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Mathematical modeling of nickel behaviour in the liquid steel flowed through the one strand tundish

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ABSTRACT

Purpose: The continuous steel casting (CSC) technology is a dynamically developing method for obtaining steel semi-finished product in the form of a continuous casting slabs, blooms and billets. During the course of the CSC process, the liquid form of steel offers a possibility of introducing alloy additions to adjust the chemical composition or modify the non-metallic inclusions. The aim of the tests was to verify the degree of chemical homogenization of the steel after the addition of nickel.

Design/methodology/approach: The device under examination is a wedge-shaped single-nozzle tundish of a capacity of 30 Mg. Computer simulation of the liquid steel flow and alloy addition behaviour in turbulent motion conditions was done using the Ansys-Fluent® computer program. Due to the complexity of alloy addition dissolution and dispersion in metallurgical processes, a decision was made to use the Species Model available within the Ansys-Fluent® program.

Findings: The computer simulation produced a picture of the flow of liquid steel and the spread of nickel within the liquid steel volume. To illustrate the chemical homogenization process spatially and in a greater detail, the Ni diffusion process was monitored at selected measurement points situated in the tundish working space region.

Research limitations/implications: Numerical model not include melting process of alloy addition.

Practical implications: The results from numerical simulation could be use to elaborate a method of controlled alloy addition feeding to the liquid steel during continuous steel casting process.

Originality/value: The paper present results of alloy addition mixing process in the liquid steel flowed through the continuous casting slab tundish.

Keywords: Tundish; Alloy addition; Continuous steel casting technology; Numerical simulation

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METHODOLOGY OF RESEARCH, ANALYSIS AND MODELLING

1. Introduction

The semi-finished product manufacturing technology includes smelting, secondary metallurgy and liquid steel casting. Due to the growing prices of energy and raw materials, as shortage deficit of their own scrap, steelworks seek solutions to optimize the existing steelmaking technologies. Currently, steelmaking furnaces serve only for preliminary preparation of liquid metal, while the making of a specific steel grade takes place in the ladle

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furnace. The secondary metallurgy stand is responsible for obtaining required chemical composition, steel purity (elimination of non-metallic inclusions (NMI) and gases) and casting temperature, as required by the specification for a given steel grade. The next link in the steel production cycle is the CSC machine, whose purpose is to cast steel casings free from external and internal defects. As the continuous casting process continues, the liquid metal solidifies, and thus created crystals form a solid structure of the continuous casting slabs or blooms and billets. Before the metal starts solidifying, however, its liquid form offers conditions favourable for modification of the physicochemical state of the steel being cast [1]. The liquid steel resides by some time in the tundish. Therefore the researches relation with optimisation of tundish metallurgy are very important and valuable [2-6]. This modification process may involve either the adjustment of chemical composition of the steel itself, or the modification of chemical composition of NMIs existing in the liquid metal. The present paper discusses the results of tests in which batches of nickel in the form of lumps were introduced to liquid steel. It was decided that nickel would be batched to the tundish. The aim of the tests was to verify the degree of chemical homogenization of the steel after the addition of nickel. The tests were carried out using a numerical simulation.

2. Testing methodology

The device under examination is a wedge-shaped single-nozzle tundish of a capacity of 30 Mg. The tundish being currently operated in industry is only equipped with a low (h=120 mm) dam with two overflow windows (Fig. 1). Two different tundish bottom levels provide a metal head of 0.7 m in the tundish pouring zone and 0.92 m in the stopper rod system zone. Argon is blown through the ceramic stopper rod that controls the flowrate of steel flowing out from the tundish to the mould. The inert gas assures the stabilization of the liquid steel flow and prevents the process of submerged entry nozzle clogging. The liquid metal flows into the tundish via the ceramic ladle shroud. The free liquid steel surface is protected against the action of external factor by tundish powder and a fibreboard panel. Figure 1 shows a virtual tundish model with indicated measurement points and the location of alloy addition feeding to the liquid steel (numerical simulation). Measurement points are positioned at different zones in the tundish working space to obtain a complete picture of the alloy addition dispersing within the liquid steel.

