Numerical simulations of liquid steel alloying in the three strand continuous casting bloom tundish

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Abstract. This paper aims to obtain fundamental information on chemical homogenisation process of liquid steel with alloy additions in the bloom tundish. For alloy feeding to liquid steel pulse step alloying method was applied. Author checked the effect of hydrodynamic conditions occurs in the internal working space of tundish on the process of alloy mixing with liquid steel. Within the work basic and proposed tundish equipments were considered. Numerical modelling technique was employed to demonstrate the process of alloy addition mixing during continuous casting process. Ansys-Fluent computer program was used for numerical simulation. For particular continuous casting strands time mixing was calculated.

1. Introduction
The continuous steel casting process is used for the manufacture of semi-finished products constituting feedstock for rolling mills. The intensive development of advanced steel grades, in which a decisive role is played by alloy additions [1], encourages searching for new technological solutions in the area of steel metallurgy. As standard, alloy additions are fed at the stand of the ladle furnace which enables the chemical and thermal correction of the liquid steel [2-7]. However, in order to optimise the time and costs of semi-finished product manufacturing, which consists of the smelting, treatment and casting of the steel grade, it is justified to aid the process of correcting chemically the steel or non-metallic inclusion immediately prior to the liquid steel pouring into the mould. Blooms, billets or slabs cast by the continuous method are characterised by a varying shape and dimensions [8-10]. Therefore, often the same continuous steel casting (CSC) machines are used in industrial practice to enable different blooms, billets or slabs types to be cast. To this end, the mould module and the tundish are exchanged and the secondary cooling zone is corrected. Because of the specificity of the process of liquid steel flow in the ladle–tundish–mould system, the tundish seems to be a device the most appropriate to being used in the process of alloying. Within the additional treatment of alloying it seems feasible to make a correction to the chemical composition of the liquid steel or non-metallic inclusions. This process will obviously be restricted by the time that is limited by the tonnage of the tundish and the speed of casting. Previous studies carried out for an one strand slab tundish have shown that the duration of mixing alloy additions with steel will be influenced not only by the mode of feeding the addition, but also by the addition feed position and equipping the tundish with flow control devices (FCDs) [11-13]. A newly developed pulse–step method (PSM) of feeding alloy additions to the liquid steel as it flows through the three strand bloom tundish is employed in the present study.
2. Continuous casting tundish

Detailed description of tundish was presented in the previous authors work [14]. Previous studies have shown that with the appropriate tundish equipment similar hydrodynamic conditions can be obtained for individual tundish nozzles [14]. The examined tundish was equipped with FCDs in the form of a subflux turbulence controller (STC) and a dam (figure 1). Through its action on the liquid steel motion, the employed STC generated optimal conditions for the process of chemical homogenisation in the tundish designed for casting slabs [11-12]. In two tundish equipment variants, the height of the dam was changed from 0.12 (low dam LD) to 0.25 m (medium dam MD). The modified dam height was also taken from the previous studies [12]. The basic tundish variant with locations for introducing an alloy addition to liquid steel is shown in figure 1a. Four alloy addition feeding positions (AAFP) situated in the immediate vicinity of the tundish pouring zone were considered.

![Figure 1. Three strand bloom tundish and considered alloy addition positions: a) low dam tundish, b) medium dam and STC tundish.](image)

3. Numerical simulation methodology

Numerical simulation of the liquid steel flow and alloy addition behaviour in turbulent motion conditions was done using the Ansys-Fluent® 12.1 computer program. The Navier-Stokes equation was solved for liquid steel. While for the alloy, the species element for prediction a local mass fraction was added to continuity equation. All numerical simulations were done by employing a double-precision solver (3ddp) using discretisation of the second order for momentum, turbulent motion, species, energy and transient formulation. Numerical simulations were performed for the sequence of casting 0.28 m × 0.28 m blooms at a speed of 0.75 m/min and with the initial steel temperature of 1823 K. The aim of alloying was to achieve the 0.096 wt% correction to the chemical composition with metallic nickel and aluminium. To illustrate the chemical homogenisation process, mixing curves were recorded at individual tundish outlets. The level of chemical homogenisation was determined using the following relationship:

\[
C_{PSM} = \left( \frac{C_f - C_0}{C_f - C_t} \right) \times 100\%
\]

