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NUMERICAL ANALYSIS OF STEEL FLOW IN THE SIX-STRAND TUNDISH WITH SUBFLUX CONTROLLER OF TURBULENCE

NUMERYCZNA ANALIZA PRZEPŁYWU STALI W SZEŚCIOOTWOROWEJ KADZI POŚREDNIEJ WYPOSAŻONEJ W PODSTRUMIENIOWY REGULATOR TURBULENCJI

The article presents the results of computer simulations of steel flow in a six-strand tundish. The tundish was equipped with a subflux controller of turbulence. The authors employed the CFD (Computational Fluid Dynamics) numerical modelling technique to demonstrate the effect of different variants of the subsflux controller of turbulence on the shape of RTD (Residence Time Distribution) curves. The computer simulations were performed for both isothermal and non-isothermal conditions. Four types of regulators were tested within this work. As a result of computations, RTD curves and the contribution of particular flow zones (stagnant flow, plug flow, and ideal mixing flow) were obtained.

Keywords: numerical simulation, tundish, steel flow, flow control devices, buoyancy number, RTD curves

Artykuł przedstawia wyniki symulacji komputerowej przepływu stali w sześciootworowej kadzi pośredniej. Kadź pośrednia została wyposażona w podstrumieniowy regulator turbulencji. Autorzy wykorzystali technikę modelowania numerycznego CFD (Computational Fluid Dynamics) do pokazania wpływu różnych wariantów podstrumieiowego regulatora turbulencji na kształt krzywych RTD (Residence Time Distribution). Symulacje były wykonane dla warunków izotermicznych i nieizotermicznych. W pracy testowano cztery rodzaje regulatorów. W efekcie obliczeń otrzymano krzywe RTD i udziały procentowe poszczególnych stref przepływu (przepływ stagnacyjny, tłokowy i dealnego mieszania).

Nomenclature

C_i – Concentration of the tracer, dimensionless (-),
C_p – Heat capacity (J/kg·K),
D_I – Diffusion coeffficient of the tracer (m^2/s),
g – Gravitational acceleration (m/s^2),
Gr – Grashof number (-),
h – Species enthalpy (J/mol)
I – Unit tensor
J_j – Diffusion flux ($kg/m^2 \cdot s$),
k – Thermal conductivity (W/m·K),
k_{eff} – Effective heat capacity (W/m·K),
L – Steel level in the tundish (m)
p – Pressure (Pa)
Q – Total volumetric flow through the tundish (m^3/s)
Q_a – Volumetric flow rate through the active region of the tundish (m^3/s)
Re – Reynolds number (-)
t – Time (s)
T – Temperature (K)
T_0 – Initial temperature (K)
ΔT – Difference between temperature of steel on the tundish inlet and average temperature of steel on the tundish outlets (K)
u – Velocity of the steel flow (m/s)
u_{ave} – Average velocity of the steel flow in the tundish (m/s)
V – Volume of steel in the tundish (m^3)
V_{dead} – Volume of dead region in the tundish (m^3)
V_{plug} – Volume of plug region in the tundish (m^3)
$V_{ideal\ mixing}$ – Volume of mixed region in the tundish (m^3)
ρ – Density (kg/m^3)

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ρ_0	– Initial density (kg/m^3)
μ	– Viscosity (kg/m·s)
ß	– Coefficient of thermal expansion (1/K)
$\bar{\bar{\tau}}$	– Stress tensor (Pa)
$\overline{\bar{\bar{\tau}}_{eff}}$	– Effective stress tensor (Pa)
$\bar{\theta}_C$	– Average mean residence time up to Θ=2, dimensionless (-)
$\theta_{\min}$	– Time of first appearance of tracer at the tundish outlet, dimensionless (-)
$\theta_{\max}$	– Time when the concentration of tracer at the tundish outlet is the greatest, dimensionless (-)
θ_t	– Time, dimensionless (-)
$\Delta\theta$	– Difference between successive values of dimensionless time (-)

