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INFLUENCE OF HYDRODYNAMIC STRUCTURE ON MIXING TIME OF ALLOY ADDITIONS WITH LIQUID STEEL IN ONE STRAND TUNDISH

The knowledge of the hydrodynamic pattern aids in designing new and modernizing existing tundishes. The device under examination is an one-strand tundish of a capacity of 30 Mg. Computer simulation of the liquid steel flow, tracer and alloy addition behaviour in turbulent motion conditions was done using the Ansys-Fluent® computer program. The hydrodynamic conditions of steel flow were determined based on the distribution of the characteristics of tundish liquid steel residence time distribution (RTD). The alloy addition was introduced to the liquid steel by the pulse-step method. Based on computer simulations carried out, steel flow fields and RTD and mixing curves were obtained, and the shares of stagnant volume flow and active flow and the mixing time were computed. Dispersion of the alloy addition in liquid steel during its flow through the tundish is a dynamic process which is determined by the hydrodynamic conditions occurring in the tundish working space.

Keywords: tundish, hydrodynamics structure, RTD curves, time mixing, numerical modeling

1. Introduction

The tundish provides a constant feed of liquid steel to the primary cooling zone of the steel slab, billet or bloom continuous casting machine (CCM). The tundish enables the casting of slabs, billets or blooms in multi-heat sequences in multi-strand CCMs. As it flows through the tundish, the liquid steel interacts with the working space, in which specific hydrodynamic conditions occur. The hydrodynamic pattern that forms in the tundish depends on the tundish shape and capacity, the steel motion velocity and temperature distribution, and on the type of flow control devices (FCD) [1-5]. The knowledge of the hydrodynamic pattern aids in designing new and modernizing existing tundishes. Therefore, simulation of hydrodynamic phenomena provides a basis for, inter alia, the selection of flow control devices (FCD) and their arrangement within the tundish working space. The hydrodynamic pattern is made up of dispersed plug flow, well mixed volume flow, stagnant volume flow, bypass or channel flow, and recycle flow [6]. There are many models available in the literature, which enable the quantitative description of individual flow types. The basis is provided by residence time distribution curves (RTD), based on which the hydrodynamic pattern can be tentatively estimated. Tundishes are often used as reactors assisting the processes of liquid steel chemical composition correction or refining processes, including non-metallic inclusion modification. However, feeding alloy additions to liquid steel during the course of continuous casting at the tundish stage is limited by two basic factors, liquid steel temperature (20-30°C above liquidus temperature of heat) and the limited time of additional treatment of liquid steel in tundish (average residence time of liquid steel). The investigation results reported earlier confirmed that there were real grounds for developing a technology for efficient feeding alloy additions to liquid steel during continuous casting process [7-9]. The present study reports the results of investigation into the hydrodynamic pattern forming in the tundish and its effect on the time of alloy addition mixing with liquid steel.

2. Characterization of the test facility and computing methodology

The device under examination is an one-strand tundish of a capacity of 30 Mg. The tundish being currently operated in industry is only equipped with a low dam and stopper rod system (SRS) (Fig.1). A detailed description of the dimensions of the tundish and the dam is provided in paper [10]. Figure 1 shows a virtual tundish model with the location of alloy addition and tracer feeding to the liquid steel. Measurement point for RTD and mixing curves are positioned at tundish outlet. Computer simulation of the liquid steel flow, tracer and alloy addition behaviour in turbulent motion conditions was done using the Ansys-Fluent® computer program. A detailed description of the mathematical model and the employed numerical procedure is presented in studies [8-10]. The liquid steel flows into the tundish at a mass flow rate of 34.43 kg/s. By defining the heat losses on respective planes making up the virtual model, the non-isothermal conditions existing during the flow of liquid steel through the tundish were considered. The hydrodynamic conditions of steel flow were determined based on the distribution of the characteristics of tundish liquid steel residence time distribution (RTD). To this aim, a virtual tracer was introduced at the entry to

