Influence of selected alloy additions on time mixing for pulse-step method of liquid steel alloying in the tundish

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In the continuous steel casting process, where the tundish performs the function of a device supplying liquid steel to the mould, the applying tundish to alloying process is quite interesting. Therefore the scientific aim of the present work is to obtain new basic information on chemical homogenization process of liquid steel with alloy additions in the tundish during using pulse–step alloying method. Authors checked the effect of the density of selected alloy additions on the process of their mixing with the liquid steel. Within the work, the following alloys additions were considered: Cu, Mn, Al, Co, Ni-Cr and Ti-Al. All alloy additions was introduced to liquid steel by pulse-step method. The authors employed the numerical modeling technique to demonstrate the process of alloy addition mixing during liquid steel flowed through the one strand slab tundish. Ansys-Fluent® program was used for numerical simulation. For the description of the alloy additions mixing with liquid steel time mixing was calculated.

KEYWORDS: TUNDISH – PULSE-STEP ALLOYING METHOD – PROPERTIES OF ALLOYS – NUMERICAL MODELING

INTRODUCTION

In the continuous steel casting process, where the tundish performs the function of a device supplying liquid steel to the mould, the applying tundish to alloying process is quite interesting. Therefore the scientific aim of the present work is to obtain new basic information on chemical homogenization process of liquid steel with alloy additions in the tundish during using pulse–step alloying method. Density is one of the key properties of alloy additions, which is expected to determine their mixing with liquid steel [1-2]. Therefore Authors checked the effect of the density of selected alloy additions on the process of their mixing with the liquid steel during alloying by pulse-step method. Alloy additions lighter than liquid steel will float, while those heavier than liquid steel will flow down towards the metallurgical vessel (furnace, ladle, tundish) bottom. For this reason, in a typical secondary metallurgy (ladle furnace) treatment, through the gas injection system, a mixing process is stimulated, thus smoothing out the effect of spontaneous spreading of additives within the liquid steel. The ladle furnace enables also the correction of liquid steel temperature, which is necessary due to the need for delivering additional heat for the alloy addition melting process. By contrast, in the standard tundish, the mixing process is determined by the feed stream and flow control devices (FCDs), which should provide the optimum hydrodynamic conditions within the entire tundish. Tundishes are equipped with various flow control devices, which can generate additional energy to effectively improve the mixing in the tundish working space [3-6]. Obviously the most effective FCDs beyond tundish pouring zone are argon curtains. Steel temperature correction is also an issue, because during steel casting, the liquid steel temperature lowers, and tundishes are not normally furnished with metal reheating systems. Therefore, the process of liquid steel alloying in the tundish should be preceded by an appropriate mass and thermal balance in order to eliminate any factors that might disrupt the continuous casting process. Within the work, the following alloys additions were considered: Cu, Mn, Al, Co, Ni-Cr and Ti-Al. All alloy additions was introduced to liquid steel flowed through one strand tundish by pulse-step method.

METHODOLOGY OF SIMULATIONS

It was assumed in computer simulations that the alloy additions would have a liquid form. Therefore, the process of alloy addition dissolution and melting in the steel was not taken into ac-

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count. This simplification was possible, because industrial experiments made previously had shown that, with an appropriately small size of alloy addition pieces, the duration of alloy addition dissolution in the steel was short enough to not significantly disturb the macro-mixing process [7]. In computer simulations, two types of nickel differing slightly in density and greatly in viscosity were considered. Nickel no. 1 was the subject of investigations reported in studied [8-10], and its properties were assumed based on data provided in studies [11-12].

Whereas, the properties of nickel no. 2 were determined using relationships based on relationships correlated with the process temperature. Obviously, as increasingly accurate information is entered to computer programs, the user gets a greater chance of obtaining more valuable results from the application point of view. Computer simulations were performed in the program Ansys-Fluent, using the Species model.

