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The Effect of Turbulence Inhibitor Design on the Movement of Liquid Steel in a Tundish - Modelling Studies

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Abstract

The article presents model test results on the flow of liquid steel through a CSC (Continuous Steel Casting) tundish equipped with various TI (Turbulence Inhibitors) designs. The tests were carried out using a physical water model of the CSC device made in accordance with the principles of similarity on a linear scale of 1:2.5 in relation to the industrial device. The tests were conducted in two stages: qualitative - visualization and quantitative - determination of RTD (Residence Time Distribution) curves. A tracer in form of an aqueous solution of $KMnO_4$ was used for visualization, while an aqueous solution of NaCl was used to determine RTD curves. The aim of the tests was to determine the effect of the geometry of four types of turbulence inhibitors (TI) on the formation of the mechanism of model liquid flow in the working space of the water model of the tundish and to interpret the results from the point of view of obtaining specific casting parameters under industrial conditions. The following casting parameters were assumed: risk of dead zones, conditions conducive to the formation of the required primary structure of billets identical in all outlets, the ability to micro-refine and homogenize steel in chemical terms.

Keywords: Steel, Tundish, Water models, Physical modelling

1. Introduction

The continuous steel casting method (CSC) is a multi-stage process that requires the use of strictly defined technological rigor in each segment of the device, from the metallurgical ladle, through the tundish and mould, to the secondary cooling zone. A particularly important problem from the point of view of obtaining high-quality continuous billets is the movement of liquid steel in the tundish [1]. It affects the mixing mechanism of the metal bath and consequently the homogenization of the liquid steel both in terms of temperature and chemical composition. It shapes the conditions of micro-refining of the liquid steel and the effective discharge of impurities into the slag phase. The movement of the liquid steel also affects the refractory lining of the tundish, which is important not only due to the costs of steel production, but above all to reduce the risk of its secondary contamination with exogenous inclusions [2]. In multi-strand devices, the method of mixing steel in the tundish influences the formation of the primary structure of continuous billets during their solidification in individual moulds and the secondary cooling zone. Ensuring the most similar thermodynamic conditions of steel solidification in all strands allows obtaining billets with the same primary structure and the required grain size [3,4].

As it results from the above description, the movement of liquid steel in the tundish of the CSC device is crucial for the correct course of the casting process. Therefore, in order to obtain the required hydrodynamic conditions, various types of flow regulators are used (from impact pad [5] to dams [6], baffles [7], weirs [8], or various types of turbulence inhibitors [9-12] or combinations of the above-mentioned flow regulators [13-16]), which constitute the construction of the tundish. However, the selection of the type and design of flow regulators requires taking into account many factors. First of all, it is necessary to determine the priority effects to be achieved through their use. This necessity is due to the fact that improving the mechanism of creating the character of the liquid steel flow conducive to obtaining a specific effect usually negatively affects others. For example, increasing the volume of the turbulent flow zone in the working space of the tundish promotes effective homogenization of liquid steel, but worsens its refining capabilities. Therefore, the proper selection of flow regulators is always the result of a certain compromise between the requirements defined as priority and other requirements.

Due to the fundamental problems associated with conducting research on the flow of liquid metals under industrial conditions (high temperature, isolated and aggressive research environment, risk of disruption of the production process, risk to those conducting research, etc.), modelling methods are used to determine the mechanisms of the formation and course of hydrodynamic phenomena in metallurgical reactors. Commonly used modelling methods are both numerical and physical methods. These methods are used in a very wide range, both for research on the processes of manufacturing alloys of non-ferrous metals [17,18] and steel production [19,20].

In the research presented in this article concerning the selection of the type and design of flow regulators installed in the tundish of the CSC device, the physical modelling method was used. During the research, a number of parameters were determined as criteria for assessing the mechanism of liquid steel flow through the tundish from the point of view of the effectiveness of obtaining the designated effects.

2. Materials and experimental methods

The research was carried out using a physical model of the CSC device. It was designed and constructed in accordance with the requirements of the similarity theory [21,22]. The model was described in detail in [23,24]. The view of the physical model of the CSC device is shown in Figure 1.