1. Introduction

Computational numerical methods are a dynamically developing branch of science, thanks to which information on the phenomena occurring inside metallurgical facilities is obtained. For several years, metallurgical processes have been the subject of simulation studies, starting from steel smelting furnaces, through the ladle furnace, to the SCC machine [1-5]. The efficient operation of the above-mentioned facilities, in combination with technology improvement and enhancing the qualifications of staff operating a particular work stand, provides a guarantee for obtaining the highest-quality product. A major problem in the obtaining of steel semi-product in the form of a steel ingot is its purity and proper internal structure. The required metal purity is achieved during the processing of the metal in a ladle furnace. Before reaching the casting mould, steel must spend a specific amount of time in the tundish. The conditions of steel flow in the tundish determine also the purity of the steel. This work focuses on the role of the tundish, whose main task is to deliver liquid steel to the casting mould. It is increasingly often assumed that the tundish can be used as a facility, where it is also possible to activate mechanisms promoting the flotation of non-metallic inclusions. The flotation of non-metallic inclusions in the tundish can be intensified by installing devices controlling the steel flow, such as dams, baffles, overflows, ceramic filters, or subflux controller of turbulence. The application of those devices in the tundish can be preceded by model studies performed on water models and numerical simulations. The results presented in this article are a continuation of simulation studies on the application of a subflux turbulence regulator in the tundish [6-10]. The article presents the results of numerical simulation studies on the flow of steel in a tundish equipped with a subflux controller of turbulence in four geometrical variants. The studies were carried out for both isothermal and non-isothermal conditions by assessing the effect of forces acting on liquid metal, which are associated with the temperature gradients of steel flowing through the tundish during steel continuous casting.

2. Characterization of the test facility

The test facility was a six-strand tundish of a capacity of 22 Mg. In the liquid metal pouring tundish zone, provision was made for the installation of a subflux controller of turbulence. The tundish geometry, the positioning of the regulator and the numbering of individual outlet are shown in Figure 1. The tundish is designed for the casting of square and rectangular castings. The analysis covered half of the test facility due to its symmetry. The studies simulated the flow of steel in the tundish without a regulator and in the tundish with regulators installed.

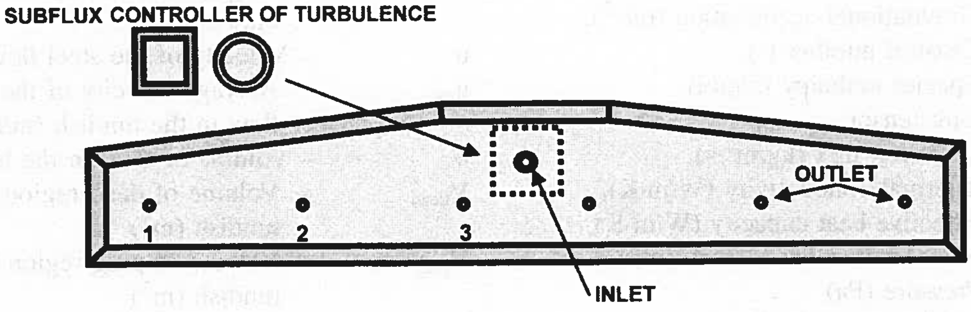

Fig. 1. Tundish and position of subflux controller of turbulence

Figure 2 shows the shapes of regulators installed in the tundish, along with their main dimensions. Four variants of regulators were considered. In the first three variants, the regulator had the shape of a rectangular prism. Additionally, the regulator in Variant 1 had inclined internal walls. In Variant 2, the corners of the regulator between its sloped internal walls and the flange were rounded. The rounding radius for this variant was 30 mm. In Variant 3, the internal walls were positioned at an angle of 90° relative to the regulator bottom. Variant 4 had the external regulator geometry changed from the rectangular prism to a cylinder, while retaining the same inclination of the internal walls as in Variant 1.

