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P. BLAŠKO[1], B. BULKO[1], J. PETRÍK[1*], P. DEMETER[1], V. SOCHA[2],
L. HANÁKOVÁ[2], P. PALFY[1], M. SOLC[1], A. VASILŇÁKOVÁ[1]

THE ADJUSTMENT OF THE TUNDISH WATER MODEL OF CONTINUOUS CASTING

Whereas approximately 96.3% of the steel produced worldwide is made by continuous casting, great emphasis is put on the superior efficiency of this process. The water model of the tundish and mathematical modeling is often used for the simulation of the steel flow during continuous casting. The experiments were performed on a model of the tundish with two outlets, at two casting speeds (0.8 $m.s^{-1}$ and 1.2 $m.s^{-1}$). Eight setups of the tundish were evaluated, which differed in the design of the dams (with or without drainage holes), in their distance from the center of the tundish, and their height. The contribution of the work is the analysis of phenomena in the tundish water model in conditions of repeatability (ten repetitions). The goal is to find the setup providing the most symmetrical flow, with the minimum difference in the residence times $\Delta\tau$ on the two outlets. Taking into account the results obtained at both casting speeds, the most preferred is setup 2 with the 87 mm high dams placed 587 mm from the center of tundish ($\Delta\tau = 0.5$). The setup 3 ($\Delta\tau = 8.25$) appears to be the least appropriate. The higher the casting speed, the higher the number of unsuitable arrangements.

Keywords: steel; tundish; water model; continuous casting; statistical methods

1. Introduction

World steel production has rapidly increased, in the last few years, from 848 million metric tons in 2000 to 1742 million metric tons in 2018. Nowadays, approximately 96.3% of the steel produced worldwide utilizes a continuous casting process [1,2]. Consequently, enormous efforts have been made to increase the quality of the final product of continuous casting. Various methods of control systems improvement have been developed in the last decades, in particular for the mold level control system. However, the long response delay of the system allows the occurrence of difficulties [3].

Because of the increasing demand for quality in metallurgical production, new engineering solutions are being developed to eliminate the remaining drawbacks of continuous casting technology. The current state of this technology allows the casting of liquid steel semifinished products with shape and cross-sectional dimensions that are close to those of the finished products [4].

The key part of the continuous casting equipment is the tundish [5], placed between the ladle and the crystallizer. Its primary role is to ensure the distribution of liquid steel to all outlets – the casting strands. The tundish serves as a storage vessel or the buffer tank, receiving molten steel from the ladle and allowing it to be cast continuously. Also, the tundish has been developed as a metallurgical reactor to serve as the final step in the liquid steel refining by the control of temperature, composition, and flow to promote the removal of non-metallic inclusions, prevent the formation of new inclusions and ensure its chemical and thermal homogeneity [6-8].

For the exact description of the residence time of the elementary volume of steel in the tundish, it is necessary to divide the internal volume of the tundish into zones [9,10]. The proportion of individual zone volumes depends not only on the shape of the tundish and its internal setup (tundish design and position of turbostop and dams) but also on the casting speed. The casting speed affects the proportion of turbulent flow volume to a laminar flow volume.

In actual production, continuous casting equipment uses casting speeds depending on the cast profile. It is possible that if the casting speed is higher, the effect of speed would not be linear. Presented experiments were made for (U) – boat shape of the tundish. While other types of tundishes are also used (for example T-shape, V-shape) [11], it is, therefore, advisable to analyze them in the future, as well.

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[1] TECHNICAL UNIVERSITY OF KOŠICE, FACULTY OF MATERIALS, METALLURGY AND RECYCLING, LETNÁ 9, 04 001 KOŠICE, SLOVAKIA
[2] CZECH TECHNICAL UNIVERSITY IN PRAGUE, FACULTY OF TRANSPORTATION SCIENCES, HORSKÁ 3, 128 00 PRAGUE, CZECH REPUBLIC

[*] Corresponding author: jozef.petrik@tuke.sk

In optimizing the tundish process, it is necessary to take into account design variations. While the term "design", represents the fixed form of tundish construction (for example number of the strands/outlets), the terms "setup" or "configuration" represent the layout of its various components. These are components that can be inserted or removed within the fixed construction of the tundish, such as turbostops (impact pad), baffles, dams, and weirs. The impact pad is a body of refractory material capable of withstanding contact with molten steel drained into the tundish. This product is characterized by high erosion resistance and high-temperature stability.