The mathematical model and the boundary conditions are detailed in study [7]. The computer simulations were done for a sequence of casting of 0.225x1.5 m slabs at a speed of 0.9 m/min and pouring temperature of 1823 K. To illustrate quantitatively the liquid steel chemical homogenisation process, mixing curves were recorded at tundish outlet. The level of chemical homogenisation was determined using the following relationship:

$$C_{PSM} = \frac{(C_t - C_0)}{(C_f - C_0)} \cdot 100\% \qquad [1]$$

where: C_f - final concentration of alloy at tundish outlet (wt%), C_{PSM} - dimensionless concentration of alloy for PSM, C_t - temporary concentration of alloy (wt%), C_0 - initial concentration of alloy (wt%). Based on the mixing curves, the dimensionless mixing time (DMT) was calculated. The DMT is defined as the time, after which the minimum required liquid steel chemical homogenisation level is maintained, which should amount to at least 95%. A reference level for calculating the mixing time required for achieving a chemical homogenization level of 95% was the alloy addition quantity recorded at the tundish outlet at the time of finishing the casting of the heat. The time interval was expressed by DTM defined by the ratio of the actual time to the average time. The average time for the tundish under examination was 726 seconds.

TUNDISH AND PULSE-STEP ALLOYING METHOD

Based on the results reported in study [8] it has been demonstrated that the pulse–step method reduces the time needed for attaining the level of 95% chemical homogenization. It has also been found that the effectiveness of the chemical homogenization process is determined by: the equipment of the tundish and the location of feeding an alloy addition [8-10]. Therefore, alloy additions in the form of either pure metals or alloys were introduced to the tundish in one of the most advantageous zones, i.e. in the tundish pouring zone between the ladle shroud and the tundish rear side wall. The tundish is a part of the machine for continuous casting of slabs. Checks were also made in the study to see how selected alloy additions would behave in a tundish with a varying configuration of its internal space equipment. Tundish variant no. 1, in which the tundish was furnished with a Subflux Turbulence Controller (STC) and a low dam, is shown in Figure 1. In variant no. 2, the STC geometry and dam height were changed. While in variant no. 3 of tundish equipment, the same STC as in variant no. 1 was used, but the dam height was changed. A detailed description of the FCD is provided in studies [8-9].

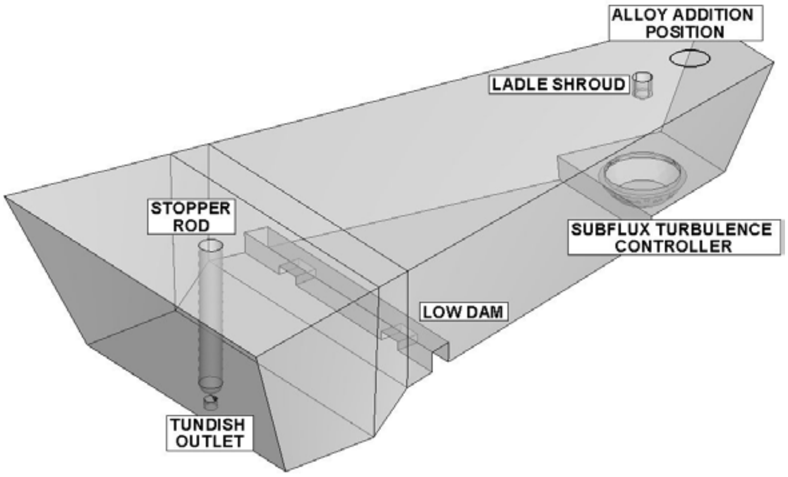

Fig. 1 – One strand tundish with alloy addition position and flow control devices for variant no. 1

Alloy additions were introduced to the steel first in a one-off batch, and then in a continuous manner in a quantity that allowed the correction of chemical composition to increase the concentration of the alloy addition by 0.056 wt%. The table 1 provides the physicochemical properties of the alloy additions discussed in the paper. For pure metals, the data shown in Table 1 were developed based on studies [11-15]. Whereas for the alloys NiCr and TiAl, the data given in studies [16-19] were used. It was assumed that the both binary alloys contained the identical content of either constituents, i.e. 50% each. This composition assured that their liquidus temperatures were below the casting temperature of the liquid steel grade under consideration. The heat capacity values for considered alloys was calculated in the computer program FactSage. The additive in the form of steel scrap had properties similar to those of the steel grade being cast.