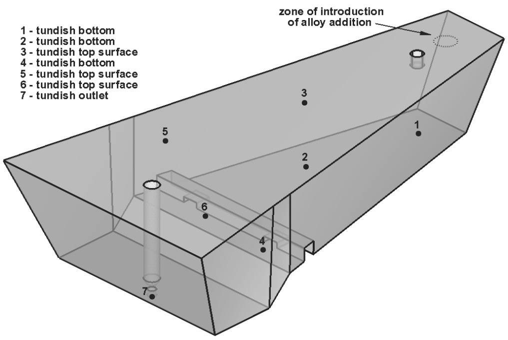

Fig.1. Tundish virtual model with measurement points

Computer simulation of the liquid steel flow and alloy addition behaviour in turbulent motion conditions was done using the Ansys-Fluent® computer program. The basic mathematical model equations describing the phenomena under examination are as follows:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0 \tag{1}$$

$$\frac{\partial}{\partial t} \cdot (\rho u) + \nabla \cdot (\rho u u) = -\nabla p + \nabla \cdot (\tau) + pg \tag{2}$$

$$\tau = \mu \left[\left(\nabla u + \nabla u^T \right) - \frac{2}{3} \nabla \cdot u I \right] \tag{3}$$

$$\frac{\partial}{\partial t}(\rho E) + \nabla \cdot \left(u(\rho E + p) \right) = \nabla \cdot \left(k_{eff} \nabla T - \sum_j hJ + \left(\tau_{eff} \cdot u \right) \right) \tag{4}$$

$$E = h - \frac{p}{\rho} + \frac{u^2}{2} \tag{5}$$

$$\frac{\partial C_i}{\partial t} + \nabla \cdot \left(-D_i \nabla C_i + C_i u \right) = 0 \tag{6}$$

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla \cdot (\rho u Y_i) = -\nabla \cdot J \tag{7}$$

where: u – liquid steel velocity, m/s, ρ – liquid steel density, kg/m^3, t – time, s, p – pressure, Pa, g – gravitational acceleration, m/s^2, τ – stress tensor, Pa, τ_{eff} – effective stress tensor, Pa, T – temperature, K, μ – viscosity, kg/m·s, I – unit tensor, E – energy, J, k_{eff} – effective thermal conductivity, W/m·K, C_i – concentration of alloy addition, kg, diffusion coefficient of alloy addition, m^2/s, Y_i – local mass fraction of each species, J – mass diffusion flux, kg/m^2·s.

The liquid metal flows through the tundish at a mass flow rate of 34.4 kg/s. For describing the turbulence, the k-ε model was chosen. The parameters k and ε, as defined for the steel flowing into the tundish, were 0.017161 m^2/s^2 and 0.064231 m^2/s^3, respectively. 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 temperature of the liquid steel flowing into the tundish was 1823 K. The heat loss flux was -2600 W/m^2 on the tundish walls and bottom and -15000 W/m^2 on the free steel table surface. The liquid steel properties are as follows: density, 7010 kg/m^3; viscosity, 0.007 Pa·s; heat capacity, 750 J·kg/K; thermal conductivity, 41 W/m·K; steel thermal expansion coefficient, 0.0001 1/K. The liquid nickel properties are as follows: density, 7650 kg/m^3; viscosity, 0.0047 Pa·s; heat capacity, 556 J·kg/K; thermal conductivity, 50 W/m·K. The mass diffusivity of nickel in the steel is 5.35e-09 m^2/s [7-8]. The free steel table surface was described using the boundary condition of a wall with zero stresses. The virtual object was built of 470,000 tetrahedral elements. All numerical simulations were done by employing a double-precision solver (3ddp) using discretization of the second order. For describing the velocity and pressure fields, the Simplec algorithm was selected. Due to the complexity of alloy addition dissolution and dispersion in metallurgical processes, a decision was made to use the Species Model available within the Ansys-Fluent® program.

3. Simulation results

The computer simulation produced a picture of the flow of liquid steel and the spread of nickel within the liquid steel volume. Figures 2a-d shows maps representing the directions of liquid steel flow in the pouring zone, the stopper system zone, the central part of the tundish and in the close proximity of the longitudinal lateral tundish wall.

