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Numerical simulation of liquid flow and mixing steel in multi-strands tundish

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Analysis and modelling

ABSTRACT

Purpose: The aim of this study was estimation of working multi- strands tundish used in the domestic steel industry for the casting of medium size-products.
Design/methodology/approach: Thus, actions were taken to determine the specific characteristics of the work object. There is practically no possibility to study metal movement on a real object, therefore the solution of this problem was to use modelling techniques. The numerical analysis based on mathematical model was chosen. The calculations were carried out in AnsysFluent.
Findings: of research concerns for casting spatial velocity fields of temperature and intensity of steel turbulence. They were complemented by F and E types residence time distribution curves. Basing on these curves percentage participation of flows were calculated and kinetics of steel mixing in tundish was determined.
Research limitations/implications: applying of commercial computational codes for analysis of work and units designing is rather a cheap tool. The optimal solution is to join numerical and physical modeling.
Practical implications: presented results of research can be used for improving the hydrodynamic conditions occurring in industrial tundish.
Originality/value: of this research is working out the characteristics of tundish working. The obtained results can improve considerably the effectiveness of CC process.
Keywords: Tundish; Continuous casting; Fluid flow; Numerical modelling; RTD curves

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1. Introduction

Modern equipment including steelmaking furnaces and secondary metallurgy units form a compact and efficient production process. The increasing quality requirements in the steel industry causes that the new technological solution are still searched for. The current state of this technology allows to cast a liquid steel into semi-finished products. However, it requires, the high quality of liquid steel introduced to the mould. The main role of the tundish is a distribution function. The final metallurgical treatments are also performed in this unit.

By shaping the conditions of the process, we can benefit the effects of spontaneous phenomena during separation and inclusions flotation. For this purpose, the different fitting of tundish workspace (dams, weirs, turbulence inhibitor) are used. It is also known that the shape and placement of flow control devices in the workspace always affects the hydrodynamic and thermal conditions in the ladle.

The study of liquid steel motion in the real object is in principle excluded. This is due to objective difficulties (high temperature, the capacity of the medium and dimensions of metallurgical aggregates). Therefore, the physical or numerical modeling was used in this research. A substantial contribution to the modelling of steel flow in the tundish has been made by the Szekely [1] and Guthrie [2,3] researcher teams. Extensive knowledge in this field is provided by the Szekely et al textbook [4]. It presents the basic aspects related to research design optimization tundish. However, examples given there, do not include multi-strand tundishes [5-7].

Modelling research (physical and numerical) are commonly used for analyzing and knowing better the phenomena that occurring in reactors applied in metallurgy of steel and nonferrous metals [5-12].

This article is part of the studies included in the work [13]. It presents an analysis of the current state of knowledge concerning the steel flow in a multi-strand tundish, used industrially for the casting of medium-sized products. The determination of the specific characteristics describing the object was also taken into consideration in that study. The paper consisted of the numerical simulation of mass, momentum and energy transport processes.

2. Description of the plant and the conditions of numerical computations

The object of the investigations was six-outlets tundish. The tundish is symmetrical with respect to the central cross-section (through the steel pouring gate axis). It has six outflow outlets available. The basic refractory lining is made up of andalusite tiles. The tundish is equipped with the turbulence inhibitor. A schematic of the tundish is illustrated in Figure 1. The other parameters and boundary conditions of the tundish are presented in Table 1. The chemical compositions (steel grade) are given in Table 2.

The simulation of the liquid steel flow in the tundish during the continuous casting process is a complex hydrodynamic problem. An appropriate mathematical model (describing this process) should take into account several characteristics of such flows. Model [13,14] describing the steel flow in the ladle includes differential equations of the flow continuity, equation of momentum and energy conservation for the structure of the liquid steel turbulent motion and an equation describing the pattern of turbulence of liquid steel motion in the tundish. For modelling the turbulence, the k-ε double-equation model [15] was used.