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the system under examination (ladle shroud), which allowed the variation in its concentration as a function of time to be recorded at the exit from the examined system (tundish outlet). Thus obtained characteristics in the form of an RTD curve enabled the assessment of the hydrodynamic pattern in the aspect of active and stagnant flows. For the quantitative evaluation of the active flow zone, the model proposed in references [11-12] was used. However, this model does not allow the quantitative evaluation of the share of the bypass and the recycle flows in the examined system, which make and integral part of the hydrodynamic pattern and influence the processes occurring in flow reactors [6]. In the present study, the examined process occurring in the flow reactor was the process of alloy addition macro-mixing with liquid steel. The alloy addition was introduced to the liquid steel by the pulse-step method, which is described in detail in paper [9]. With the pulse-step method, the alloy addition was introduced in the amount allowing the correction of liquid steel chemical composition by 0.05 wt%. The alloy addition was fed to the liquid steel in four characteristic locations in the tundish, as shown in Figure 1. The dimensionless time (DT) was calculated as the ratio of the current time to the average time of steel residence in the tundish. The casting of a single steel heat lasts 4 DT. The dimensionless concentration of the alloy addition in the liquid steel for pulse-step method was calculated from the relationship [13-15]:

$$C = \frac{C_t - C_0}{C_r - C_0} \tag{1}$$

where: C_t - temporary alloy concentration, C_0 - initial alloy concentration, C_r - required alloy concentration.

To evaluate the hydrodynamic pattern on the process of alloy addition mixing in the liquid steel, the tundish was equipped with different FCD variants. The modified working space of the tundish influenced the liquid steel stream distribution and modified the hydrodynamic pattern in the volume, within which the digestion of the alloy addition took place. All tundish working space equipment variants, along with the specification of the industrial tundish (tundish no. 1), are presented in Table 1. All of the proposed FCDs are described in detail in papers [7-9].

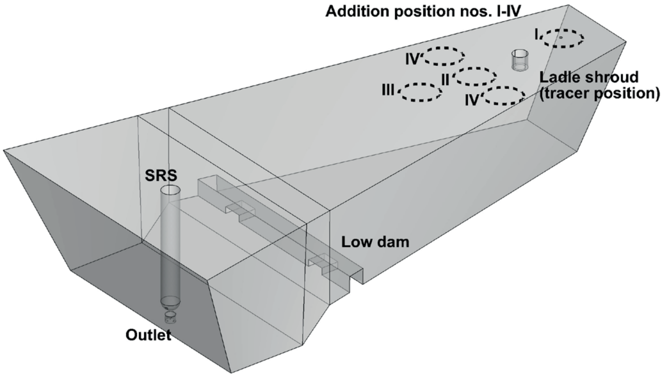

Fig. 1. Virtual low dam tundish model with addition and tracer positions

3. Results and discussion

Based on computer simulations carried out, steel flow fields and RTD and mixing curves were obtained, and the shares of stagnant volume flow and active flow and the mixing time were computed. Figure 2 shows maps of steel flow in the central plane intersecting the tundish pouring zone and the stopper rod system zone. The flow of liquid steel in the central part of the tundish with a low and a medium dam has a descending pattern and takes place in a vertical configuration. As a result of the influence of the subflux turbulence controller (STC) in the tundish pouring

TABLE 1

Tundish modification variants

Tundish no.	Type of flow control devices						
	Dam with two overflow windows		Dam with one overflow window, h=400 mm	Weir	STC no. I	STC no. II	STC no. III
	h=120 mm	h=250 mm					
1	×	-		-	-	-	-
2	×	-	-	-	×	-	-
3	×	-	-	-	-	×	-
4	×	-	-	-	-	-	×
5	×	-	×	×	-	-	-
6	×	-	×	×	×	-	-
7	×	-	×	×	-	×	-
8	×	-	×	×	-	-	×
9	-	×	-	-	-	-	-
10	-	×	-	-	×	-	-
11	-	×	-	-	-	×	-
12	-	×	-	-	-	-	×
13	-	×	×	×	×	-	-
14	-	×	×	×	-	×	-
15	-	×	×	×	-	-	×