The flow patter, as mapped through computations, looks as follows: the main feeding stream, after flowing to the tundish, continues towards the bottom and then to the lateral walls of the

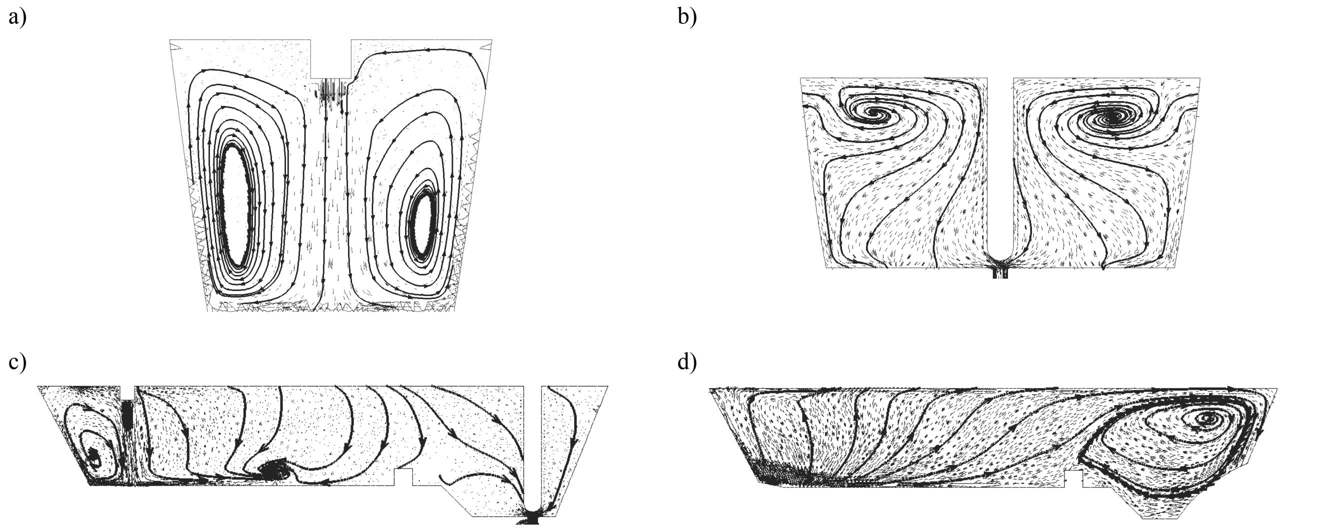

Fig. 2. Liquid steel flow direction in the tundish: a) tundish pouring zone, b) stopper rod system zone, c) central plane of tundish, d) plane near tundish side wall