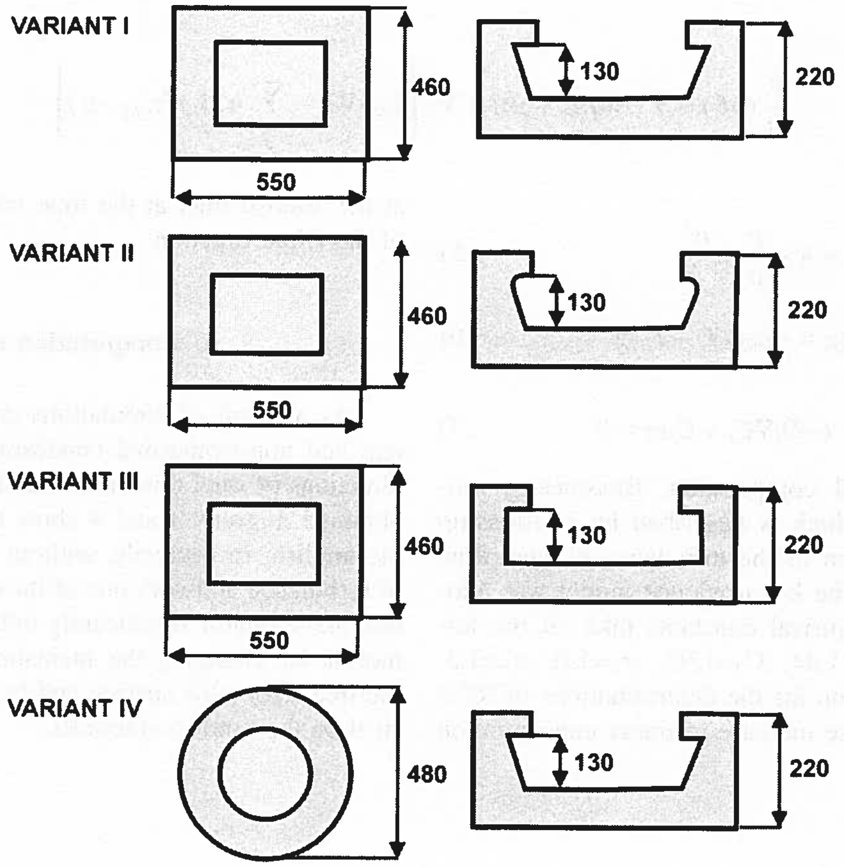

Fig. 2. Different variants of subflux controller of turbulence [11]

3. Testing methodology

Considering the spatial flow of steel in the tundish is a prerequisite for the assessment of the hydrodynamic properties of facilities examined. For this purpose, spatial computational grids specific for those facilities were generated. Two variants of simulation were considered; the first variant was intended for isothermal conditions, while the other for non-isothermal conditions. This approach results from the fact that the majority of studies cited in literature concern non-isothermal flows. This in turn is caused by an "a priori" made assumption on a little significant effect of the variable temperature field on the formation of hydrodynamic conditions in the tundish. However, some publications put forward suggestions that the effect of temperature may cause significant changes in the pattern of metal motion. Therefore, the goal of the present work is to find out what effect is exerted on the hydrodynamic conditions by heat exchange between the steel flowing through the tundish and the environment. Physical quantities, such as density, ρ; viscosity μ; heat capacity, C_p; thermal conductivity, k; and the coefficient of thermal expansion of liquid steel, β, were taken based on literature data [12-20]. These values are as follows: ρ=7010, μ=0.007, C_p=750, k=41, β=0.0001. For the non-isothermal conditions of steel flow trough the tundish, the magnitudes of heat fluxes on particular tundish walls and bottom have been determined to be

– 2600 W/m^2, whereas on the regulator walls – 1750 W/m^2. The losses on the free metal table surface are – 15000 W/m^2 [12-20]. For all considered variants of non-isothermal simulations it was assumed that the temperature of steel flowing to the tundish was 1550°C. The basic mathematical model equations describing the phenomena under examination are as follows:

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

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

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

$$\frac{\partial}{\partial t}(\rho E)+\nabla\cdot(u(\rho E+p))=\nabla\cdot\left(k_{eff}\nabla T-\sum_j h_j J_j+(\bar{\tau}_{eff}\cdot u)\right) \tag{4}$$

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

$$(\rho-\rho_0)g\approx-\rho_0\beta(T-T_0)g \tag{6}$$

$$\frac{\partial C_i}{\partial t}+\nabla\cdot(-D_i\nabla C_i+C_i u)=0 \tag{7}$$

In non-isothermal computation, Bussinesq's model was employed, which is described by relationship (6). For the description of the turbulence of steel flow through the tundish, the k- turbulence model was adopted, whose semi-empirical constants take on the following values: C_1= 1.44, C_2=1.92, σ_k=1.0, σ_ε=1.3. The boundary condition for the determinations of RTD curves was the impulse increase in tracer concentration at the tundish inlet at the time t=0, having the features of the Dirac function.