TABLE 2

Structure of liquid steel flow calculated for considered tundish variants

Tundish no.	Volume of stagnant flow, %	Volume of plug flow, %	Volume of ideal mixing flow, %	Average residence time of steel, s
1	36.2	9.3	54.5	735
2	28.2	12.9	58.9	726
3	32.6	11.5	55.9	729
4	35.1	12.1	52.8	729
5	34	15.4	50.6	729
6	30	21.1	48.9	721
7	29.7	18.8	51.5	723
8	30.8	17.5	51.7	722
9	34.2	9.3	56.5	732
10	34.1	12.5	53.4	724
11	33.6	14.1	52.3	726
12	36.2	12.4	51.4	725
13	29.6	21.3	49.1	718
14	28.4	19	52.6	720
15	28.1	19.5	52.4	719

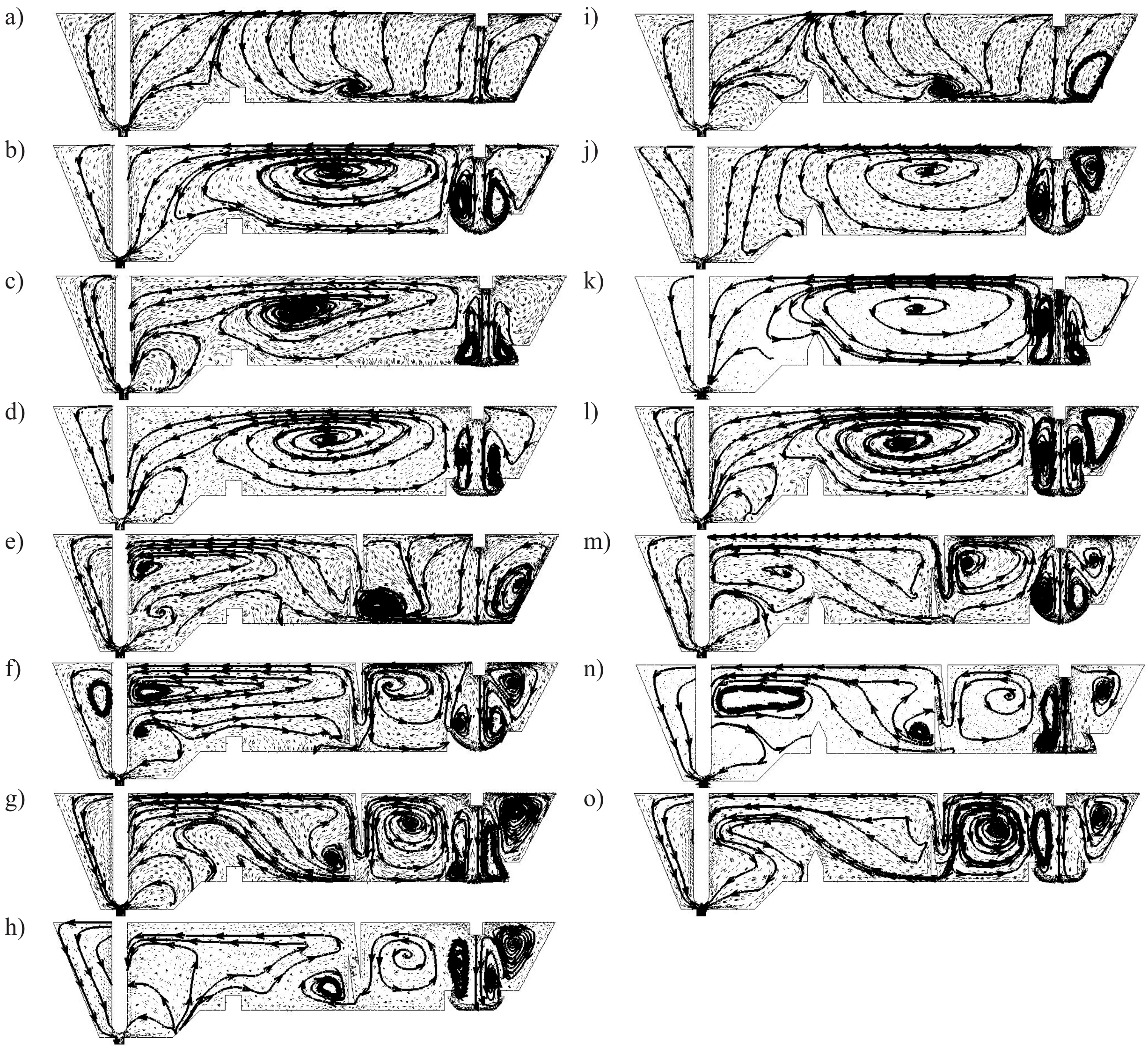

Fig. 2. Liquid steel flow fields for considered tundish variants: a) tundish no. 1, b) tundish no. 2, c) tundish no. 3, d) tundish no. 4, e) tundish no. 5, f) tundish no. 6, g) tundish no. 7, h) tundish no. 8, i) tundish no. 9, j) tundish no. 10, k) tundish no. 11, l) tundish no. 12, m) tundish no. 13, n) tundish no. 14, o) tundish no. 15