Tab. 1 – One strand tundish with alloy addition position and flow control devices for variant no. 1

Alloy addition	Density, kg/m³	Viscosity, Pa·s	Heat capacity, J/kg·K	Thermal conductivity, W/m·K	Diffusivity, m²/s
Aluminium	2100	0.00052	1180	91	$8.6\cdot10^{-09}$
Manganese	5470	0.00344	840	22	$4.6\cdot10^{-09}$
Copper	7660	0.00159	520	163	$4.8\cdot10^{-09}$
Cobalt	7690	0.00261	690	36	$4.2\cdot10^{-09}$
Nickel no. 1	7650	0.00470	556	50	$5.3\cdot10^{-09}$
Nickel no. 2	7790	0.00159	556	50	$5.3\cdot10^{-09}$
Nickel-chromium	6900	0.00400	806	48	$4.5\cdot10^{-09}$
Titanium-aluminium	3360	0.00185	1005	60	$6.0\cdot10^{-09}$
Steel scrap	7010	0.00700	750	41	$4.8\cdot10^{-09}$

RESULTS AND DISCUSSION

MIXING CURVES AND TIMES FOR CONSIDERED TUNDISH VARIANTS

From the computer simulations, an illustration of the chemical homogenization process was derived in the form of mixing curves (Fig. 2). In figure 2, the zone of 95% chemical homogenization is marked off with broken lines. The distribution of the mixing curves varies, depending on the alloy addition type under consideration and the tundish equipment variant. While the change in STC does not essentially change the hydrodynamic conditions, the change of the dam height has already a definite influence on the alloy addition spreading within the bulk of liquid steel. In the presented diagrams, the mixing curves feature characteristic peaks that take on the form of a gradually dwindling sinusoid. In the case of tundish equipment variant no. 1, 3 peaks occur, while tundish variants no. 2 and no. 3 have 5 peaks, each. The increase in the number of peaks indicates an intensification of the mixing process in the higher-dam tundish variants. Hence, the maximum alloy addition concentrations in these variants are lower. The position of the peaks in relation to the X axis changes very slightly, while their position relative to the Y axis changes significantly, especially for alloy additions, such as Al, TiAl and Mn. Figure 2 represents mixing times for the alloy addition under discussion. The shorter mixing times, i.e. 0.39, 0.47 and 0.87 DMT, were obtained for Ni, Co and Cu, respectively. Whereas, the longest mixing times were obtained for Al and TiAl, amounting to, respectively, 2.5, 2.6 and 2.61 and 2.23, 2.38 and 2.34 DMT. The difference between the best and the worst mixing times is 2.22 DMT, which implies that the effectiveness of the alloying process will be determined not only by tundish equipment and the alloy addition feed location, but also by the type of the alloy addition itself. The obtained mixing times suggest that alloy additions should be considered in two groups, i.e. those of a density, respectively, lower and higher than the cast steel density. The first group will include Al, Mn, TiAl and NiCr, while the second group, Ni, Cu and Co. From the obtained results it has been found that particular tundish equipment variants influence differently on the both groups of alloy additions in terms of the mixing time. For example, the tundish according to variant no. 1 better influences on the alloying process, reducing the mixing time of lighter alloys. By contrast, in the case of alloy additions heavier that the cast steel grade, a definite increase in mixing time is noticed in the tundish variant no.1. This phenomenon is reverse in the tundish variants no. 2 and 3.