This model has a segmented structure. Its individual structural elements belong to the main and auxiliary segments, which guarantee the fulfilment of the assumed functional features of the research station. The principles of similarity are fulfilled only in the main segment. The remaining segments play the role of auxiliary elements, which enable the fulfilment of the necessary conditions in the main segment. The main segment of the model is a structural element in which phenomena occur that are important from the point of view of the expected results of the experiment.

The main segment of the model is the four-strand tundish model in which all the conditions of kinematic and dynamic similarity are met [23-24].

The subject of the study is a four-strand tundish of a delta-type CSC device. Selected characteristics of this CSC device are given in Table 1. The tundish is installed in a device operating in one of the domestic steelworks. Steel is poured into the tundish through a ceramic cover/immersion nozzle placed in its plane of symmetry.

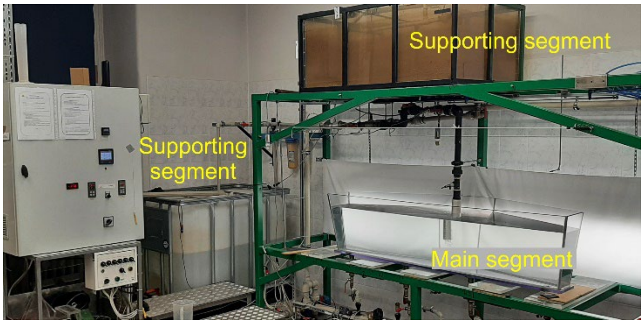

Fig. 1. View of the physical (water) model of the CSC device

Table 1.
Selected process and technological parameters of the industrial CSC device

Parameter	Description
device type	arched
number of mould strands	4
tundish type	delta with inclined walls
tundish capacity	nominal 16.5 Mg maximum 18 Mg
working level of liquid steel	650 - 750 mm
cross section	140 x 140 mm, 160 x 160 mm and 220 x 220 mm

Due to the characteristic dimensions of the real object, a linear reduction scale of S_L = 1:2.5 = 0.4 was adopted for the tundish model. The tundish model was made of PMMA (poly(methyl methacrylate)) plates, the joints were made by welding. The characteristic dimensions of the tundish model and its view are shown in Figure 2.

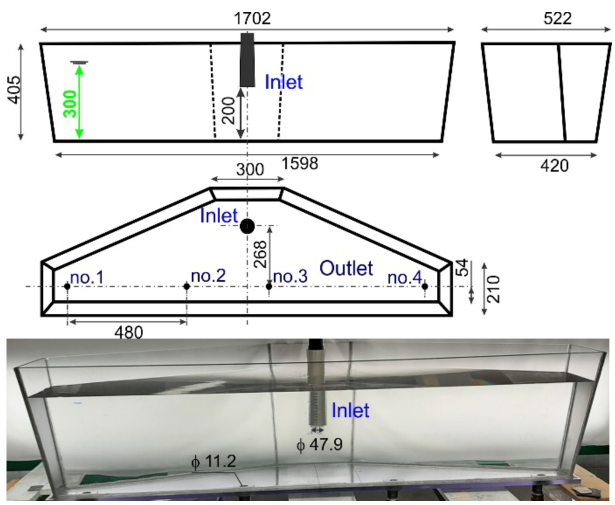

Fig. 2. The geometric dimensions / mm and view of the tundish model

The immersion nozzle/ceramic shroud (which replicates the one used in real conditions) was also made to a 1:2.5 reduction scale, just like the tundish model. The shroud pipe model takes into account the scaling of the inner and outer diameters. However, maintaining the proportion between the immersion depth in the model and the industrial tundish is of particular importance. The only parameter that does not have a major impact on maintaining the geometric similarity in case of the shroud pipe is its length. This is important in terms of matching its length to the existing hydraulic infrastructure of the test stand. Therefore, the shroud pipe model was slightly shortened. The shroud pipe model was made using FDM (Fused Deposition Modelling) additive technology – 3D printing. The view of the printed shroud pipe model is shown in Figure 3.