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 mixing time was calculated. The mixing time is defined as the time, after which the minimum required liquid steel chemical homogenisation level is maintained, which should amount to at least 95%. The time interval was expressed by dimensionless time (DT) defined by the ratio of the actual time to the average time. The average time for the tundish under examination was 1270 seconds. The previous studies have confirmed the usefulness of the numerical model for simulating the chemical homogenisation process during steel flow through the tundish and the possibility of simulating the alloying process and recording the mixing process on a macro scale, with omitting the stage of the alloy addition melting in the steel [11-12]. Table 1 shows computer simulation variants (cases) discussed in the article.
Table 1. Considered variants of tundish configuration and liquid steel alloying

| Case No. | Tundish flow control devices variants | Alloying variants | Alloy addition feeding position | Type of alloy |
|----------|--------------------------------------|------------------|---------------------------------|---------------|
|          | LD + STC                             |                  |                                 |               |
|          | LD + STC                             |                  |                                 |               |
|          | MD + STC                             |                  |                                 |               |
|          |                                       |                  |                                 |               |
| 1        | x                                    |                  | x                               | Ni            |
| 2        | x                                    |                  | x                               | Ni            |
| 3        | x                                    |                  | x                               | Ni            |
| 4        | x                                    |                  | x                               | Ni            |
| 5        | x                                    |                  | x                               | Ni            |
| 6        | x                                    |                  | x                               | Ni            |
| 7        | x                                    |                  | x                               | Ni            |
| 8        | x                                    |                  | x                               | Ni            |
| 9        | x                                    |                  | x                               | Ni            |
| 10       | x                                    |                  | x                               | Ni            |

Work [15] has shown that the chemical homogenisation process is also influenced by the type of alloy addition, chiefly in terms of its density as related to the steel density. Therefore, two metals, Ni and Al, were tested within the investigation; the former of which is slightly heavier while the latter is much lighter than steel. The physicochemical quantities that describe the steel and the metals introduced to it are given in table 2.

Table 2. Properties of considered alloy additions and steel

| Materials | Density (kg m$^{-3}$) | Viscosity (Pa s) | Heat capacity (J kg$^{-1}$ K$^{-1}$) | Thermal conductivity (W m$^{-1}$ K$^{-1}$) | Solute diffusivity (m$^2$ s$^{-1}$) |
|-----------|-----------------------|------------------|-------------------------------------|------------------------------------------|----------------------------------|
| Aluminum  | 2100                  | 0.00052          | 1180                                | 91                                       | 8.6·10$^{-9}$                    |
| Nickel    | 7790                  | 0.00159          | 556                                 | 50                                       | 5.3·10$^{-9}$                    |
| Steel     | 7010                  | 0.007            | 750                                 | 41                                       | -                               |

4. Computational results

4.1. Hydrodynamic conditions

From the performed computer simulations, a picture of liquid steel flow in the tundish working volume was obtained. Figure 2 shows the pathlines of liquid steel flow in the volume of the tundish. In the tundish with no STC, steel motion in the central part shows a descending behaviour (figure 2a). Only in the bottom lowering zone the steel streams flow horizontally towards the tundish front wall. Whereas, increasing the dam height results in the formation of an additional steel circulation under the influence of reverse streams flowing in from the tundish nozzles side (cases 5-6). A clearly horizontal arrangement of the streams circulating within the working space is noticeable when the tundish supply zone is equipped with STC, regardless of the dam height (figure 2b). The effect of the tundish equipment and the change in hydrodynamic conditions is also visible in locations, where the alloying process is initiated.
In the case of a tundish equipped with a dam only, an alloy addition is transferred to the central part of the working space, whereas, introducing the alloy addition simultaneously at both tundish side walls should provide a reasonably uniform distribution relative to the longitudinal axis of the tundish (cases 1–4). However, as can be seen, in the case of introducing the addition in the location denoted with the number 2 there is the risk of its asymmetric distribution within the liquid steel volume (case No. 2). This fact may clearly interfere with obtaining consistent chemical homogenisation conditions at all tundish nozzles. By contrast, in the case of retrofitting the tundish with the STC, the steel streams located in the plane transverse to the tundish axis, transform into ascending streams and a clear asymmetry in steel flow shows up. For multi-nozzle tundishes, the symmetry of hydrodynamic patterns forming in the working space gains added importance, because not only the mixing time span, but also the uniformity of the obtained time at individual tundish nozzles becomes important. Since a reasonably consistent picture of steel flow relative to individual tundish nozzles should provide similar conditions of chemical homogenisation. Therefore, the steel flow pattern obtained immediately above the nozzles will be an additional factor affecting the chemical homogenisation process. The most uniform distribution of liquid steel flow in the mould supply zone was obtained for tundish with STC and LD. By contrast, the most differential patterns for outlets zone were observed in tundish variants with only MD and MD with STC. In the case of the examined tundish, the hydrodynamic pattern is determined both by the streams supplying, as well as by the FCDs. In view of the above, the proposed tundish equipment modification will certainly influence the process of chemical steel homogenisation.

4.2. Influence of alloy additions locations on time mixing

The idea behind the proposed alloy addition feed method is to obtain the mixing curve characteristic of stationary reactors in optimally shortest possible time considering the continuous casting blooms forming in the mould. For the facility under discussion, it becomes additionally important also to uniform the chemical composition with respect to all nozzles and to supply the moulds with steel of identical chemical composition. This section provides results concerning the effect of the alloy addition feed location on the mixing process in the tundish with low dam (Figure 3).