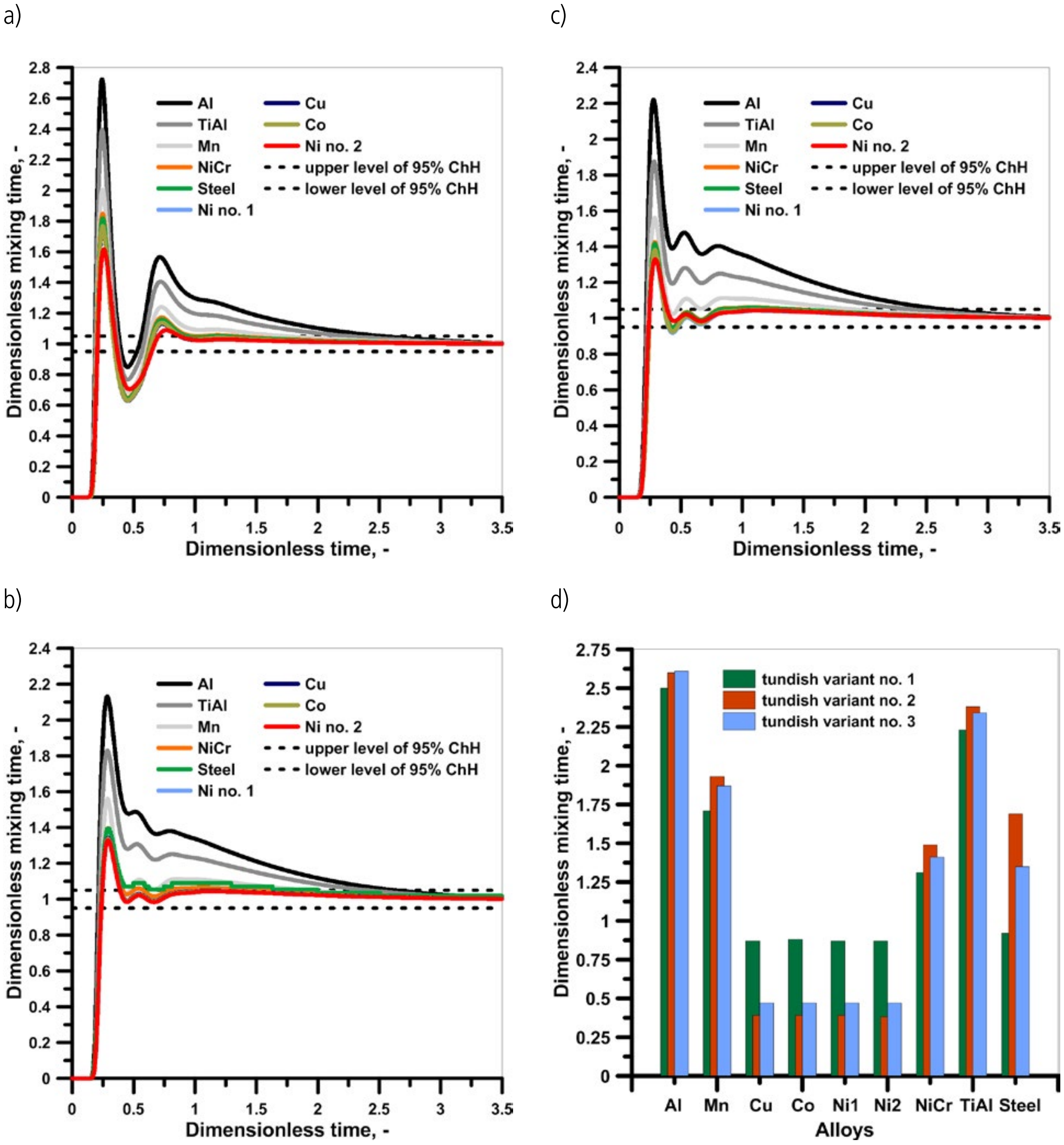

Fig. 2 – Chemical homogenisation process for pulse-step liquid steel tundish alloying method: mixing curves for tundish variant no. 1, b) mixing curves for tundish variant no. 2, c) mixing curves for tundish variant no. 3, d) mixing time for considered tundish and alloy additions