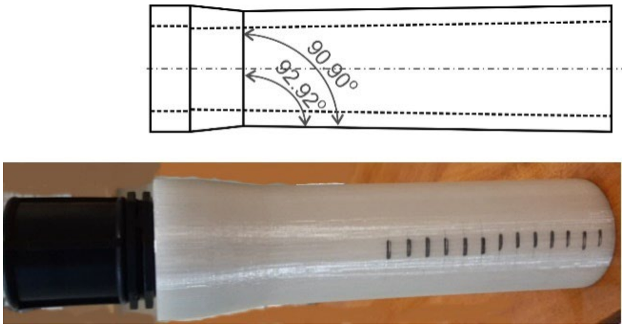

Fig. 3. Geometry of the shroud pipe (ladle shroud) used in the water model tests

Model tests were performed on 4 different turbulence inhibitor geometries. The models were also made in a scale of 1:2.5, the same as the tundish model. They were made using FDM additive technology. The TI was mounted in the tundish model in the axis of the shroud pipe. Figure 4 shows a view of the manufactured inhibitors and their mounting location in the tundish water model.

The designed TIs are characterized by two basic features. Two of them are based on a rectangular plan and two are equipped with a rounded front wall. The rounding of the front wall can increase the strength of the inhibitors during their hot work. Although it is not possible to determine this in model tests, it was decided to investigate whether such a design significantly affects their work efficiency. The second feature is the lowering of the front wall in both types of TIs in order to direct the steel flow towards the outlets of the tundish.

Before starting the research, it was necessary to perform appropriate calculations of the process parameters for laboratory conditions.

Based on the Froude similarity criterion (1), the velocity scale S_V, flow time scale S_t and flow rate scale S_Q were determined for the model liquid based on the relations (2-4) [25]. The above-mentioned parameters were used to determine the similarity of the dynamic and kinematic liquid flow in the tested object [25,26].

$$\mathrm{Fr} = \frac{V^2}{g \cdot L} \tag{1}$$

Time scale depends on the linear scale according to the equation:

$$S_t = \sqrt{S_L} \tag{2}$$

while the velocity scale is determined by the following relationship:

$$S_V = \sqrt{S_L} \tag{3}$$

for the flow rate scale S_Q the relationship is:

$$S_Q = S_V \cdot S_L^2 = S_L^{5/2} \tag{4}$$

where: V– velocity, m · s $^{-1}$, g – acceleration of gravity, m s $^{-2}$, L – characteristic dimension, m; S_L – linear scale adopted.

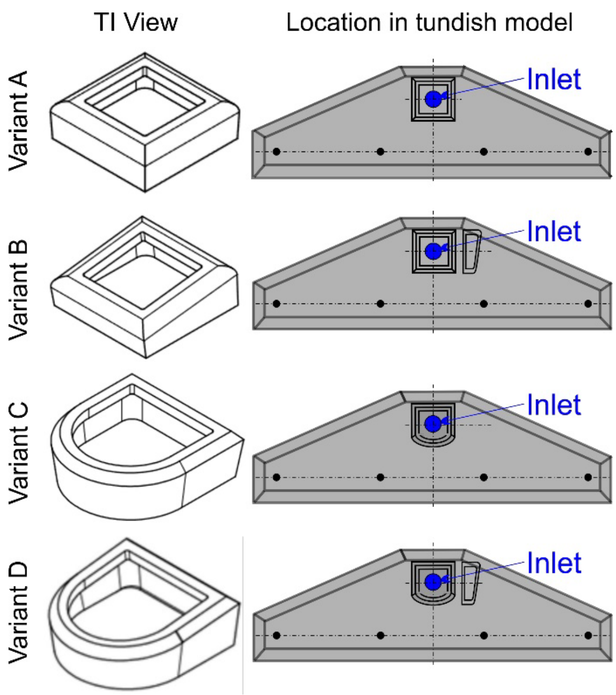

Fig. 4. View of the produced inhibitors and their installation locations in the tundish water model

Based on the Froude similarity criterion (1), the velocity scale S_V, flow time scale S_t and flow rate scale S_Q were determined for the liquid model based on the relations (2 - 4) [25]. The above-mentioned parameters were used to determine the similarity of the dynamic and kinematic liquid flow in the tested object [25,26].

Calculations of similarity conditions for the tundish were made assuming that under the actual process conditions the cross-section of the cast square ingot is 160 x 160 mm at the linear casting speed of V_{casted} = 1.8 m·min^{-1} = 0.03 m·s^{-1}. For the calculations it was assumed that the density of steel in the solid state is 7600 kg·m^{-3}, while in the liquid state it is 7011 kg·m^{-3} [21].