The baffles, dams, and weirs are an auxiliary component in the tundish. They are used to separate slag, prevent slag from flowing into molds, and improve steel quality. Good erosion resistance and high-temperature stability are required for these components. Perforated baffle obstructs the entire cross-section of the tundish, weirs and dams only part of it. Steel flows under the weirs, and over the dams [1,12].

The quality of the casting process and its final product can be controlled by the optimal setup of the tundish; this is the main reason for the modeling of the casting process.

Unfortunately, instability, uncertainties, and disturbances such as clogging and unclogging of the outlets, unwanted surface waves, uncertain sensor and actuator dynamics [3] can occur during the continuous casting, which makes it difficult to describe and simulate.

Investigations of steel flow or inclusions separation in the industrial plant tundish are problematic, because of the high temperature, the lack of optical accessibility of the melt, the need for a large number of experiments as well as their technological difficulty. For these reasons, mathematical, and physical modeling (water models) are used for the simulation of the steel flow during continuous casting [13,14].

Therefore, the results obtained by the mathematical model should be verified by physical modeling – laboratory experiments with water model, and, if possible, by industrial experiment. The results of mathematical models simulations confirmed by the results of water modeling provide important information for the implementation of innovative solutions in industrial conditions [15-18].

Both modelings provide the determination of the range and location of the intermixed zone, the optimization of steel flow by the tundish setup, and the residence time. The intermixed (transient) zone forms when different steel grades are cast in a single sequence, without the interruption of the casting [17,19,20].

Investigations using the water model are already well known and widely applied [21]. The kinematic viscosities of molten steel and that of water are similar. So far, tundish water models were used for qualitative as well as quantitative investigations. The water model enables the visualization of the flow, the measurement of the residence time, the study of the intermixed zone, the observation of the tundish setup influence on the flow, and the research of the inclusions separation [6].

The model of a tundish is designed to simulate, among other things, absorption, flotation, thermal and chemical homogenization of steel. It enables relatively quick and safe acquisition of information for the design and development of equipment at a relatively low cost. The reduced-scale physical model is designed to work according to the theory of physical similarity and modeling. The complexity of processes occurring in the real tundish does not allow to simulate all possible variants of the processes [12,22-25].

Therefore, it is necessary to ensure the quality of the measurement beyond the verification of the accuracy of experimental measuring instruments [26]. The purpose of the measurement management system in agreement with the standard ISO 10012:2004 [27] is to control the risk that the measurement equipment or measurement process will yield incorrect results. Such results of the measurement negatively affect the final quality of products with economic or moral consequences, for example, the loss of goodwill.

Sufficient reliability of results cannot be achieved without verifying the results under repeatability conditions. Repeatability conditions bring the model closer to the industrial use of tundish, in which the casting is repeated many times under approximately the same conditions. Papers that take into account the repeatability of modeling, such as [18], are rare.

Based on the above mentioned, the present paper deals with the evaluation of the "quality" of the water model with two outlets. The "quality" means the balance: are the conditions on both outlets given by the residence time the same, depending on casting speed and the setup of the tundish? To ensure repeatability, the experiment was repeated ten times for eight setups and two casting speeds, 0.8 m.s^{-1}, and 1.2 m.s^{-1}.

2. Experimental setup

The analyzed water model of the continuous casting machine consists of two changeable ladles, a ladle shroud, and a boat-shaped, two-strand tundish [21] (see Fig. 1).

The model was on a 1:3 scale compared to the industrial tundish. The water with a temperature of 20°C substitutes the liquid steel with a temperature of 1600°C, it allows the simulation of steel flow in real conditions. A tundish can operate in two standard modes. If the level of water in the tundish is constant and the volume of water flowing into the tundish is equal to the volume draining at tundish outlets, it operates in a steady state mode; presented analyses were performed in this steady state (conditions). If the tundish works in non-steady state conditions (so-called transient casting), the volume of the liquid flowing into the tundish changes with time together with the level of the liquid in the tundish [21]; it takes place during the exchange of ladles.