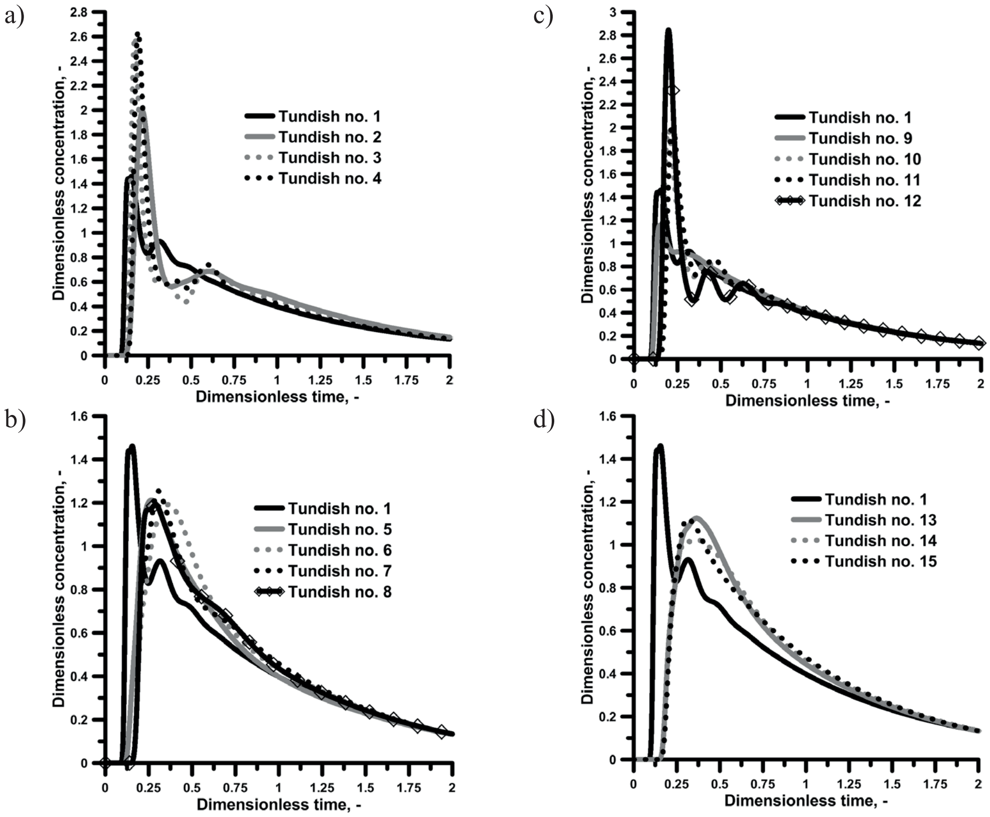

Fig.3. RTD curves for considered tundish variants

zone, the feeding stream is directed towards the upper liquid steel surface. In this connection, in tundishes equipped with STC and having a low or medium dam, circulation steel motion forms in a horizontal configuration, which extends from the dam zone to the STC zone. A reverse motion that forms in the stopper rod zone, takes on different forms, depending on the tundish configuration. In tundishes with no STC, the reverse stream flows up to, more or less, the mid-tundish, where by its contact with the feeding stream, a small steel circulation region forms, as shown in Figures 2a and 2i. By contrast, in STC-equipped tundishes, the reverse stream reaches the pouring zone, inducing steel motion in a horizontal configuration in the central tundish part, also between the stopper rod and the dam. Only in tundishes with STC no. I, the influence of the reverse stream on the motion of the tundish feeding stream is negligible in the stopper rod zone, as the feeding stream distinctly descends towards the bottom in a horizontal configuration. An interesting effect on the flow pattern is generated by the high dam – weir system, as on the pouring zone, steel motion in a vertical configuration is seen, while past the high dam towards the stopper rod system, the steel motion assumes a horizontal pattern. In tundish equipment variants nos. 6-8 and 13-15 including an STC, and a low, medium or high dam with a weir, a strong steel circulation region occurs in the zone between the STC and the high dam, which is caused by the ascending streams flowing from the STC and the streams descending at the weir. In fully equipped tundishes (6-8 and 13-15), the formation of the flow directions of individual streams is significantly influenced not only by the change in the STC internal geometry, but also by the change in the height of the dam located immediately at the tundish outlet zone. The presented flow maps indicate a considerable diversification of individual streams that form in the tundish working space. In each of the tundish variants, regions of circulation form, both in a vertical and horizontal configurations, which make up partially the volume of the stagnant flow and partially the recycle flow. The difference between the above flows is that the recycle flow is an active flow, in the volume of which part of the liquid steel elements return to the initial reactor region, that is the pouring zone, and then flow again towards the tundish nozzle for a duration not exceeding two average residence times. By contrast, the stagnant volume flow is a region, in which a closed system of liquid steel recirculation forms, where mass exchange with the streams flowing in the active volume is hampered.