Table 2 shows the calculated model liquid flow rates for the industrial parameters given above.

Experimental studies using the test stand - CSC device model were divided into two groups: qualitative and quantitative studies. Qualitative studies included visualization of the way the model liquid mixes in the tundish model. Quantitative studies were conducted to develop F-type RTD characteristics. The specified characteristics allow to determine the time of the tracer reaching the individual tundish nozzles and estimate the minimum mixing time of the tracer in the model liquid.

Table 2.
Values of casting process parameters in industrial conditions and in the model

Parameter	Unit	Value
Casting speed	$m \cdot min^{-1}$	1.8
Billets sizes	mm	160 x 160
Mass flow of steel	$kg \cdot s^{-1}$	23.35
Volumetric flow of steel	$m^3 \cdot s^{-1}$	0.0033
Volumetric flow of model liquid – water	$dm^3 \cdot min^{-1}$	20.22
Model scale - S_L	-	0.4000
Time scale - S_t	-	0.6324
Velocity scale - S_V	-	0.6324
Flow rate scale - S_Q	-	0.1012

F-type RTD characteristics contain cumulative information on the hydrodynamic conditions of steel flow through the tundish and allow for a preliminary assessment of the quality of the objects in terms of mixing liquid steel. This assessment is made based on the analysis of the determined distribution of the residence time of liquid particles in the experimental track, measured from the moment of its entry into the tundish to the moment of its exit from the tundish through the outlet holes. For this purpose, during the experiment, changes in the tracer concentration are recorded in response to a given input signal - step (Heaviside) [27,28] at the inlet to the tundish model.

Taking advantage of the fact that changes in the tracer (NaCl) concentration in the model liquid cause a linear change in conductivity, the conductivity value is measured using conductometers (located at the inlet and outlet of the tundish model), the sensors of which are installed at the outlet of the tundish model. The measurement is non-contact and does not affect the nature of the model liquid flow through the tundish model in any way. Sampling is carried out at three-second intervals and is essentially inertial, which allows obtaining results with the required accuracy in real time.

In quantitative studies the tracer was an aqueous NaCl solution, whereas in visual (qualitative) experiments NaCl was replaced by an aqueous $KMnO_4$ solution.

In case of visualization – qualitative studies, a step extortion (Heaviside) is also used at the model inlet. The image of the flows was recorded in the central plane. This camera setting allows undisturbed observation of the model fluid circulation. The film material is processed in a dedicated proprietary computer program. The program allows extraction of individual film frames into photos at a precisely defined moment of the experiment with an accuracy of 1/100 s, photographic processing and regulation of the playback speed of the recorded film material.

3. Results and discussion

The test results were analysed in two groups: qualitative tests involving the visualization of the model liquid mixing in the tundish and quantitative tests to develop the F-type RTD characteristics.

3.1. Visualization

Figures 5-8 show exemplary tracer flow visualization results for the analysed variants of experiments (four TI variants (see Fig. 4)) – in form of images (3 replications were performed for each experiment). The research at this stage was performed for each experiment in the range of 0 – 1800 s. The results presented in Figures 5-8 cover the time range from 30 s to 480 s. These images were taken at equal time intervals for each variant, measured from the beginning of the experiment.

