ISIJ International*. 57(12), 2175-2184. https://doi.org/10.2355/isijinternational.ISIJINT-2017-377.

[9] Cupek, J., Tkadleckova, M., Merder, T., Walek, M., Saternus, M. & Pieprzyca, J. (2023). Computational fluid dynamics (CFD) analysis of medium flow and removal of inclusions in a two-strand tundish. *Metalurgija*. 62(3-4), 335-338.

[10] Janiszewski, K. (2013). Refining of liquid steel in a tundish using the method of filtration during its casting in the CC machine. *Archives of Metallurgy and Materials*. 58(2), 513-521. DOI: 10.2478/amm-2013-0029.

[11] Bulkowski, L., Galisz, U., Kania, H., Kudliński, Z., Pieprzyca, J. & Barański, J. (2012). Industrial tests of steel filtering process. *Archives of Metallurgy and Materials*. 57(1), 363-369. DOI: 10.2478/v10172-012-0035-2.

[12] Wang, X.-Y., Zhao, D.-T., Qiu, S.-T. & Zou, Z.-S. (2017). Effect of tunnel filters on flow characteristics in an eight-strand tundish. *ISIJ International*. 57(11), 1990-1999. https://doi.org/10.2355/isijinternational.ISIJINT-2017-165.

[13] Blasko, P., Bulko, B., Petrik, P., Demeter, P, Socha, V., Hanakova, L., Palfy, P., Solc, M. & Vasilnakova, A. (2022) The adjustment of the tundish water model of continuous casting. *Archives of Metallurgy and Materials*. 67(1), 97-104. DOI: https://doi.org/10.24425/amm.2022.137477.

[14] Warzecha, M., Merder, T., Warzecha, P. & Hutny, A.M. (2019). Hydrodynamic conditions of flow in the tundish depending on selected technological parameters for different steel groups. *Archives of Metallurgy and Materials*. 64(1), 65-70. DOI: 10.24425/amm.2019.126219.

[15] Cwudziński, A. (2011). Numerical simulation of behaviour a non-metallic inclusions in an one-strand slab tundish with steel flow control devices. *Archives of Metallurgy and Materials*. 56(3), 611-618. DOI: 10.2478/v10172-011-0066-0.

[16] Wu, J., Jin, Y., Gan, F., Li, X., Liu, Z., Lin, P., Huang, Z. & Ling, H. (2023). Digital twin design of a turbulence inhibitor in a tundish based on the production cluster mining algorithm. *Metals*. 13(10), 1651, 1-17. https://doi.org/10.3390/met13101651.

[17] Zhao, S., Zhu., S., Ge, Y., Wang, J., Xu, D., Li, Z. & Chen. C. (2023). Simulation of fluid flow and inclusion removal in five-flow T-type tundishes with porous baffle walls. *Metals*. 13(2), 215, 1-15. https://doi.org/10.3390/met13020215.

[18] Gupta, V. K., Jha, P. K. & Jain, P. K. (2021). Modeling of wall shear stress induced inclusion transport and removal in multi-strand tundish. *ISIJ International*. 61(9), 2445-2456. https://doi.org/10.2355/isijinternational.ISIJINT-2020-667.

[19] Sowa, L. (2015). Effect of steel flow control devices on flow and temperature field in the tundish of continuous casting machine. *Archives of Metallurgy and Materials*. 61(4), 2071-2078. DOI: 10.1515/amm-2015-0216.

[20] Warzecha, P., Hutny, A.M., Warzecha, M., Merder, T. (2016). Optimization of steel flow in the tundish by modifying its working area. *Archives of Metallurgy and Materials*. 61(4), 2071-2078. DOI: 10.1515/amm-2016-0333.

[21] Cwudziński, A. (2018). Numerical and physical modeling of liquid steel behaviour in one strand tundish with gas permeable barrier. *Archives of Metallurgy and Materials*. 63(2), 589-596. DOI: 10.24425/118978.

[22] Walek, J., Tkadleckova, M., Velicka, M. Machu, M., Cupek, J., Huczala, T., Cibulka, J., Ruzicka, J. & Michalek, K. (2023). Physical experiments and numerical simulations of the influence of turbulence inhibitors and the position of ladle shroud on the steel flow in an asymmetric five-strand tundish. *Metals*. 13(11), 1821, 1-18. https://doi.org/10.3390/met13111821.