Temperature and the level of water were continuously measured. On the ladle and the tundish are placed sensors of the local water level (CH-8501, Baumelectric company) with a maximum permissible error (MPE) of 0.5 mm. The electromagnetic flow sensors (DN 25, ABB company) are placed in the ladle shroud tube and in the outlets. Their MPE is 3% of the casting speed (for speeds greater than 0.7 m.min^{-1}). The conductivity probes

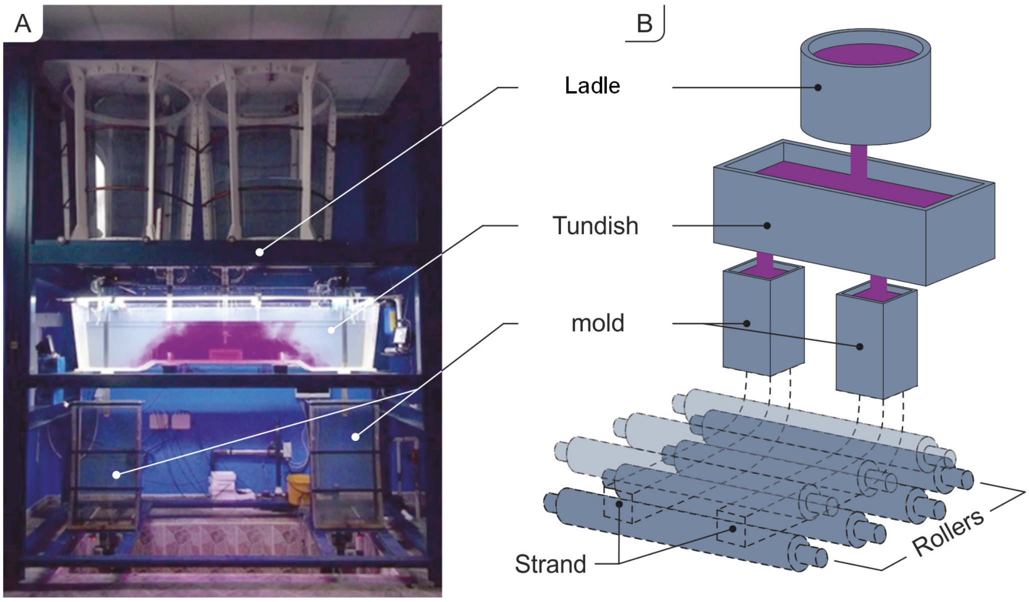

Fig. 1. The water model of continuous casting machine (A) and schematic of real continuous casting machine (B)

(type 601, Moravian instruments, j.s.c., Zlin, Czech Republic) are placed in the ladle shroud and in the outlets of the tundish. Their resolution is 0.001 S and MPE 1.2%. They also measure the temperature of the water with MPE 2%. The A/D converter (DATA ELEKTRONIK, s.r.o, Brno, Czech Republic) processes the values of water conductivity changes, monitored by conductivity probes. The converter sends the processed data to the PC, equipped with the Control Web (CW) software. The data are presented in charts of the dimensionless concentration vs. time (s).

The water model is controlled by system Simatic (Siemens AG, Munich, Germany) that can control all volumetric flows and levels of water. This system is similar to the control system used in the real continuous casting machine.

The goal of the model is to observe minimum residence time t_{min} for alternative setups of the flow modifiers in the tundish as can be seen in TABLE 1. Each setup was tested at two different casting speeds of 0.8 $m.s^{-1}$ and 1.2 $m.s^{-1}$, which corresponded to the actual casting speed of the steel. Fig. 2 shows