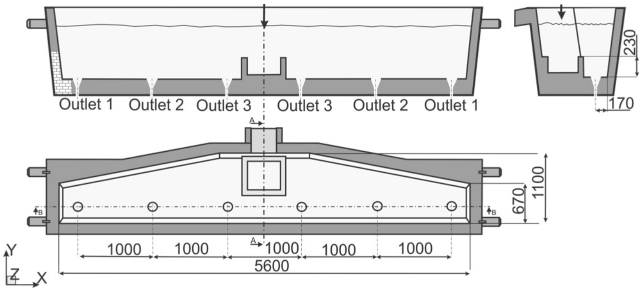

Fig. 1. Scheme diagram showing tundish geometry

To solve this system of differential equations, appropriate initial and boundary conditions must be set (Table 1). In Figure 2 the boundary conditions used in the computations are shown. The contact surface between steel and air (upper surface of the object) was taken as the free surface and assumed to be a flat surface. For the evaluation of the tracer concentration in the steel during the casting process, two kinds of boundary conditions were assumed at the gate:

- at the moment of t = 0, one-off addition of the tracer in a mass fraction of $X_m = 0.0047$,
- an identical (C=1) concentration of the additive throughout the measurement duration.

Table 1.
Parameters and boundary conditions used in modelling [13,16]

Parameters	Value	Parameters	Value
Nominal capacity, (Mg)	22	Inlet temperature, (K)	1829
Molten steel level, (mm)	780	Density, (kg·m^{-3})	6947
Shroud diameter, (mm)	50	Viscosity of molten steel, (kg·m^{-1}·s^{-1})	0.0045
Outlet diameter, (mm)	17	Specific heat, (J·kg^{-1}·K^{-1})	830.8
Casting speed, (m·min^{-1})	1.9	Thermal conductivity, (W·m^{-1}·K^{-1})	40.5
Slab section, (mm)	160x160	Heat flux at surface, (W·m^{-2})	15000
Inlet turbulence intensity, (%)	5	Heat loss at wall, (W·m^{-2})	2600

Table 2.
Chemical compositions of the steel grade used for the computation simulation, in wt-%.

	C	Mn	Si	P	S	Cr	Ni	Cu	N
min.	0.14	0.60	0.10	–	–	–	–	–	–
max.	0.18	0.70	0.15	0.04	0.04	0.3	0.3	0.4	0.012

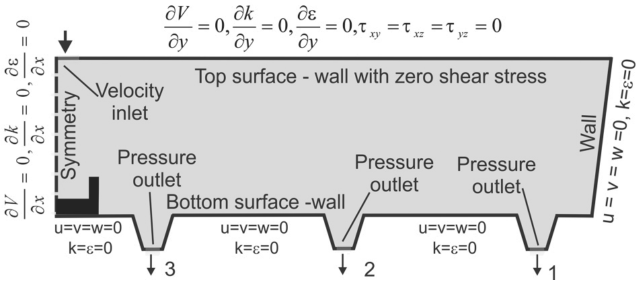

Fig. 2. Boundary conditions adopted in the calculations

The geometry of the tundish is symmetrical with respect to the plane passing through the gate axis, so only half of the object was considered in the computation. The target computational grid consisted of 380 000 control volumes. The density of the grid was increased in the vicinity of the tundish inlet and outlets. The problem was solved numerically by the control volume method in the three-dimensional (3D) space. AnsysFluent code (education version) was used for numerical simulation [17].

3. Results and discussion

To facilitate comparison of results, the object was sectioned by characteristic planes. The forecasted steel movement in the ladle to the pre-defined levels of control are shown in Figure 3.

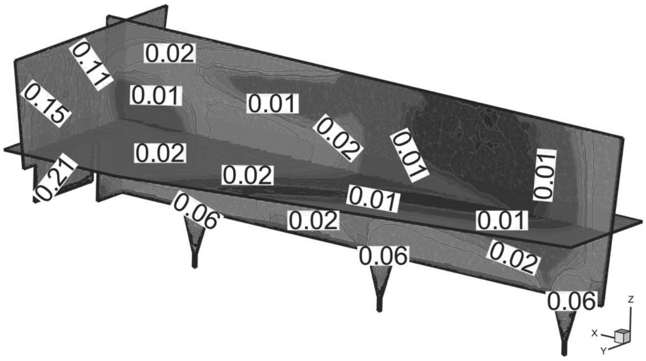

Fig. 3. Velocity field of steel flow (m·s^{-1}) at the selected levels

By analyzing the projected steel flow (Fig. 3), two regions are observed: a near-gate region (limited by the turbulence inhibitor) and a post-gate region.