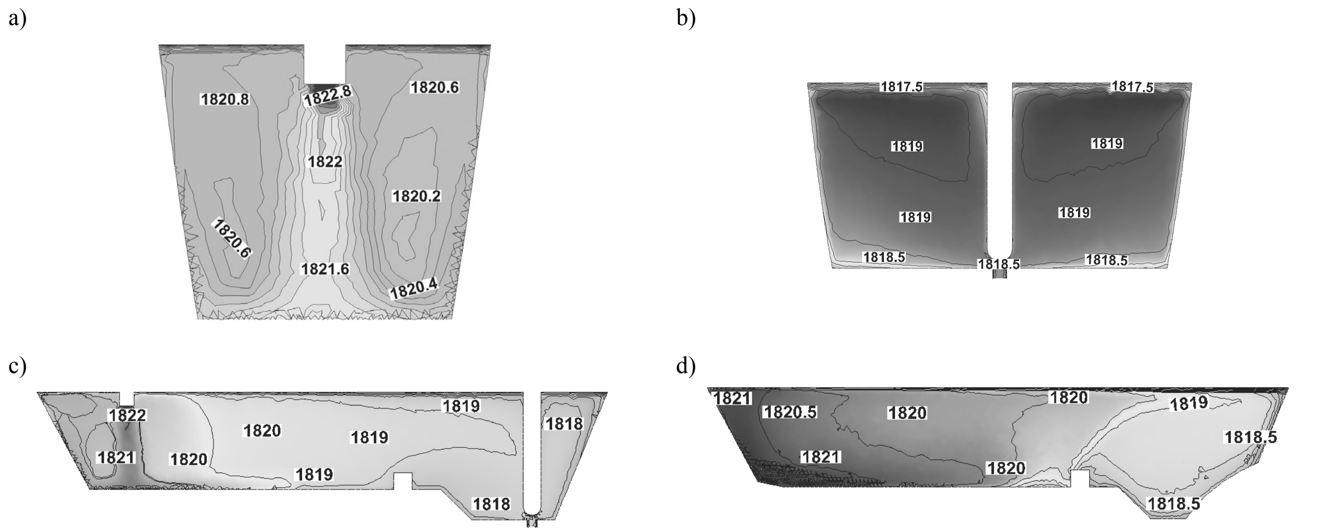

Fig. 3. Liquid steel temperature in the tundish: a) tundish pouring zone, b) stopper rod system zone, c) central plane of tundish, d) plane near tundish side wall

tundish. Part of the metal in the pouring zone starts circulating, while the remaining body of the liquid steel flows towards the free steel surface and up to the stopper rod system zone (Fig. 2d). After reaching the stopper rod system zone, part of the liquid steel starts to circulate within a region situated immediately below the free steel table surface. Next, the liquid steel flows towards the discharge nozzle.

Figure 2c shows the liquid steel flow pattern in the central tundish part, where a metal motion having a distinctly descending behaviour is observed. The complex metal flow behaviour is also confirmed by the maps representing the temperature field of the liquid steel. It can be seen in Figure 3a-d that the feeding stream, upon flowing to the pouring zone, starts to flow towards the lateral walls, rather than along the tundish centre. This is evidenced by the liquid steel isotherms for the part of the metal at a temperature of 1820 K (Figs. 3c and 3d).

Figures 4a-f represents the fields of nickel distribution in the liquid steel after a dimensionless time of 0.067 and 0.339, respectively, from the moment of introducing the nickel to the tundish. It can be seen in the tundish pouring zone that, after being introduced, the Ni starts to circulate under the influence of inertia forces caused by the feeding stream.

The inhomogeneity of Ni distribution in the liquid steel volume, observed in the initial period, diffuses and already after a dimensionless time (DT) of 0.339 the Ni distribution is similar on either side of the ladle shroud. Figure 4b shows a strong interaction between the liquid steel and the alloy addition, whereby after 0.339 DT an increased Ni concentration occurs in the upper part of the stopped system's working space, along the feeding stream flow direction. The dynamics of the mixing process is illustrated by the distribution of Ni on either side of the stopper rod (Fig. 4e). Figure 4c-f, on the other hand, shows that after 0.339 DT the alloy addition concentration in the liquid metal is close to the target concentration resulting from the added amount of the alloy addition and the amount of the steel in the tundish.