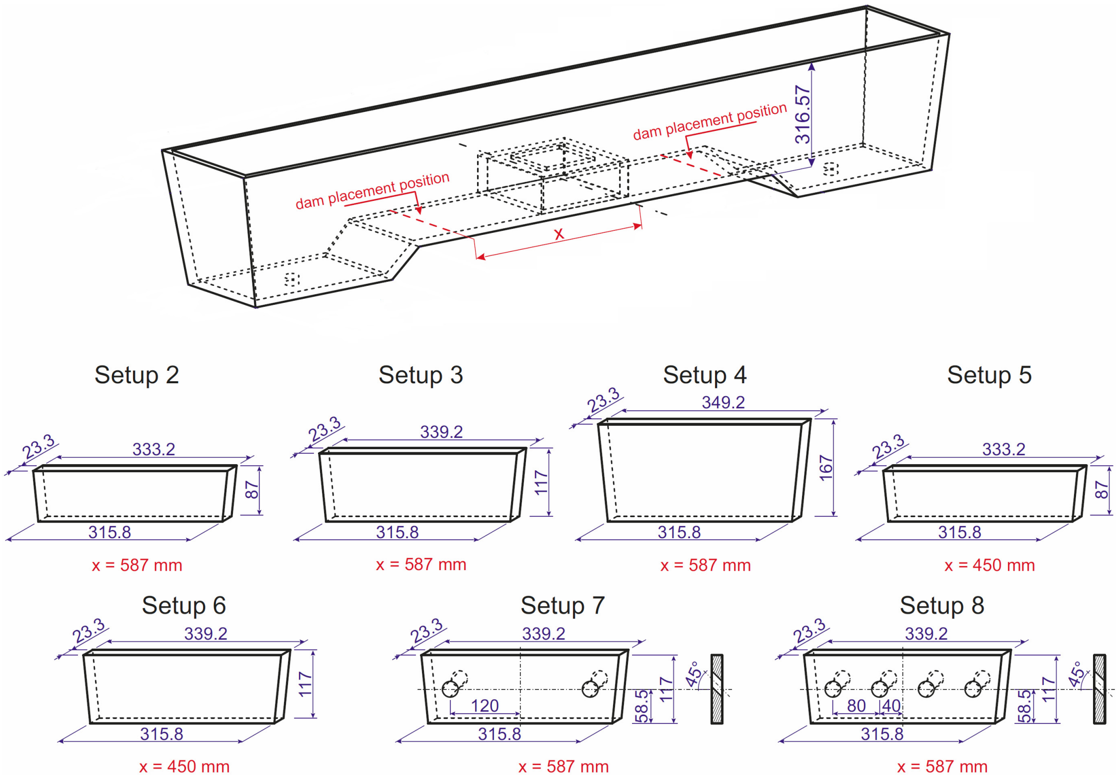

Fig. 2. Example of measured C-curve with highlighted times of tracer injection (A), minimal residence time (B), and maximal residence time (C) and real C-curves for setup 1-8

TABLE 1

Operating conditions

Setup	Casting speed		Tundish bottom dam						
			Position		Height			Texture	
	0.8 m/min	1.2 m/min	450 mm	587 mm	87 mm	167 mm	117 mm	Compact	Drainage
1	✓	✓	no dams	no dams	no dams	no dams	no dams	no dams	no dams
2	✓	✓		✓	✓			✓	
3	✓	✓		✓			✓	✓	
4	✓	✓		✓		✓		✓	
5	✓	✓	✓		✓			✓	
6	✓	✓	✓				✓	✓	
7	✓	✓		✓			✓		✓ two holes
8	✓	✓		✓			✓		✓ four holes

the schematic setup of tundish, dam placement, and dam dimensions for each tested setup. Each tundish setup (configuration) involved flow modifier "turbostop" with a specific dam type and position, except setup 1 without dams. The bottom dams were placed specifically. For setups 5 and 6 bottom dams were placed 450 mm from the center of the tundish model. For setups 2, 3, 4, 7, and 8 bottom dams were placed 587 mm from the center of the tundish model. The tundish bottom dams had different heights. The tundish dams were 87 mm high for setups 2 and 5, 167 mm for setup 4, and 117 mm for setups 3, 6, 7, and 8. The tundish bottom dams were solid for setups 2, 3, 4, 5, and 6, and perforated for setups 7, and 8. The perforated dams in setup 7 had two drainage holes with a diameter of 27 mm at an angle of 45°. In setup 8, the dams had four drainage holes with the same diameter and angle as in setup 7.

3. Data collection principle

The salt marker (tracer) KCl was used to adjust the water conductivity and fugitive dye $KMnO_4$ was used as the contrasting substance that allows visual observation of the flow (Fig. 1). The time of their injection into the stream ($\tau_0 = 0s$) was registered by conductivity probe No. 1 placed in the ladle shroud. The flow of injected KCl and $KMnO_4$ in the tundish depends on a tundish setup. Subsequently, the tracer reaches the outlets, where it is detected by the conductivity probes No. 2 and 3, which are placed in the tundish outlets and record the changes in the conductivity of water. The time of the first detection of the change in conductivity is τ_{min} – minimum residence time.

Measured values of conductivity are converted into dimensionless concentrations using Eq. (1). The plot of dimensionless concentration against time enables the construction of C – curves.