When looking at the forecast steel motion (Fig. 3), these regions differ distinctly in a separate steel motion pattern. In the near-gate region, circulation (with a considerable share of the ascending component) is generated. This may favour the interphase precipitation of nonmetallic inclusions. Due to the slag flow-over, this circulation may, however, expose the metal surface (causing the so called “metal eye”). This may result in the reoxidation of the steel. The analysis of the velocity field shows the presence high speed of steel at the surface – metal slag. This is a phenomenon that unfavourably affects on the motion of non-metallic inclusions. This rapid motion can cause the transition to steel slag. In the near-gate region is also visible unfavorable phenomenon. It occurs in the steel – nonmetallic inclusions – refractory lining system. This phenomenon is characterized by large velocity of steel at the ladle walls. This structure may hinder adhesion phenomena of non-metallic inclusions to the refractory lining. At considerable velocities, steel elutes the nonmetallic inclusions off and causes the erosion of the refractory lining.

An important characteristic requiring in the evaluation of tundishes is the distribution of liquid steel temperature. Predicted temperature distribution of liquid steel shows the Figure 4.

The characteristics of steel motion in the tundish can be supplemented by the flow turbulence characteristics. The spatial distributions of turbulent kinetic energy (k) for liquid steel was generated for this purpose. The picture of these characteristics for the ladle presents Figure 5.

The predicted temperature distribution of liquid steel in the ladle (Fig. 4) provides relevant information about the temperatures formation at the ladle inlets. These values differ slightly (the difference is 4 K). However, in steady conditions the steel temperature decreases about 16K. The obtained steel temperature values show that the tundish working space has been correctly chosen from the thermal point of view. Moreover, they also confirm the stability of continuous steel casting process.

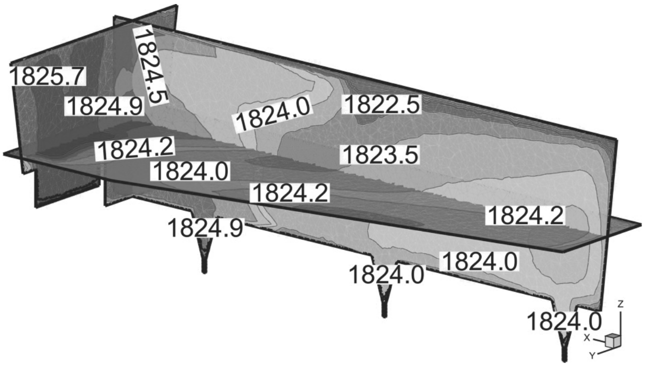

Fig. 4. Isolines of the steel temperature (K) at the selected levels

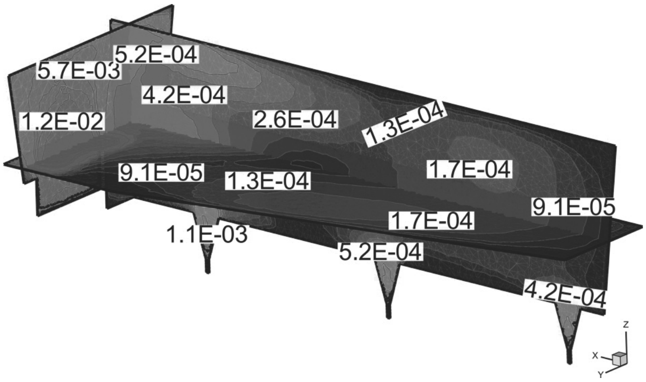

Fig. 5. Isolines of steel turbulent kinetic energy (m^2·s^2)

Turbulence kinetic energy distributions clearly illustrate the behavior of the liquid steel in the ladle. Figure 5 shows how the liquid steel in the ladle spreads toward the walls and surrounds the outlet No. 3, the area closest to near-gate region. This may disturb the local steel flow and can cause problems of steel casting to the mould cooperated with the outlet. This arrangement is not conducive to the removal of inclusions by the free outflow to the surface of an interfacial metal – slag. It can also cause erosion of the lining and elution of nonmetallic inclusions from the walls and bottom of the ladle, causing pouring them to the outlet No. 3

Additional evaluation of the correctness of the tundish design is done by determining the distribution of tracer concentrations in liquid steel and developing the Residence Time Distribution (RTD) characteristics - curves E and F [18]. These are the examinations belonging to the canon of studies on flow reactors.