4. Computation results

As a result of simulations carried out for isothermal and non-isothermal conditions, velocity fields and directions of steel flow in the tundishes considered were obtained. Figures 3 and 4 show the motion of steel in the tundish, respectively, without the subflux controller of turbulence and with one of its variants. It can be seen that the regulator significantly influences the liquid steel motion by changing the mainstream direction towards the free steel table surface and by limiting the action of steel on the tundish sidewalls.

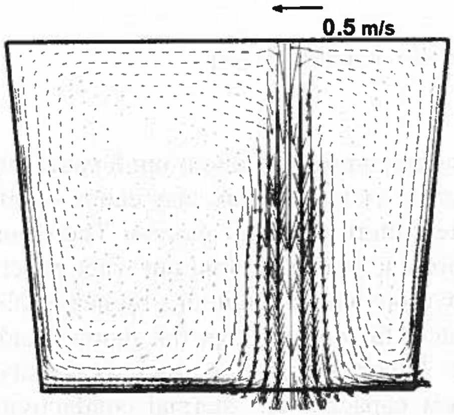

Fig. 3. Vectors of steel flow in the tundish without subflux controller of turbulence

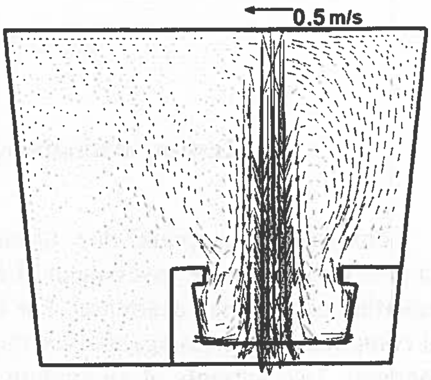

Fig. 4. Vectors of steel flow in the tundish with subflux controller of turbulence

The use of a virtual tracer in the simulations enabled residence time distribution (RTD) curves to be plotted for the tundish variants examined. Describing the state of fluid flow in the facility under analysis with the computed shares of flow zones, the RTD curves provide a valuable guidance to the users and designers of tundishes [21-24]. The RTD curves obtained for individual tundish inlets under isothermal and non-isothermal conditions are summarized in Figures 5-19. It can be seen that only in the case of the tundish without the regulator (Fig. 5÷7), no significant differences in the tracer distribution, caused by considering the energy equation in the model, occurred for particular inlets. In the remaining cases (Figs. 8÷19), apparent differences in marker concentration distribution occurred between particular tundish inlets. This indicates a substantial change in hydrodynamic conditions within the tundish and a relationship between metal temperature and velocity and the flow behaviour. This relationship can be determined by calculating the dimensionless buoyancy number according to the following formula [17, 25-31]:

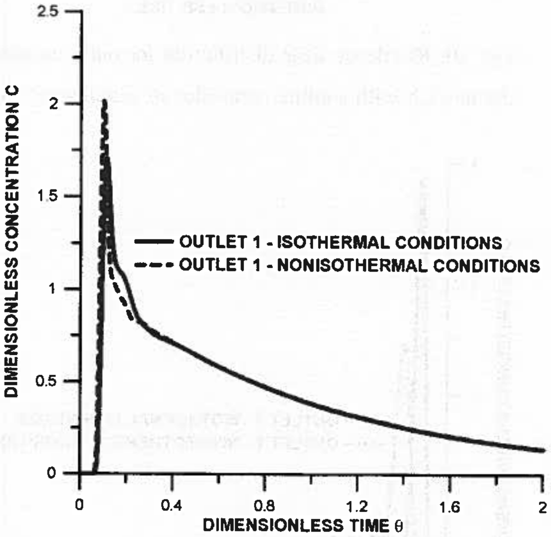

Fig. 5. Residence time distribution for outlet number 1 in the bare tundish

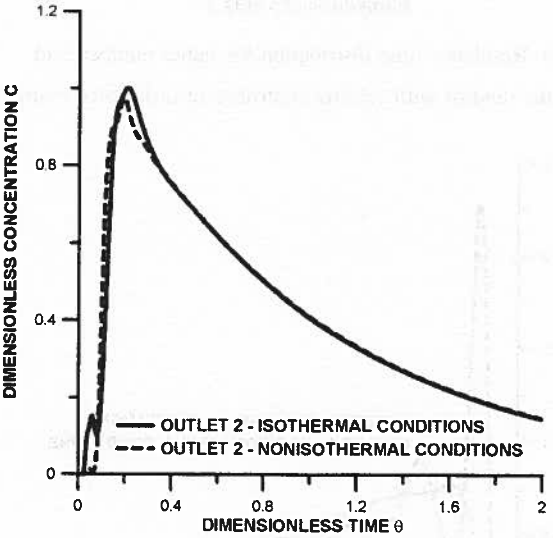

Fig. 6. Residence time distribution for outlet number 2 in the bare tundish

tundish

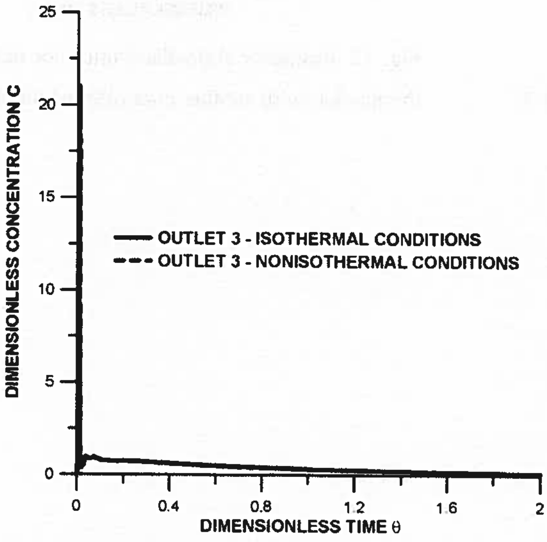

Fig. 7. Residence time distribution for outlet number 3 in the bare tundish

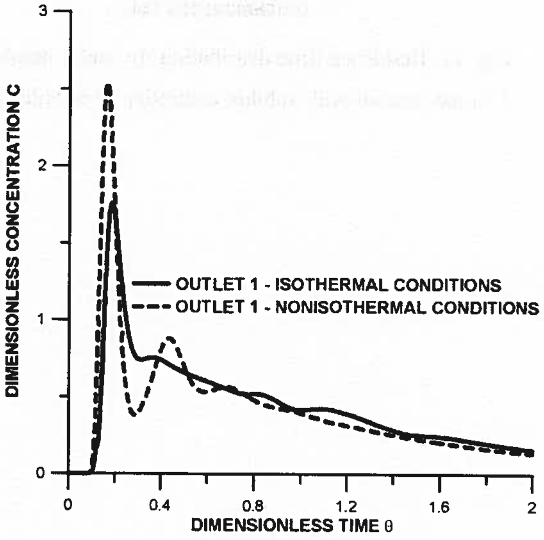

Fig. 8. Residence time distribution for outlet 1 in the tundish with subflux controller of turbulence (variant 1)

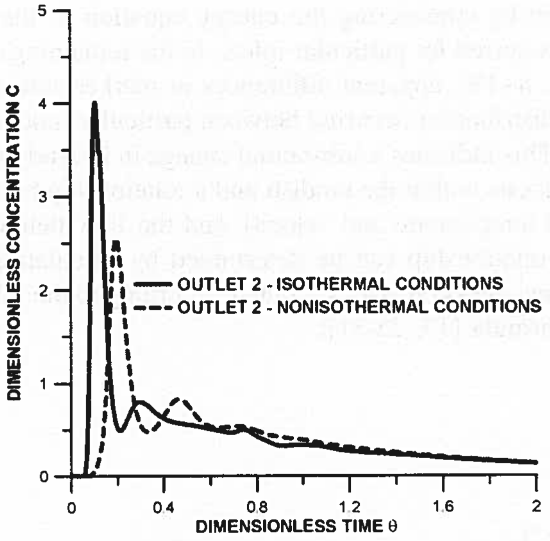

Fig. 9. Residence time distribution for outlet number 3 in 2 in the tundish with subflux controller of turbulence (variant 1)