The main investigated parameter that describes the water flow in the tundish is a minimum residence time τ_{min}. It is defined as the shortest period, by which the injected salt and dye entering the tundish (injected in time τ_0, point A in Fig. 3) appear at its outlets. In the real conditions, t_{min} significantly correlates with time during which the inclusions in steel can float to its surface and into the slag layer [11,21].

In the case of the so-called short-circuit flow very low values of τ_{min} occur. It means that water entering the tundish gets arrives at outlets by the shortest possible path. This phenomenon can cause so-called dead zones.

The desirable goal is to achieve the longest possible value of the minimum residence time and the symmetric flow in the tundish. The design of the tundish, its geometry, dimensions, shape, and also setup, and the steel affect the flow of the liquid in the tundish.

As can be seen from Fig. 3a), in addition to the minimum residence time τ_{min}, (point B), the maximum residence time τ_{max} (point C) are significant points of the C-curve. The maximum residence time τ_{max} is defined as the time required for reaching the maximum concentration of salt tracer in the outlets of the tundish model [28-30]. The dimensionless concentration of the salt tracer (Cs) for C-curves is calculated by Eq. (1).

$$Cs = \frac{mc}{Mmc} \tag{1}$$

Where mc is measured concentration, in time and Mmc is the maximal measured concentration. For this research, all measurements were shortened and focused only on reference points (minimal and maximal residence times). Real C-curves for setups 1-8 can be seen in Fig. 3b)-i).

4. Statistical analysis

To determine the above mentioned parameters it was necessary to select the most appropriate statistical test. First, the normality of statistical distribution was tested for each dataset by the Jarque-Bera test [31]. It showed that no dataset has normal statistical distribution.

Since the datasets under consideration have a different distribution than normal, parametric tests are not suitable to determine the statistical significance of the analyzed differences. Therefore, a nonparametric Mann-Whitney U (or the Mann-Whitney-Wilcoxon) test was used. The significance level of the test α was set to 0.05; the null hypothesis (the difference between the medians of the datasets is not statistically significant) is rejected when $p < \alpha$.