In this case, numerical computations were carried out for a predetermined velocity field, while assuming non-stationary conditions.

The forecasted variations in the dimensionless tracer concentrations is shown in Figure 6. Two variants, after 100 and 500 seconds, are presented.

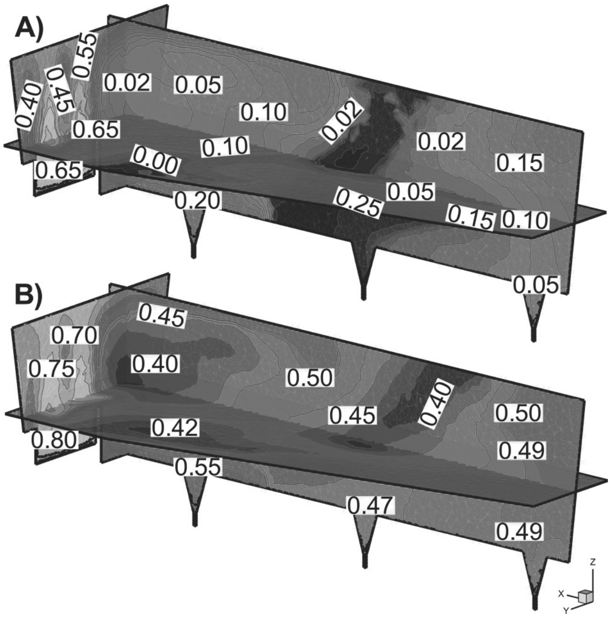

Fig. 6. Isoconcentration lines of the tracer at - (a) 100 s, (b) 500s

It can be seen in Figure 6 that the traces moves in the steel primarily due to the forced convection resulting from the steel flow in the plant under examination.

Figure 7 shows mixing curves for the tundish outlets. The presented characteristics is used for evaluation of the steel mixing conditions in the tundish [19]. On its basis, the transient zone can be evaluated. This is done by defining the range as determined from the differences of the times necessary for obtaining concentrations at the assumed levels (the dimensionless concentration range) of the concentration forecast for a given steel grade. Two transient zone ranges at a dimensionless concentration level of 0.2-0.8 and 0.4-0.6 were considered. The values of transient zone range for respective outlets are given in Table 3.

Table 3.
The transient zone

Parametr	The transient zone, (s)				Mass of steel, (Mg)
	Outlet 1	Outlet 2	Outlet 3	Average	
0.2-0.8	1025	1013	1026	1021	34.8
0.4-0.6	288	287	215	263	8.9

When examining the values in Table 3 we can see that the time of transient zone formation (the range of 0.2-0.8) is slightly different on individual tundish outlets. For the range of (0.4-0.6), on the other hand, the time for outlet No. 3 is considerably shorter. Knowing the range of the transient zone for a given tundish it is possible to determine the mass of casted steel, which deviates in its chemical composition and material properties from those forecast for the planned steel grade. The calculated steel mass is given in Table 3.

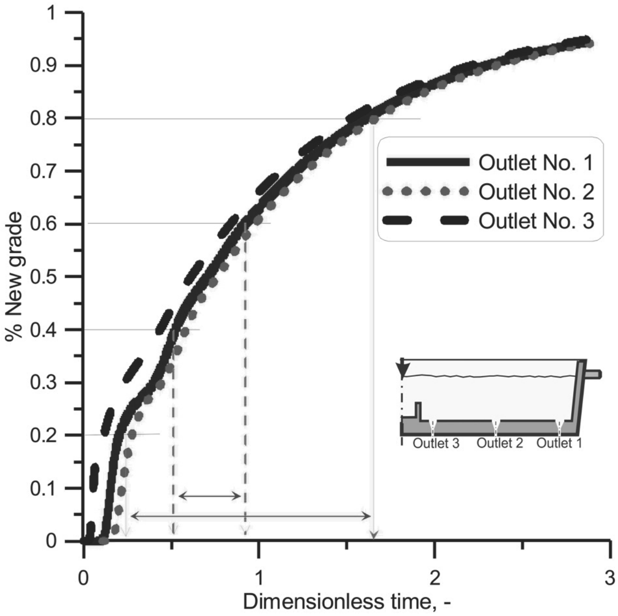

Fig. 7. Mixing characteristics as determined for the tundish

The presented F-type curves is used for the quality evaluation of the flow. However these are sensitive as a measure in the quantitative evaluation of the shares for particular flow types occurring in tundishes. For the qualitative and quantitative evaluation of flow in tundishes, RTD characteristics are used (the E curve). By analyzing these curves, the macroscopic pattern of flow in a plant under examination can be evaluated. Three liquid steel flow regions are distinguished in the tundish: a well mixed volume flow zone, a dispersed plug flow zone, and a stagnant (dead-volume) flow zone.