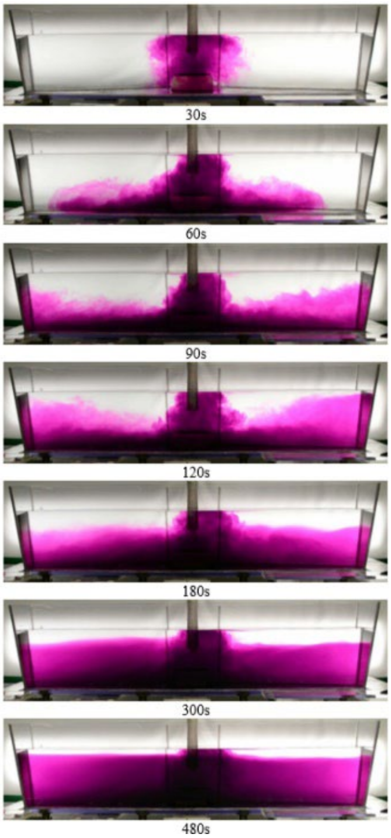

Fig. 5. Visualization of the model liquid flow for the analysed variant A

The analysis of the obtained visualization results (Fig. 5-8) allows to state the expected similar nature of the tracer flow in the tundish model for all variants of the experiment. It proceeds in such a way that in the inlet zone, a typical impact of turbulence inhibitors on the incoming stream of model liquid is observed, which reflects from their bottom and directs upwards towards the free surface of water. No excessive undulation of the model liquid surface (free surface of water) was observed, which is a positive phenomenon (see Fig. 9). This means that there is no risk of slag continuity breaking in the pouring zone during steel casting in industrial conditions. The use of TI limits the range of the turbulent flow zone (ideal mixing) and in the plane of outlets 2 and 3 it obtains laminar flow characteristics. This transition causes the model liquid stream to fall towards outlets 1 and 4. After reaching the side walls of the tundish model, the model liquid stream reflects from them and is directed in a circulating manner to the zone between outlets no. 1, 2 and 3, 4. The main model liquid stream is transported to the lower part of the tundish model, which is the cause of the unfavorable phenomenon of dead zones in its upper part. Although this phenomenon occurs in all variants of the experiment, some differences can be observed depending on the type of TI geometry used. It was observed that the smallest range of the dead zone in the region of the model free surface of water occurs for variants B and D of the experiment.