INFLUENCE OF ALLOYS PROPERTIES ON LIQUID STEEL ALLOYING PROCESS

The obtained mixing time results for individual alloy additions have demonstrated that the chemical homogenization process will influenced by their physicochemical properties. Figure 3 illustrates the results for the effect of alloy addition density on the chemical homogenization process. For the density, a distinct effect of this parameter on the mixing time can be seen. The higher the specific density an alloy addition has, the shorter the mixing time can be attained, regardless of the equipment of the tundish internal space. In the case of alloy additions of a density higher than that of the liquid steel, no effect of viscosity on the chemical homogenization process can be noticed. By contrast, for alloy additions lighter than the liquid steel, their viscosity increases linearly with density, so it is hard to point out clearly which quantity influences the mixing time more intensively. Even though less viscous additives should more readily spread within the liquid steel, yet this process may effectively disturb the alloy addition density that is lower than that of the steel. In this connection, the mixing time results for nickel nos. 1 and 2 are shown in figure 4. Both alloy additions differed in kinematic viscosity. As can be seen from the results in figure 4, identical mixing times were obtained for an alloy addition with a different kinematic viscosity. With a similar density value, in the alloy addition viscosity range under consideration, the viscosity of the alloy addition was found not to be a quantity decisive of the chemical homogenization process.

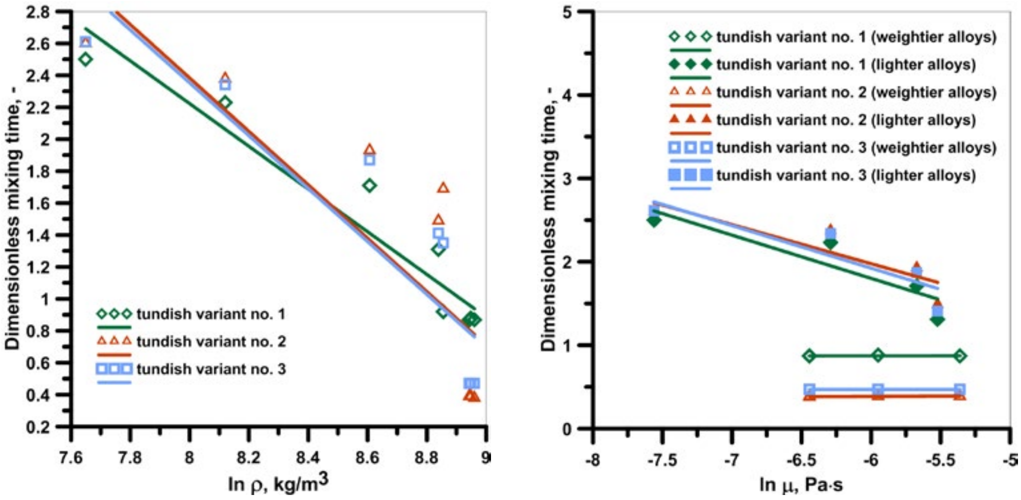

Fig. 3 – Influences of selected alloys properties for mixing time a) alloys density, b) alloys viscosity