For the evaluation of the correctness liquid steel refining in tundishes, it is important to determine the share of particular flow types. The dead-volume flow zone in the tundish unfavourably affects the gravity removal of nonmetallic inclusions (non-metallic flotation) and the distribution of steel temperature. The dispersed plug flow zone favours the free flotation of nonmetallic inclusions from the bulk of steel. In contrast, in the well mixed volume flow zone, intensive coagulation and coalescence phenomena occur, which significantly facilitates the flowing of nonmetallic inclusions out to the slag phase.

Figure 8 presents non-dimensional residence time characteristics (the E-type curve) for the tundish under examination.

When examining the curves (Fig. 8) it can be noticed that they differ for individual outflow outlets. In particular – in their initial phase, that is from the moment of dimensionless time equal 0 up to the time of dimensionless time equal 0.5. In order to determine the flow shares and the average residence time (Table 4) for tundish outlets, relevant computations were made using the relationships [18]:

$$V_d = 1 - \frac{\dot{V}_a}{\dot{V}} \Theta_{av} \tag{1}$$

$$V_{dp} = \frac{\left(\Theta_{\min} + \Theta_{peak}\right)}{2} \tag{2}$$

$$V_m = 1 - V_d - V_{dp} \tag{3}$$

where: V_d, stagnant volume, V_{dp}, dispersed plug volume, V_m, well mixed volume, Θ_{av}, mean dimensionless time, $\Theta_{\min}$, minimal dimensionless time, Θ_{peak}, peak dimensionless time.

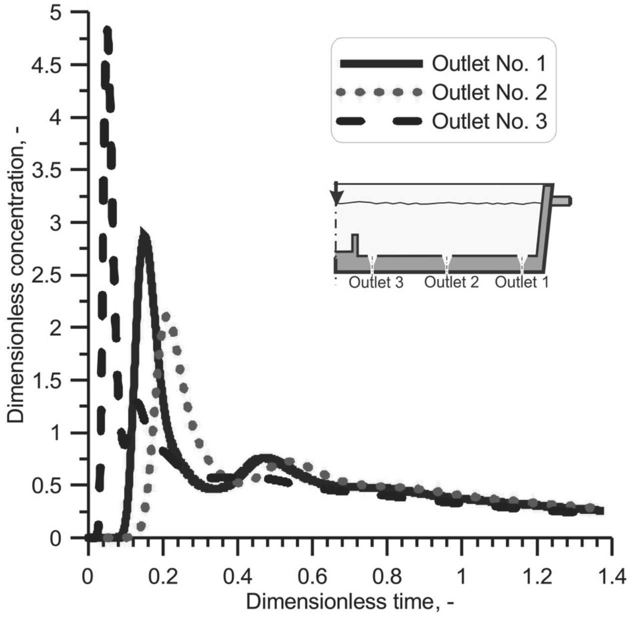

Fig. 8. Residence time distribution characteristics for the tundish

Important parameter of the tundish is the resident time of the fluid in the tundish. The real time spent by the fluid element in the tundish can be determined experimentally by measuring tracer concentration and solving equation [18]:

$$t_{av} = \int_0^\infty C\,t\,dt \Big/ \int_0^\infty C\,dt \cong \frac{\sum C_{i\,sym} t_i \Delta t_i}{\sum C_{i\,sym} \Delta t_i} \tag{4}$$

The computed values of particular shares types of liquid steel flow in the facilities under investigation are given in Figure 9.

Table 4.
Mean residence time in the six-outlets tundish

Outlet number	1	2	3
Mean residence time (t_{av}), s	738	789	651

The flow share values for outlets No. 1 and 2, given in Fig. 9, are similar, but for outlet No. 3 differ considerably. The values of outlet No. 3 indicate a very small share of the dispersed plug flow. This unfavourable flow share proportion indicates the occurrence of a bypass flow between the gate and outlet No. 3 of the tundish.