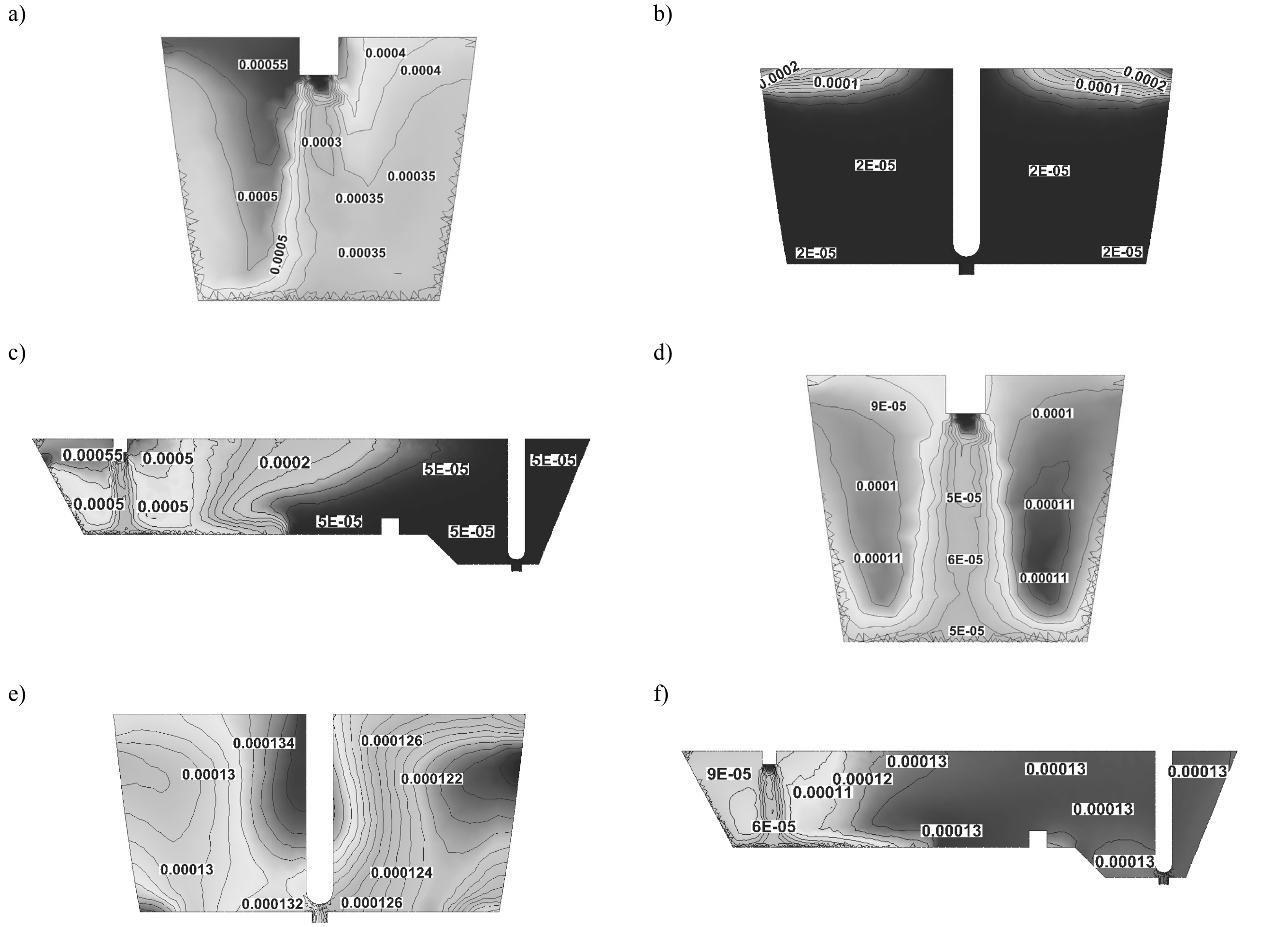

Fig. 4. Nickel concentration in the liquid steel from now on alloy addition adding: a) tundish pouring zone after 0.067 DT, b) stopper rod system zone after 0.067 DT, c) central plane of tundish after 0.067 DT, d) tundish pouring zone after 0.339 DT, e) stopper rod system zone after 0.339 DT, f) central plane of tundish after 0.339 DT