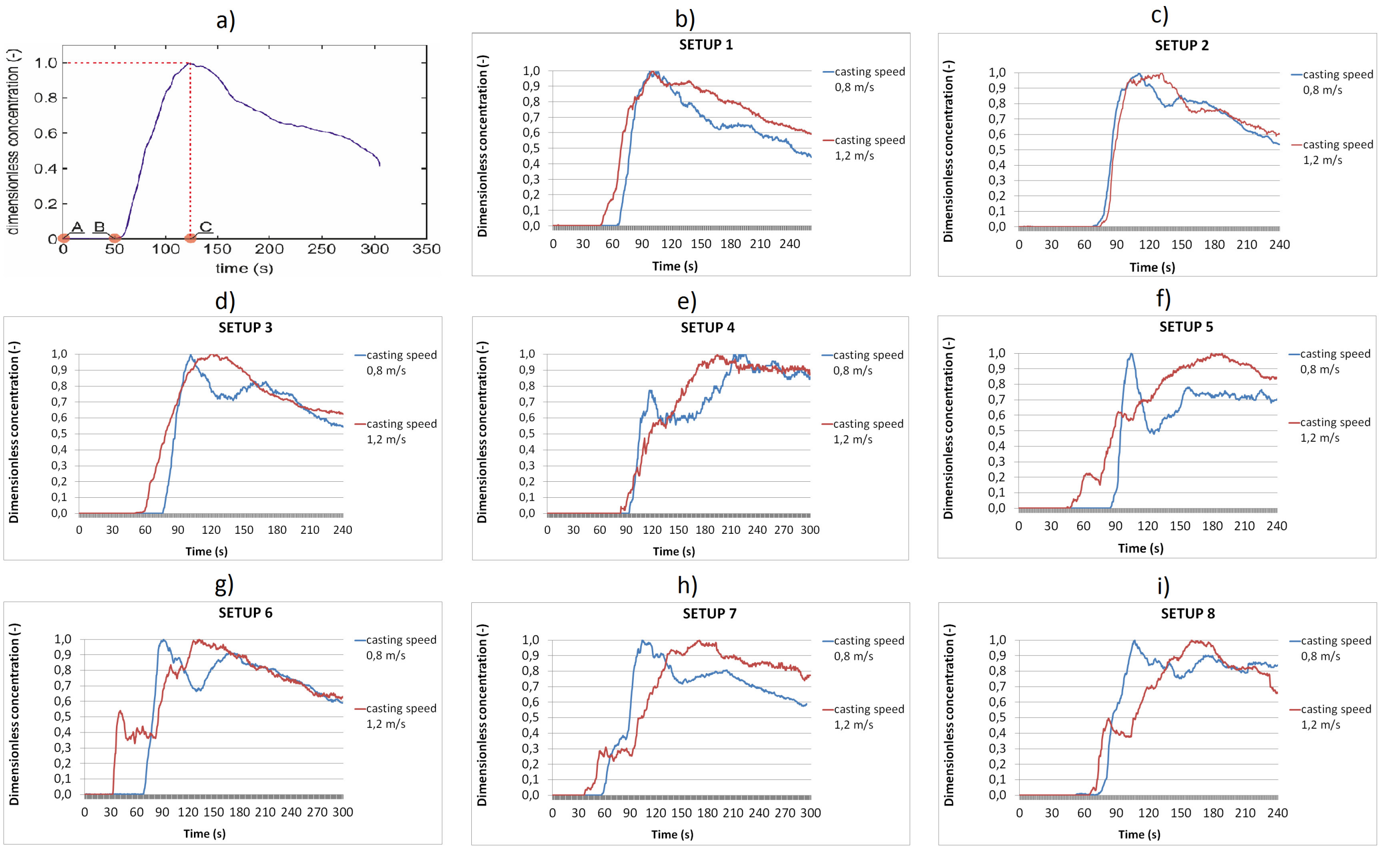

Fig. 3. The setup of the tundish – the bottom dams

The outliers (X_{out}) were calculated using inequality (2).

$$Q1 - 0.5IQR > X_{out} > Q3 - 1.5IQR \tag{2}$$

Where $Q1$ is the first quartile, $Q3$ is the third quartile; IQR is the interquartile range ($Q3 - Q1$).

5. Results

The parameters of individual datasets are shown in boxplots in Fig. 4-6, which visualize the statistical parameters important for processing of datasets with non-normal distribution, i.e. median, first quartile, third quartile, minimum and maximum, the crosses mark the outliers (X_{out}).

The minimum residence times $\tau_{\min}$ for both tundish outlets (left and right) were measured ten times for each setup of the tundish (1-8) and each of the two casting speeds (0.8 m.min^{-1} and 1.2 m.min^{-1}), i.e. there were performed ten experimental runs for each tundish model setup and casting speed.

These measured data were subjected to statistical analysis to evaluate the statistical significance of the difference between residence times τ measured at the left and right outlets, depending on the setup of the tundish, and casting speed.

The goal of the analysis was to find the setup with the best flow of the liquid with:

- the longest minimum residence time $\tau_{\min}$,
- the lowest difference between left (L) and right (R) outlet $\Delta\tau$, calculated by Eq. (3),
- the highest possible measurement accuracy, determined by medians.

$$\Delta\tau = abs(\tau_{\min}R - \tau_{\min}L) \tag{3}$$

The statistically significant difference between the left and right outlet residence time at the casting speed of 0.8 m.min^{-1} was found only in setups 1 and setup 3. As shown in TABLE 2 and Fig. 4, the best balance of the model (the lowest difference between $\tau_{\min}$ medians of the left and right outlet) was found in

TABLE 2

The results of Wilcoxon test: p – values, and the difference $\Delta\tau$ between medians of left and right outlet (casting speeds 0.8 m.min^{-1} and 1.2 m.min^{-1})

Casting speed, m.min^{-1}	setup	1	2	3	4	5	6	7	8
0.8	p-value	0.00192	0.54322	0.03742	0.07522	0.70503	0.11982	0.20953	0.87965
	$\Delta\tau$	7.0	1.0	8.0	9.5	2.0	6.5	0.5	6.5
1.2	p-value	0.57003	0.62014	0.00113	0.03735	0.42614	0.38396	0.57017	0.04491
	$\Delta\tau$	1.5	1.0	9.5	6.0	17.5	5.0	2.0	24.0

setups 2, 5, and 7. The retention time values for setup 3 (right outlet) and 8 (left outlet) have a greater variance compared to the other setups. Both setups have the same distance of the dam from the center of the tundish (587 mm) and the same height of the dam (117 mm). In the case of setup 8, the dam is perforated.