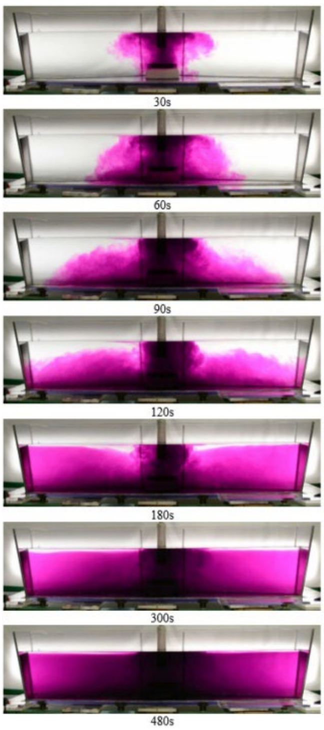

Fig 6. Visualization of the model liquid flow for the analysed variant B

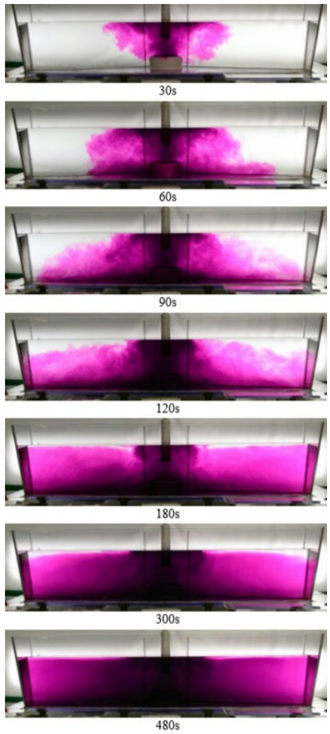

Fig.7. Visualization of the model liquid flow for the analysed variant C

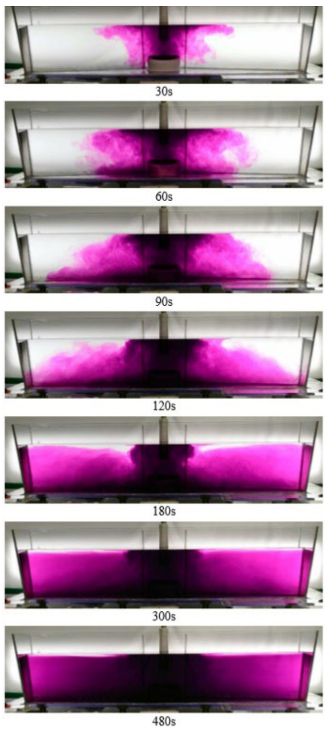

Fig. 8. Visualization of the model liquid \flow for the analysed variant D

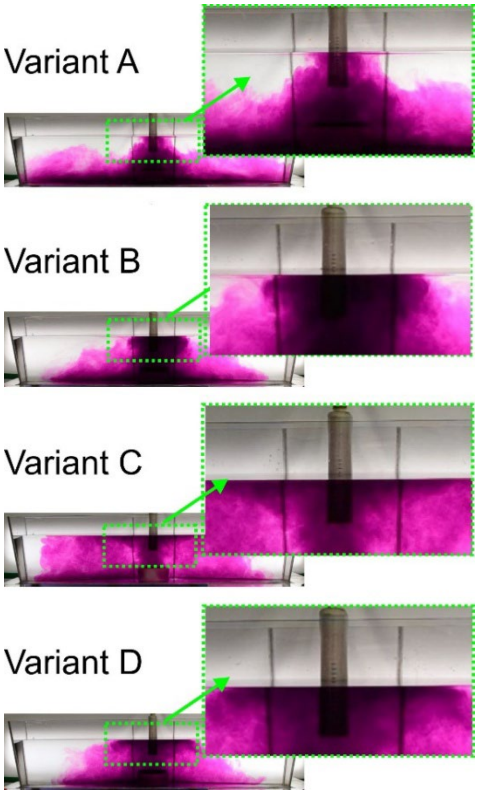

Fig. 9. Visualization of the free surface of water for the analysed variants A – D

3.2. RTD curves

Figure 10 shows an example of the F-type RTD curve for variant A. The curves are presented in dimensionless values according to the relationships described in [28-30] for direct comparison of individual measurements. The curves were obtained by forcing a step change in the tracer (NaCl) concentration at the inlet from 0 to C_{max} and recording it at the reactor outlets [29]. This method is often used in modelling flows in a tundish because it directly reflects the sequential casting technique.

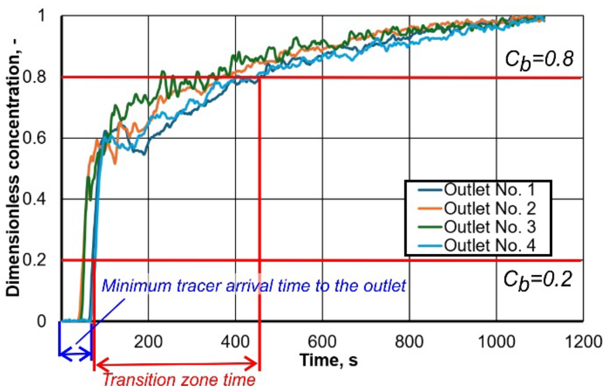

Fig. 10. An exemplary RTD F-type curve for experiment variant A

By analysing the obtained curves for all tested variants, it is possible to determine the nature and dynamics of mixing of the model liquid in the volume of the tundish model. First of all, it was found that in all variants the nature of the flow is very similar. This is also confirmed by the visualization results.

In all variants, a clear difference was noted in the time of the tracer reaching outlets 2 and 3 located closer to the inlet zone of the tundish compared to outlets 1 and 4 located at the extreme walls of the tundish. Then, a very rapid increase in the marker concentration in the model liquid in the inlet region was observed. This increase should be interpreted as a range of turbulent flow (ideal mixing). In the further tundish working zone in all variants, the mixing kinetics of the model liquid decreases, which should be interpreted as a transition from the range of turbulent mixing to plug flow. A further decrease in the flow energy causes a decrease in its velocity and, consequently, the formation of dead zones (practical cessation of mixing of the model liquid) [25,27].

Table 3 presents a summary of the transition zone time values for all analysed variants during sequential casting of different steel grades, as well as the tracer arrival time values for individual nozzles. The method of determining the individual values is presented in Figure 10.

The results presented in Table 3 were grouped into pairs (outlets 2 and 3 - the middle of the tundish, outlets 1 and 4 - the extreme outlets), for which average values were calculated. In each case the measurement error did not exceed 5%. This allowed a direct comparison of the differences in delay time between them. This approach made it possible to determine the effect of the applied flow regulator variant (TI) on the even distribution of the tracer between the considered outlet pairs. In practice, it is not possible to completely equalize the time of reaching individual outlets from the tundish. However, for variants A and C, it was possible to significantly reduce these differences.