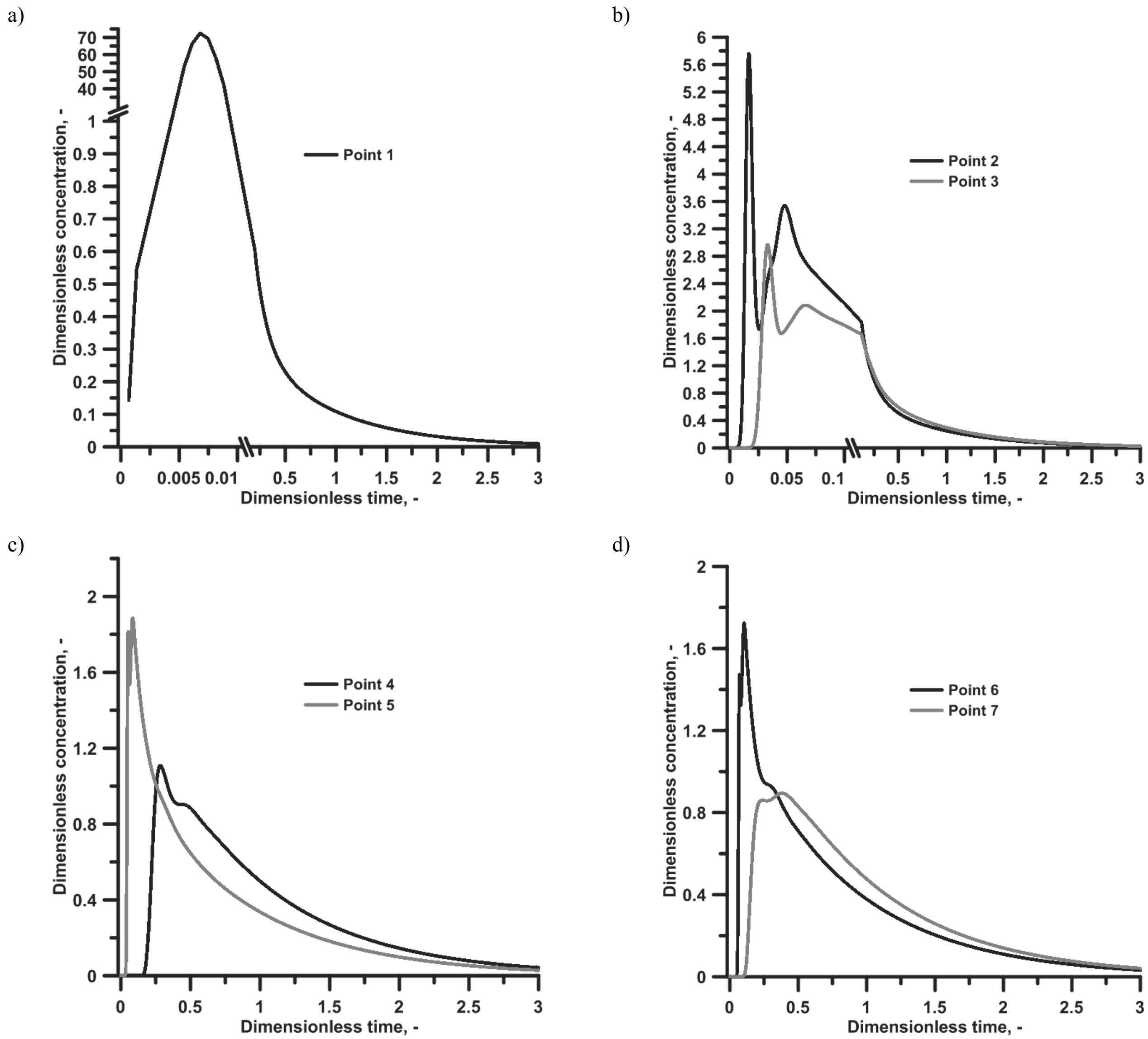

Fig. 5. Nickel concentration in the liquid steel: a) measurement point no. 1, b) measurement points no. 2 and 3, c) measurement points no. 4 and 5, d) measurement points no. 6 and 7

To illustrate the chemical homogenization process spatially and in a greater detail, the Ni diffusion process was monitored at selected measurement points situated in the tundish working space region. Figures 5a-d represents the results of this monitoring in the form of time characteristics describing variations in the Ni content of liquid steel during steel casting. The characteristics shown in this figure concern a period during which the ¾ of the melt was cast.

It can be seen that with casting time the Ni content of liquid steel falls down to very low levels. This implies that adding only a single batch of the alloy addition would not be sufficient to adjust the chemical composition for the entire steel melt. There are, however, clear grounds for allowing the introduction of alloy additions to the steel in the tundish, because, as shown in Figure 5, the alloy addition will reach all working spaces of the tundish.

In addition, the distribution of the peaks of individual curves confirms the direction of flow of the main steel stream, as represented in the maps. By adding a batch of the alloy addition in the feeding stream, it can be expected to be well mixed with the liquid steel.

4. Conclusions

From the obtained computer simulation results, the following have been found:

- the pattern of steel flow in the tundish under examination is characterized by a distribution of streams such that a main stream and side streams can be distinguished, which cause the motion of steel promoting the mixing process;
- feeding an alloy addition in the tundish pouring zone leads to its good spreading within the liquid steel volume;
- maintaining the set alloy addition level in the entire continuous steel casting process requires a method of controlled and repeated alloy addition feeding to be developed to achieve the proper adjustment of chemical composition of the steel.

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