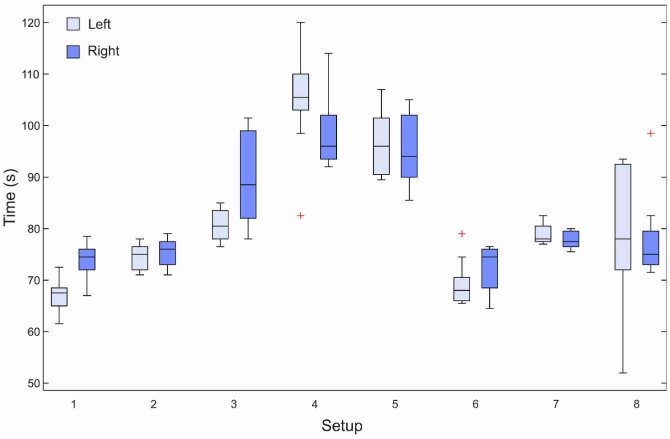

Fig. 4. All setups under casting speed $v = 0.8$ m.min^{-1}

The statistically significant value of $\Delta\tau$ at the casting speed of 1.2 m.min^{-1} was found in setups 3, 4, and 8. As shown in TABLE 2 and Fig. 5, the best balance of the model (the lowest value of $\Delta\tau$) was found in setups 1, 2, and 7. Unlike the case of the speed 0.8 m.min^{-1}, the distance and height of the dams with the significantly higher variance of the retention time are not related to each other. On the other hand, a high variance was observed at the left outlet of setup 8 with the perforated dam at both casting speeds.

Taking into account the results obtained at both casting speeds, the most preferred setups are 2 and 7. Regardless of the casting speed, the statistically significant value of $\Delta\tau$ was found only in setup 3. The lowest values of $\Delta\tau$ were attained in setups 2 and 6 (see TABLE 3 and Fig. 6).

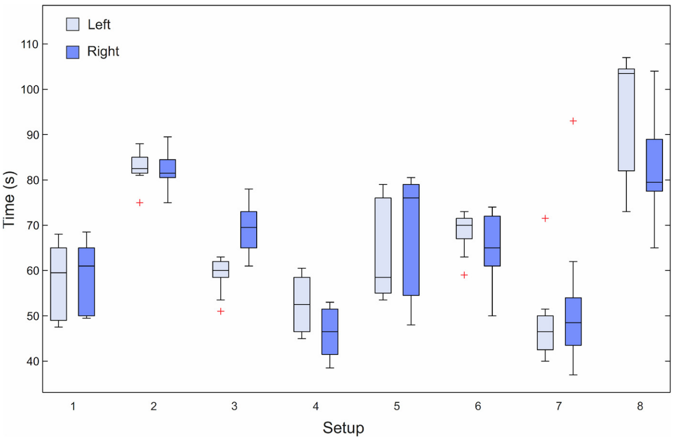

Fig. 5. All setups under casting speed $v = 1.2$ m.min^{-1}

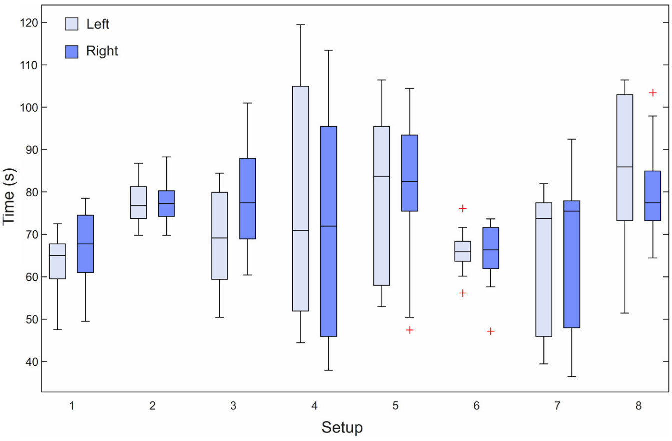

Fig. 6. All setups regardless of the casting speed

TABLE 3

The results of Wilcoxon test: p-values, and the difference $\Delta\tau$ between medians of the left and right outlet (both casting speeds)

Setup	1	2	3	4	5	6	7	8
p-value	0.57003	0.62014	0.00113	0.03735	0.42614	0.38396	0.57017	0.04491
$\Delta\tau$	2.75	0.5	8.25	1.0	1.25	0.5	1.75	8.5

TABLE 4

Average values and standard deviations of residence times τ_{min} measured of left and right outlet (casting speeds 0.8 m.min^{-1} and 1.2 m.min^{-1})