Figure 3 shows E-type time residence curves for the examined variants of tundish equipment. When examining the position of the peaks and the shape of the E RTD curves it can be noticed that the use of the STC results in an increase in the dispersed plug flow share of the overall steel flow pattern. The greater tracer concentration value in the peak for the STC tundishes proves that a STC installed in the pouring zone limits the process of formation of several paths, along which mould feeding streams could flow, thus reducing the dispersion in the hydrodynamic system. By the STC action on the stream flowing to the tundish, a main and integrated stream flowing from the pouring zone towards the tundish nozzle is formed. The tracer concentration distribution for the tundish with a low or medium dam, including the distance of the RTD curve peaks from the y axis, confirms the formation of similar hydrodynamic patterns in both working spaces.

By contrast, in the tundish with a high dam and a weir, the main stream formed by the STC becomes split by the weir into intermediate streams, and the tracer concentration value in the peak decreases below the level recorded in the tundish currently used in industry. The proposed equipment in the STC – high dam – weir configuration shifts the peak away from the axis of ordinates and indicates an increase in the dispersed plug flow share of the overall steel motion pattern. The process of tracer dispersion in individual tundish regions is additionally intensified by the medium dam installed in the tundish working space, as indicated by the lower values of the curve peaks for variants 13-15, compared to tundish variants 6-8. The length of the curve tail, as measured from the peak to 2 average times, informs about the span of the stagnant zone. In the case, where the curve peak moves away from the y axis and, at the same time, its value on the y axis grows, then an increase in stagnant volume flow will follow. However, should a sinusoidal distribution of the RTD curve occur, the steel circulation in the stagnant zones will decrease, and part of the streams will feed the active recycle flow zone.