The process of casting square blooms is characterized by a lower casting speed, compared to casting slabs, which considerably extends the average time of steel residence in the tundish and thus the period, in which the alloying process can be carried out. Figure 3a shows mixing curves with the
indicated 95% chemical homogenisation zone. The time of casting a single heat is 3.78 DT. Therefore, exceeding this duration in the case of mixing time disqualifies a given tundish variant as possible to be used in the alloying process. While it can be seen that the alloy addition shows up at individual nozzles at the same time, attaining the maximum concentration or a similar distribution of alloy addition concentration in the same period of time is difficult. Especially for the steel streams flowing into nozzle no. 3 a clearly higher nickel content is observed. Figure 3b illustrates results for the mixing time necessary for obtaining 95% chemical homogenisation. In the facility under discussion, a considerable asymmetry of alloy addition distribution is observed for nozzles situated on either side of the longitudinal tundish axis. This is especially true for the alloy addition feed location denoted with the number 2. The difference in mixing time between nozzles situated on the opposite sides relative to the longitudinal tundish axis amounted to over 1.8 DT. The most advantageous mixing time, fairly uniform for all nozzles, was obtained during feeding nickel at both side tundish walls simultaneously.

4.3. Influence of flow control devices on time mixing

Based on the results obtained for the steel alloying process during slab casting, the effect of the FCD on the behaviour of the alloy addition in the bloom tundish was verified. For the facility under consideration, the STC has been proposed, whose task is to attenuate turbulences in the pouring zone. Therefore, for TFCD variants 2 and 4, the average steel flow velocity was, respectively, 0.0159 and 0.0153 m/s. These values are by 0.006 and 0.0051 m/s smaller than those obtained for the tundish equipped only with a low or medium dam. Figure 4a shows mixing curves for the tundish equipped with the STC. For this tundish variant, the attenuation of the turbulence in the pouring zone has brought about considerable changes in the hydrodynamic pattern of liquid steel flow and has been reflected in the distribution of nickel in the bulk of the melt being cast. Much faster equalisation of the nickel content level in the bulk of steel is visible already at a time below 1 DT. However, for the extreme nozzles, too large an asymmetry of nickel distribution within the steel has occurred. The too high concentration of nickel in the liquid steel on the side of nozzle 3 prevents the 95% chemical homogenisation level from being attained in the period of time, during which the steel grade under consideration is being cast. In this connection, an additional factor in the form of individual streams supplying particular nozzles occurs in multi-nozzle tundishes, which modifies the hydrodynamic patterns influencing the chemical homogenisation process. The additional reduction of steel flow velocity by using the STC also seems unfavourable (lesser mixing energy apart from pouring zone). This is especially so because non-isothermal conditions predominate in the CSC process, and the forming temperature gradients together with low metal flow velocities cause localised modifications to the hydrodynamic patterns due to the action of natural convection forces. Figure 4b shows mixing time for different tundish equipment variants. It can be seen that the STC prevents the 95% chemical homogenisation level from being attained during melt casting. Whereas, increasing the dam height equalizes the mixing time recorded at individual nozzles also in the case of feeding nickel in the zone between the ladle shroud and the rear wall.

**Figure 4.** Behaviour of nickel in the bulk of liquid steel during casting: a) mixing curve for case No. 5, b) ) mixing time for considered tundishes and AAFPs
4.4. Behaviour of lighter alloy in the bulk of liquid steel

This section provides results for the behaviour of aluminium in the liquid steel. Due to its density being much lower than that of steel, aluminium is an extremely attractive constructional material. However, as against the ladle furnace, in the tundish, only the supply stream energy can stimulate the process of alloy addition spread in the volume of steel. Therefore, the success of the chemical homogenisation process will be determined by the hydrodynamic pattern created by the supply stream and the FCD. Figure 5a shows the curves of mixing aluminium with steel. The hydrodynamic patterns existing in the tundish working space do not allow the efficient spread of the aluminium being lighter than steel. It can be seen that a batch of aluminium poorly disperses in the steel volume, and the aluminium concentrations recorded at individual nozzles are by almost 100% higher than the nickel contents. For this reason, the process of homogenisation of aluminium concentration was considerably extended. Like for nickel, also for aluminium the most favourable equipment turned out to be TFCD variant 3, and the alloy addition locations, 1 and 4 (Figure 5b). That being said, it should be noted that the mixing time for aluminium is near to the time of casting the entire heat.

5. Conclusions

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

- Reducing the intensity of liquid steel flow through the use of the STC causes localized modifications to the hydrodynamic pattern, whereby obtaining the 95% chemical homogenisation level at individual tundish nozzles becomes impossible.
- For the three-nozzle tundish, the optimal hydrodynamic conditions for the steel alloying process were achieved by increasing the dam height to 0.25 m.
- The most advantageous mode of feeding the alloy addition to the steel when casting square blooms is introducing it simultaneously in two places localized at the side walls of the tundish. This variant allows similar mixing times to be attained at individual tundish nozzles.
- In the case of an alloy addition in the form of a metal much lighter than steel, the mixing time reaches values close to the heat casting time, which will surely contribute to the chemical non-uniform of square blooms being cast.

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Acknowledgments
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