The optimal working space of a tundish should be characterized by small differences between the average steel residence times for the outlets, which is not the case in the tundish examined.

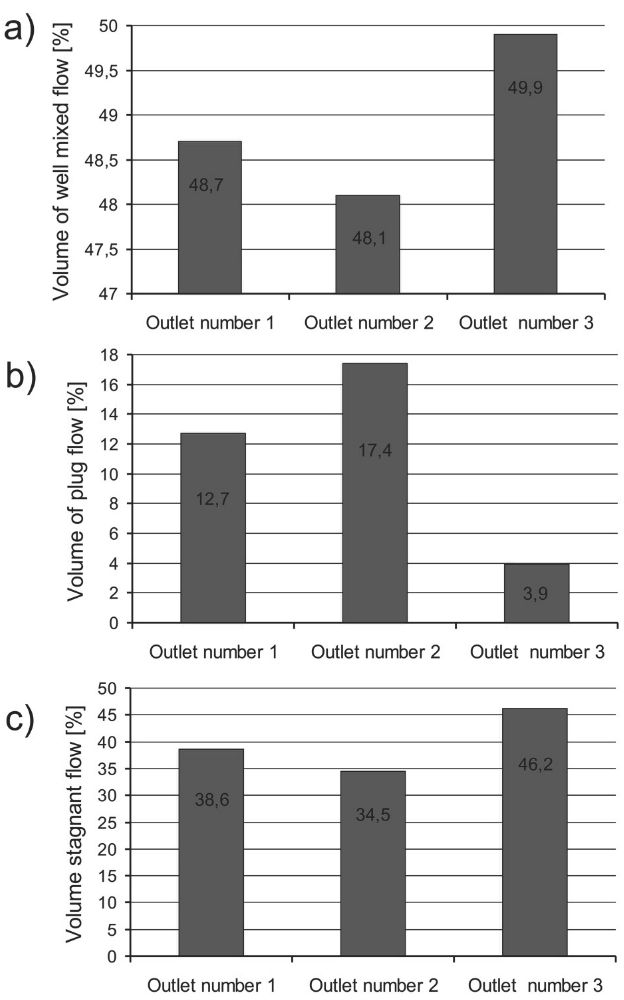

Fig. 9. Parameters of fraction flow in all outlets the tundish: (a) volume of well mixed flow, (b) volume of plug flow, (c) volume of stagnant flow

4. Conclusions

The application of the mathematical modelling technique of steel flow in the tundish is an effective method for substituting costly and difficult industrial experimental tests for the diagnosis or optimization of the tundish design. It should be added that industrial experimental tests were carried out on an real plant and it showed good consistence with the numerical simulation results [8].

The performed numerical simulations provided a basis for developing the flow and its thermal characteristics in the tundish.

The analysis of the flow characteristics suggests that the hydrodynamic conditions prevailing in the plant are unfavourable for the removal of nonmetallic inclusions. Particularly unfavourable conditions occur in the area of the middle outflow outlets.

The thermal (steel temperature field) analysis of the tundish shows that the temperature of steel decreases about 16K, while the value of steel temperature at the outlets differ only slightly (4K). This indicates a tundish geometry that has been correctly chosen in the thermal aspect.

The obtained characteristics of the RTD allowed to determine the transition zone. Such a zone for the analyzed ladle, depending on the applied field is 263s and 1021s, which corresponds to 34.8Mg and 8.9Mg mass of casted steel. For the range (0.4 - 0.6), differentiation of the transition zone for each outlet of tundish (Table 3) can be observed.

The RTD characteristics have also allowed to determine flow shares: the well-mixed volume flow, dispersed plug flow and dead volume flow shares to be determined. The average flow shares for the tundish under study are follows: the well mixed volume flow - 48.9%; the dispersed plug flow - 11.3%; and the stagnant volume flow - 39.8%. The unfavourable share proportions occur for the middle outlets (No. 3 and 4).

The presented results have showed the need for modifying the tundish working space, especially due to the unfavourable flow conditions prevailing in the area of the middle outflow outlets. This will provide better casting conditions for the middle strands and enhance the capability to refine steel by removing nonmetallic inclusions, without compromising the thermal properties of the tundish.

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