Based on the obtained residence time curves, the shares of active flow (dispersed plug and well mixed volume flows) and stagnant volume flow were calculated. The share of stagnant volume flow in the low-dam tundish amounted to 36.2%, while by installing one of the proposed STCs the stagnant zone was reduced by 8; 3.6 and 1.1 %, respectively, for the tundish with STC no. 1, STC no. 2 and STC no. 3. The flow controllers (STC) had influenced the dispersed plug flow formation in a similar manner, as the observed increase in dispersed plug flow share, as against the low-dam tundish, was 3.6; 2.2 and 2.8 %, respectively, for the tundish with STC no.1, STC no. 2 and STC no.3. A completely different effect of flow controllers is for the well mixed volume flow share. In the case of the tundish with STC no. 3, the flow controller decreased the well mixed volume flow share by 1.7 % as against the tundish used currently in industry, while STC no. 1 and no. 2 increased the well mixed volume flow share by 4.4% and 1.4 %, respectively. Installing additionally a medium dam in the working space of STC tundish variants resulted in an increase in the stagnant volume flow share of the tundish working volume, compared to variants 2-4. The tundish equipped with a high dam and a weir exhibits a nearly 6% increase in the dispersed plug flow share compared to the tundish being currently in use industrially. With the use of a medium dam and a high am with a weir, as well as a STC, a stagnant volume flow share of 30% was achieved, with a simultaneous over twofold increase in dispersed plug flow compared to the low-dam tundish. The percentage share of well mixed volume flow was at a level of around 50%. Based on the obtained qualitative and quantitative characteristics describing the hydrodynamic conditions in the tundish it was inferred that tundish variants 13-15 with the largest volume of active flow would exhibit the best conditions for the efficient introduction of an alloy addition to the liquid steel.

Figure 4 shows the alloy addition and liquid steel mixing curves for the low-dam tundish variant, as recorded at the tundish nozzle. The obtained mixing curve for one-off alloy addition introduction to the liquid steel has a distribution similar to that of the RTD curve. The obtained mixing curves were recorded when feeding the addition to the liquid steel in zone no. I lying between the ladle shroud and the rear tundish wall. The duration of alloy addition mixing with liquid steel should be as short as possible. Therefore, such conditions should prevail in the hydrodynamic system, which would ensure the required alloy addition concentration in the 95% chemical homogenization zone to be attained as soon as possible and maintained. Based on the obtained mixing curves it was concluded that even continuous feeding of the alloy addition to the liquid steel did not ensure that the required 95% level of chemical homogenization would be achieved in a fast and efficient manner. Only, using the pulse-step method it was possible to considerably reduce the mixing time, as confirmed by the distribution of the mixing curve in the 95% chemical homogenization zone. From the obtained mixing curves, the mixing time, meaning the time needed for attaining and maintaining the 95% level of chemical homogenization at the tundish nozzle, or in the volume of steel flowing to the mould, was calculated. Figure 5 represents the dimensionless mixing time for all of the tundish variants. The shortest mixing times were achieved for tundish variants nos. 11 & 12. For both of the above-mentioned tundish variants, RTD curves with a sinusoidal tail distribution were obtained, which indicates active recycle flow. The increase in active flow volume with the simultaneous reduction of the stagnant volume flow volume did not contribute to the reduction of the mixing time. The investigation carried out has also demonstrated that the best mixing time can be achieved in the tundish with the largest stagnant zone, too. It has therefore been concluded that the time of alloy addition mixing in the tundish for the developed pulse-step method would not be correlated with the volumes of active and stagnant volume flows. All the more so because in the tundish with the largest stagnant zone (variant no. 12) active liquid steel circulation regions (recycle flow) have formed, which compensate for the adverse influence of the stagnant zone and intensify the process of alloy addition digestion in the liquid steel. Therefore, the dynamics of the process of liquid steel homogenization in the tundish will be determined chiefly by the directions of flows of individual steel streams and their distribution in the tundish working space. To confirm this claim, additional computer simulations were performed, in which the alloy addition was introduced in successive alloy addition feed zones I-IV according to tundish equipment variants nos. 1 & 12. For each of the alloy addition feed zones, the mixing curve was recorded at the tundish nozzle, and on its basis the mixing time was calculated. The mixing times illustrated in Figure 6 confirm the advanced hypothesis that in a steady hydrodynamic system with a specific volume of stagnant volume flow and active flow, the intensity of alloy addition digestion in liquid steel is determined by the directions of flows of individual steel streams. Since depending on the location of alloy addition introduction, the process of alloy addition digestion in liquid steel will be initiated by other streams moving along their own paths towards the tundish nozzle. The knowledge of the volume fraction of the stagnant and active zones enables one only to determine the share of both flows, not providing the capability to indicate their specific location in the working space of the tundish. Dispersion of the alloy addition in liquid steel during its flow through the tundish is a dynamic process which is determined by the hydrodynamic conditions occurring in the tundish working space.