Table 3.
Transition zone extent and tracer arrival time at tundish outlets

Experiment variant	Arrival time, s						Delay between outlets
	No. outlet 1	No. outlet 4	Avg.	No. outlet 2	No. outlet 3	Avg.	
A	64.0	68.0	66.0	39.5	44.5	42.0	24.0
B	87.0	92.5	89.8	44.0	53.5	48.8	41.0
C	87.5	73.0	80.3	53.0	58.0	55.5	24.8
D	97.0	90.0	93.5	52.5	52.5	52.5	41.0
	Time of transient zone, s						
	No. outlet 1	No. outlet 4	Avg.	No. outlet 2	No. outlet 3	Avg.	
A	394	367	380.5	318	309	313.5	
B	600	579	589.5	493	453	473.0	
C	494	457	475.5	426	411	418.5	
D	348	397	372.5	403	441	422.0	

The duration of the transition zone in individual outlet pairs was analysed in a similar way. On this basis, it was found that its occurrence was very similar in all variants of the experiment. The only exception was variant D. In this case, in contrast to the others, the duration of the transition zone is longer for outlets located closer to the inflow zone than for external outlets located closer to the side walls of the tundish. In general, it can be stated that the range of the transition zone duration for all variants is very similar, and the differences between individual outlet pairs are insignificant from a practical point of view.

3.3. Analysis of model research results

The comparative method was used to analyse the obtained research results. Four parameters were determined to be relevant to the impact of the tested design (geometric) TI variants on the expected effects of the continuous steel casting process. These parameters, together with the criteria used for their evaluation, are presented in Table 4.

Table 4.
IT performance effectiveness parameters and criteria for their evaluation

No.	Parameter	Assessment criterion
1	tendency of the system to form large dead zones	visualization
2	the ability to effectively micro-refine a steel bath	average tracer arrival time to each outlet pair
3	conditions for the formation of a homogeneous primary structure in the individual strands of the device	tracer arrival time difference between each pair of outlets
4	the efficiency of chemical homogenization of liquid steel	average duration of the transition zone for each outlet pair

Comparing the results of the tests carried out for the individual variants of the turbulence inhibitor design, their similar efficiency was found. The recorded differences in the analysed parameters are small. However, they confirm the fact that the cause-and-effect nature of their occurrence causes the improvement of one process parameter to occur at the expense of another. Table 5 presents the binary results of the comparative analysis of the individual variants of the turbulence inhibitor design from the point of view of their effectiveness parameters (the "Parameter" column contains the number of the parameter included in Table 4).

Table 5.
Summary of the effectiveness parameters of the analysed IT variants

Parameter	Variant A	Variant B	Variant C	Variant D
1	-	+	+	+
2	+	-	+	-
3	-	+	-	+
4	+	+	+	+

4. Conclusions

The analysis of the visualization results and the criteria for assessing the effectiveness of the tested turbulence inhibitor variants determined on the basis of RTD curves allows to draw the following conclusions:

1. The flow and mixing of the model liquid is similar in all variants of the experiment. A tendency to form dead zones is observed in the zone of the model free surface of water. The volume of this zone takes on a particularly dangerous volume in variant A of the experiment.
2. No excessive undulation of the model liquid surface was observed as a result of using the tested TI geometry variants.
3. Variant C is characterized by the most favorable conditions for temperature homogenization, due to the shortest difference in the time it takes the tracer to reach the individual pairs of outlets.
4. The most favorable results from the point of view of the average time of the tracer reaching the individual pairs of outlets from the tundish (the smallest range of the transition zone) were obtained for variant A, however, the remaining parameters in this variant differ from other considered TI variants, which is the reason for abandoning the possibility of its use in industrial conditions.
5. The average time of the tracer reaching the individual pairs of nozzles for variants B and D are very similar and allow predicting good conditions for micro-refining of liquid steel in tundish.
6. The scope of the transition zone occurrence in all variants is similar and the determined differences are not significant from the industrial point of view.

In summary, it should be stated that despite similar results of model tests for all tested TI geometry variants, variant A can be excluded from use in industrial conditions due to the high risk of dead zone formation in the bath surface area (liquid steel - slag). Variants C and D, which were intended for tests in industrial conditions, have the most favorable effect on the flow conditions in the tundish.

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