[23] Yue, Q., Zhang, B. & Wang. X.Z. (2017). Mathematical simulation for effects of flow control devices in two-strand slab tundish. *Metalurgija*. 56(1-2), 127-130.

[24] He, F., Wang, H. & Zhu. Z. (2019). Numerical investigation of effect of casting speed on flow characteristics of molten steel in multistrand tundish. *ISIJ International*. 59(7), 1250-1258. https://doi.org/10.2355/isijinternational.ISIJINT-2018-835.

[25] Chattopadhyay, K., Isac. M. & Guthrie R.I.L. (2011). Physical and mathematical modelling to study the effect of ladle shroud mis-alignment on liquid metal quality in a tundish. *ISIJ International*. 51(5), 759-768. https://doi.org/10.2355/isijinternational.51.759.

[26] Aguilar-Corona, A., Morales, R., D., Diaz-Cruz. M., Palafox-Ramos, J. & Rodriquez-Hernandez, H. (2002). Modelling the effects of off-centered ladle streams on fluid flow of liquid steel in a slab tundish. *Steel Research*. 73(10), 438-444. https://doi.org/10.1002/srin.200200012.

[27] Cwudziński, A. (2019). Influence of subflux turbulence controller and ladle shroud asymmetric using on hydrodynamic conditions in one strand slab tundish. *Metals*. 9(1), 68, 1-13. https://doi.org/10.3390/met9010068.

[28] Bulko, B., Priesol, I., Demeter, P, Gasparovic, P., Baricova, D. & Hrubovcakova, M. (2018). Geometric modification of the tundish impact point. *Metals*. 8(11), 944, 1-11. https://doi.org/10.3390/met8110944.

[29] Cwudziński, A. (2014). Numerical and physical modeling of liquid steel active flow in tundish with subflux turbulence controller and dam. *Steel Research International*. 85(5), 902-917. https://doi.org/10.1002/srin.201300284.

[30] Chakraborty, S. & Sahai, Y. (1992). Mathematical modelling of transport phenomena in continuous casting tundishes. Part 1 Transient effects during ladle transfer operations. *Ironmaking & Steelmaking*. 19(6), 479-487.

[31] Morales, R. D., de Barreto, J., Lopez-Ramirez, S., Palafox-Ramos, J. & Zacharias, D. (2000). Melt flow control in a multi-strand tundish using turbulence inhibitor. *Metallurgical and Materials Transactions B*. 31B, 1505-1515. https://doi.org/10.1007/s11663-000-0035-x.

[32] Solorio-Diaz, G., Morales, R. D., Palafox-Ramos, J., & Ramos-Banderas, A. (2005). Modelling the effects of a swirling flow on the temperature stratification of liquid steel and flotation of inclusions in a tundish. *ISIJ International*. 45(8), 1129-1137. https://doi.org/10.2355/isijinternational.45.1129.

[33] Joo, S., Han, J. W. & Guthrie, R.I.L. (1993). Inclusion behavior and heat-transfer phenomena in steelmaking tundish operations: Part II. Mathematical model for liquid steel in tundishes. *Metallurgical and Materials Transactions B*. 24B, 767-777. https://doi.org/10.1007/BF02663137.

[34] Merder, T., Jowsa, J. & Bogusławski, A. (2005). The analysis of the conditions of steel flow in the tundish performer by a numerical method. *Archives of Metallurgy and Materials*. 50(4), 933-953.

[35] Zhang, L. (2005). Fluid flow, heat transfer and inclusion motion in a four-strand billet continuous casting tundish. *Steel Research International*. 76(11), 784-796. https://doi.org/10.1002/srin.200506097.

[36] Sahai, Y. & Ahuja, R. (1986). Fluid flow and mixing of melt in steelmaking tundishes. *Ironmaking & Steelmaking*. 13(5), 241-247.

[37] Sahai, Y. & Emi, T. (1996). Melt flow characterization in continuous casting tundishes. *ISIJ International*. 36(6), 667-672. https://doi.org/10.2355/isijinternational.36.667.