Setup	Casting speed							
	0.8 m min^{-1}				1.2 m min^{-1}			
	left outlet		right outlet		left outlet		right outlet	
	$\bar{\tau}_{min}$	σ	$\bar{\tau}_{min}$	σ	$\bar{\tau}_{min}$	σ	$\bar{\tau}_{min}$	σ
1	67	3.153	73.85	3.614	57.8	7.653	58.85	7.401
2	74.7	2.573	75.5	2.625	82.7	3.490	82.4	3.900
3	80.6	3.007	89.35	9.183	59.15	3.923	69.1	5.896
4	105.15	9.983	99.25	7.558	52.75	5.770	46.35	5.477
5	96.6	6.540	95.1	7.066	64.25	10.639	68.35	13.024
6	69.3	4.360	72.4	4.267	68.55	4.456	65.2	7.162
7	78.8	1.798	77.8	1.602	48.5	8.882	52.7	15.731
8	78.5	12.863	77.85	8.069	95.2	12.913	82.95	11.186

Average values of residence times $\tau_{\min}$ measured at both outputs and both casting speeds have listened in TABLE 4.

6. Discussion

There are several influencing quantities acting on the continuous casting of steel. Some are well known; we know their influence and their ranges. Some have a minuscule impact compared to other influencing variables and we may neglect them. Besides, quantities with unknown effects may occur with a certain probability. These quantities are usually not constant, but their influence changes to some extent with time. It follows from the above that repeated casting (casting from one ladle) is never carried out under identical conditions.

If we simulate the processes in the tundish by the water model, such a process is also disturbed. However, in the water model, the impact of influencing quantities on the process needs not to be the same as during industrial casting, some have larger and some smaller effects or, possibly, different quantities may be in play.

It is, therefore, appropriate to monitor the casting process in conditions of repeatability. This is to say, to monitor the influencing quantities, of which we assume that their statistically significant effect on the process is constant, or at least within regulated limits; and subsequently, repeat the process, assuming that only random effects exist. Regarding the water model, such analyses are seldom published. A rare example is a paper [18] where an experiment was performed six times at the same experimental setting under conditions of repeatability.

In the present paper, ten repetitions were made for one setup of the tundish. The motivation for the increase in repetitions (compared to the above-mentioned six) was the expected non-normal distribution of the measured results, which was also confirmed. Further increase in the number of repetitions, although it would certainly increase the quality of the analysis, would be prohibitively time-consuming and economically demanding. Therefore, non-parametric tests had to be used for the evaluation.

The objectives of the research were primarily focused not on the construction of the tundish, but the statistical evaluation of the stability of the given arrangement. For this reason, the experiment was carried out in a very simple, symmetrical tundish model with two outlets. A more complex model, for example with three outlets, described in more detail in [32] brings some complications to the statistical analysis.

The presented evaluation of the water model from the point of view of its balance, i.e. the smallest possible time difference between the outlets and the stability of this difference over time, is exceptional in the literature. As mentioned above, the setup of the tundish affects the difference in residence times $\Delta\tau$ at both outlets.

From a statistical perspective, the requirement of the normality of input data is the limiting factor. In the case of a normal distribution of the results, other statistical methods could be applied to calculate measurement accuracy, for example, ANOVA, Z-score, and Mandel's statistics. It would be appropriate to focus on a wider range of casting speeds, up to limit speed used in practice and to observe the model's sensitivity and stability.

7. Conclusion

- The goal of modeling is to identify a such setup of the tundish that provides the symmetrical flow of the medium, with the minimum difference in the residence times $\Delta\tau$ at the two outlets. Taking into account the results obtained at both casting speeds, the most preferred are setup 2 (p-value $0.62014 \gg 0.05, \Delta\tau = 0.5$) and to a lesser extent also setup 7. Setup 3 (p-value $0.0011 \ll 0.05$, $\Delta\tau = 8.25$) is the least suitable with the maximum observed difference between the right and the left outlet $\Delta\tau$. The number of undesirable setups increases with increasing casting speed (2 and 3 respectively according to p-value; and mean values of $\Delta\tau = 4.36$ and 8.32 respectively).
- The results presented in the paper are limited by the design of the model used (with two outlets) and the range of casting speeds.
- The contribution of this work is analysis under repeatability conditions, ie with a higher number of repeated experiments under the same conditions.

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