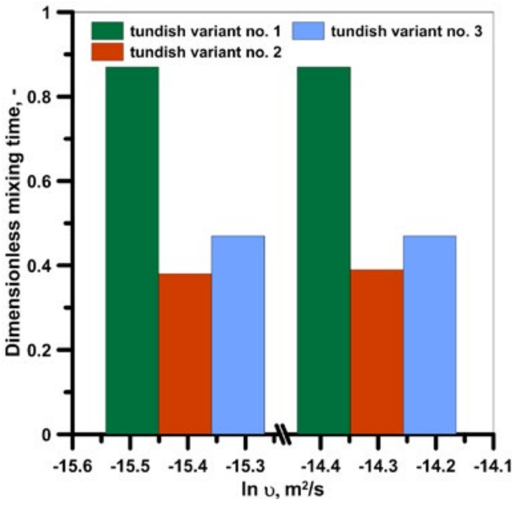

Fig. 4 – Mixing time for nickel with different value of kinematic viscosity

BEHAVIOR OF AL (LIGHTER ALLOY) AND NI (WEIGHTIER ALLOY) IN THE LIQUID STEEL

To more accurately assess the process of chemical homogenization as a result of the modified flow of liquid steel in the tundish working space and the effect of the physicochemical properties of alloy additions, detailed results are presented for steel movement and Al and Ni concentrations in tundish variant no. 1. Figure 5 shows the pattern of liquid steel flow in four characteristic planes. Three of them are arranged in parallel to the tundish bottom at three heights, namely 0.25, 0.57 and 0.918 m. While the other one is arranged perpendicularly to the tundish bottom. This plane intersects the tundish longitudinally through the pouring and the nozzle zones. Additionally liquid steel streams in the working volume was generated. In the alloy addition feed zone, steel streams are visible, which flow in clearly from the ladle shroud region towards the rear and side tundish wall. While the STC causes the stopper rod zone feed steel streams to flow along the tundish until the zone limited by the front wall. On the other hand, immediately at the tundish bottom, distinct reverse streams form, which have two regions of intensive steel circulation. Whereas, at the mid-height, the metal circulates from the stopper rod zone to the STC zone, dividing thereby the facility into a zone of reverse streams flowing in to the feed zone and a zone of streams feeding the stopper zone. An inflow of reverse streams to the STC zone can also be seen in the plane perpendicular to the bottom. These streams combined with the feed streams form a region of vertical steel circulation within the tundish working space. A strong liquid steel circulation region is also observed immediately under the alloy addition feed zone. While in the stopper rod system zone, the streams feeding the tundish nozzle are descending in character, with small recirculation zones located at the liquid steel free surface.