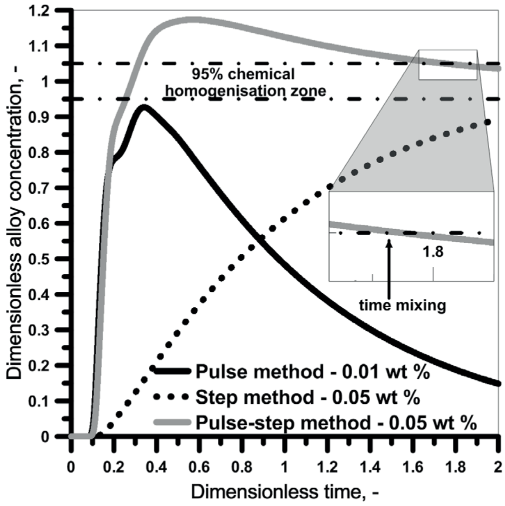

Fig.4. Mixing curves for different method of alloy injections

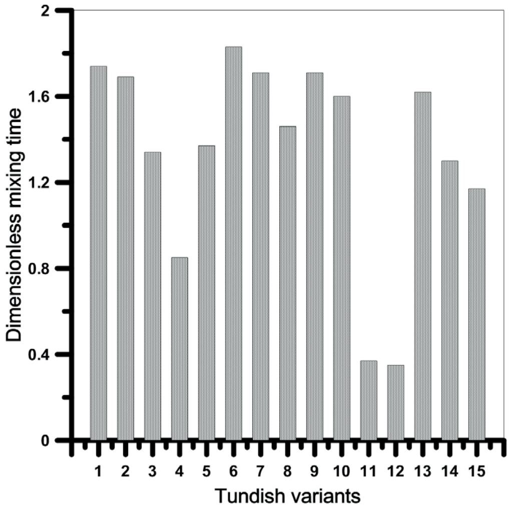

Fig. 5. Time mixing for considered tundish variants

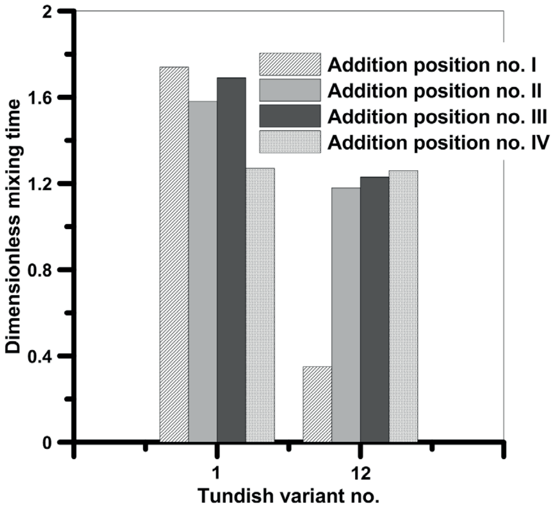

Fig.6. Time mixing for different alloy addition positions

4. Summary

From the performed computer simulations it can be found that:

- Flow control devices (FCDs) modify the hydrodynamic pattern of steel motion within the tundish working space by generating stagnant volume flow zones and active recycle flow zones.
- The active recycle flow zone may compensate for the adverse influence of the stagnant volume flow zone on the dynamics of the process of alloy addition dispersion in the liquid steel at the tundish stage.
- In tundishes with the active recycle flow zone, a reduction of time mixing of the alloy addition with liquid steel was achieved.
- Based on the investigation carried out, no relationship have been found between the dispersed plug or well mixed volume flow volume and the mixing time.
- The mixing time of alloy addition with liquid steel for the pulse-step method of alloy addition feeding to liquid steel is strictly dependent on the location of process initiation and on the hydrodynamic pattern of liquid steel motion that will occur in the location of initiation.

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