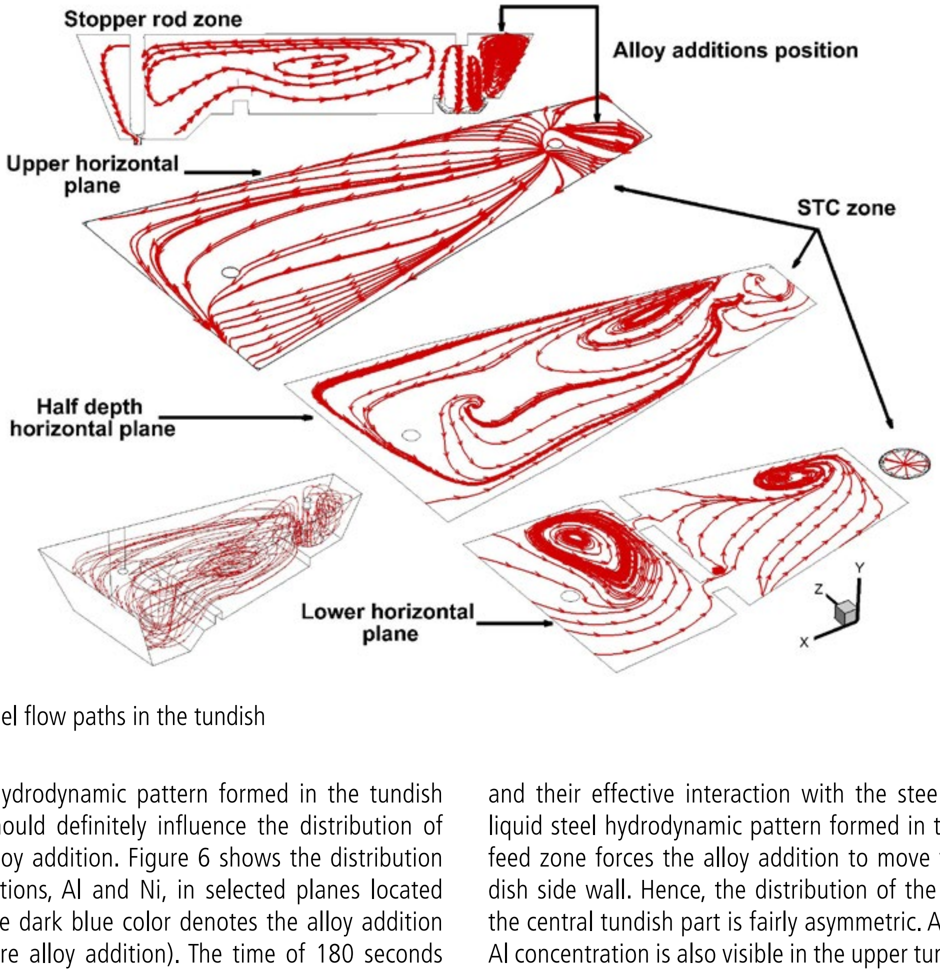

Fig. 5 – Liquid steel flow paths in the tundish

The liquid steel hydrodynamic pattern formed in the tundish working space should definitely influence the distribution of the introduced alloy addition. Figure 6 shows the distribution of two alloy additions, Al and Ni, in selected planes located in the tundish. The dark blue color denotes the alloy addition concentration (pure alloy addition). The time of 180 seconds corresponds approximately to the time of attaining the first peak on the mixing curve. Hence it can be seen that for Al, its degree of dissipation in the liquid steel is much smaller than that of Ni. The behavior of an alloy addition in the form of Al, as recorded within the tundish working space, is consistent with observations made by steel industry engineers concerning the difficulties associated with feeding Al or Ca to the tundish steel and their effective interaction with the steel being cast. The liquid steel hydrodynamic pattern formed in the alloy addition feed zone forces the alloy addition to move towards the tundish side wall. Hence, the distribution of the alloy addition in the central tundish part is fairly asymmetric. A definitely higher Al concentration is also visible in the upper tundish zone, which is caused, on the one hand, by ascending streams generated by the STC and, on the other hand, by the Al density being much lower compared to liquid steel. While the Ni density, being lower than that of liquid steel, contributes to a better interaction between the alloy addition and individual steel streams and its more efficient dispersion within the liquid steel bulk.

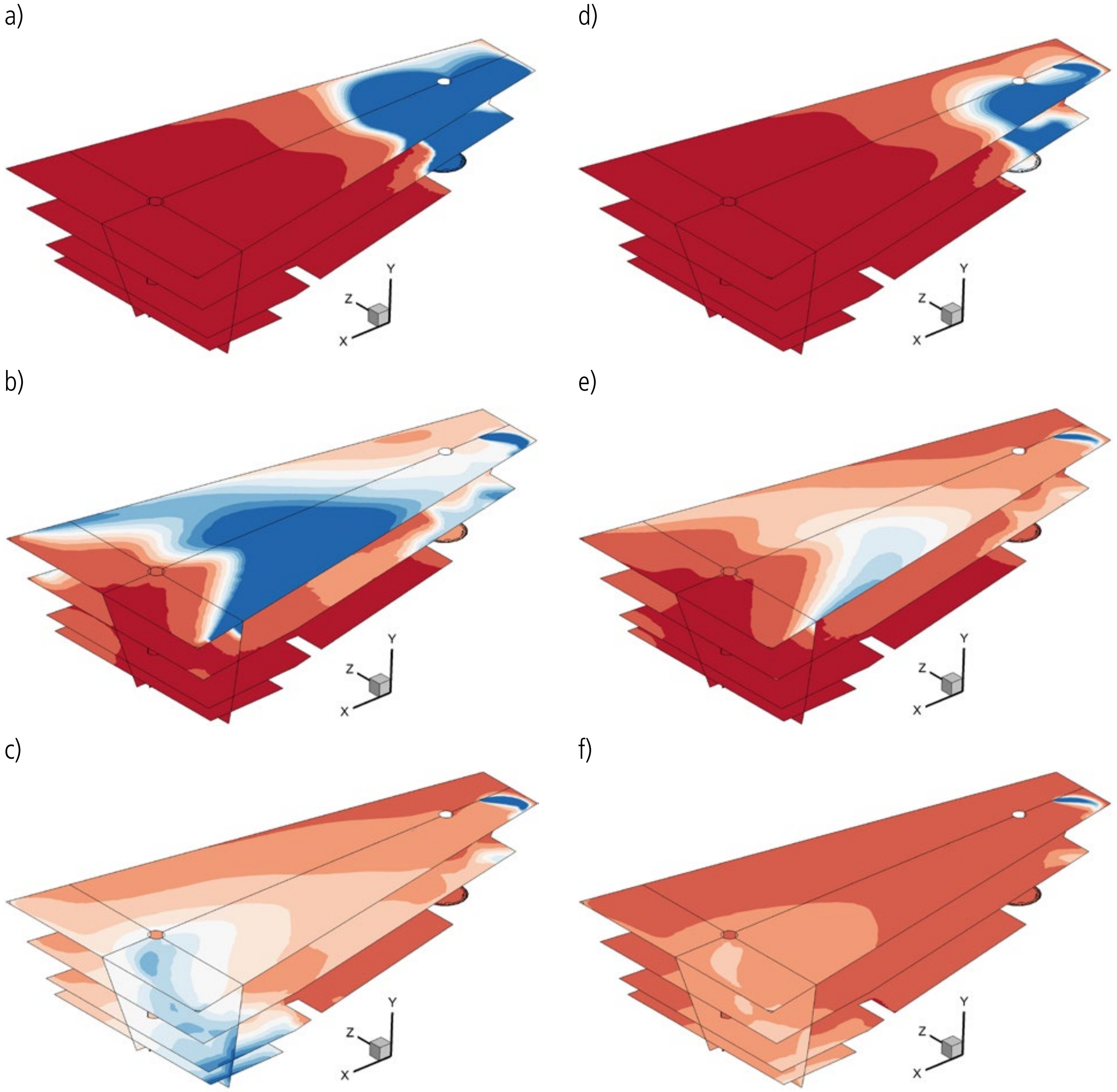

Fig. 6 – Behavior of alloy addition in the liquid steel during selected period of time after alloy feeding: a) Al - 30 sec, b) Al - 90 sec, c) Al - 180 sec, d) Ni - 30 sec, e) Ni - 90 sec, f) Ni - 180 sec

CONCLUSIONS

Based on the computer simulations carried out, it has been found that:

- The magnitude of mixing time needed for attaining a 95% chemical homogenization is influenced by the alloy addition type.
- The lighter the alloy addition relative to the liquid steel, the harder it is distributed within the liquid steel bulk, in spite of formed hydrodynamic patterns existing in the tundish.
- The mixing time as a function of the alloy addition assumes a relationship similar to a linear one, which implies that as the alloy addition density increases, especially above the density of the steel grade being cast, the mixing time shortens.
- The shortest alloy addition mixing times with the constant at a level of 0.39 DMT were obtained for the tundish according to tundish equipment variant no. 2 and for feeding alloy additions in the form of Ni, Co and Cu.

ACKNOWLEDGEMENTS

This scientific work has been financed from the resources of National Science Centre, Poland in the years 2017-2019 as the Research Project No. 2016/23/B/ST8/01135

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