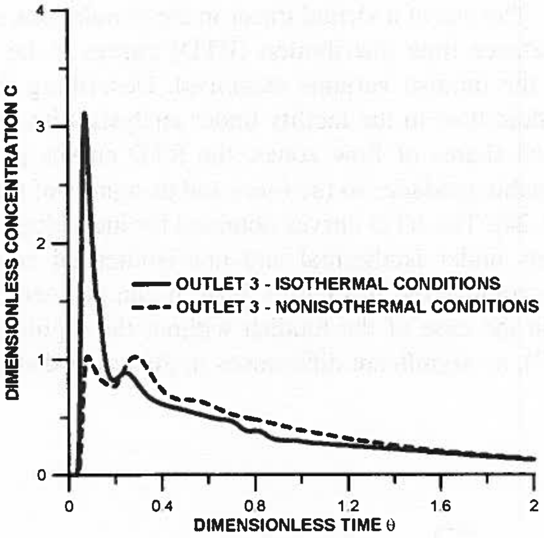

Fig. 10. Residence time distribution for outlet number the tundish with subflux controller of turbulence (variant 1)

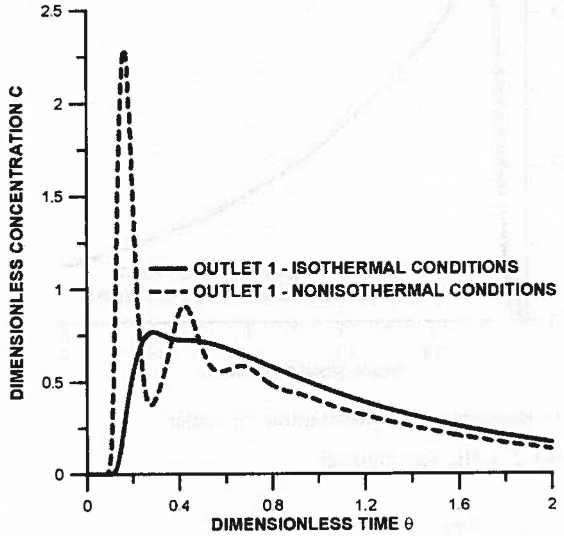

Fig. 11. Residence time distribution for outlet number 1 in the tundish with subflux controller of turbulence (variant 2)

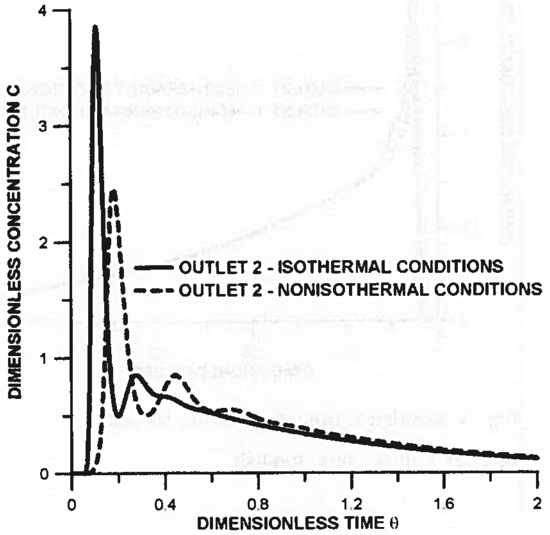

Fig. 12. Residence time distribution for outlet number 2 in the tundish with subflux controller of turbulence (variant 2)

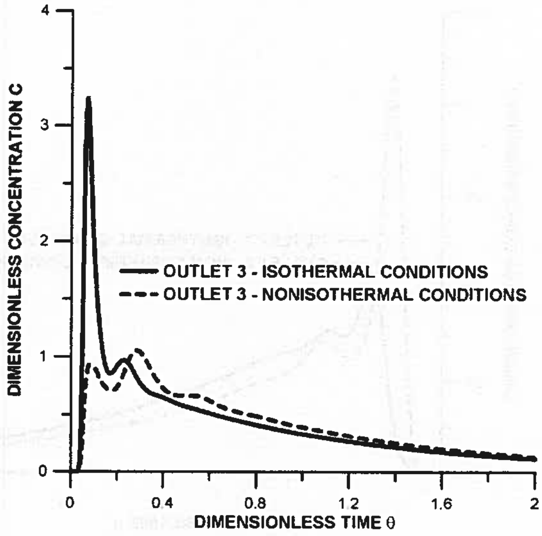

Fig. 13. Residence time distribution for outlet number 3 in the tundish with subflux controller of turbulence (variant 2)

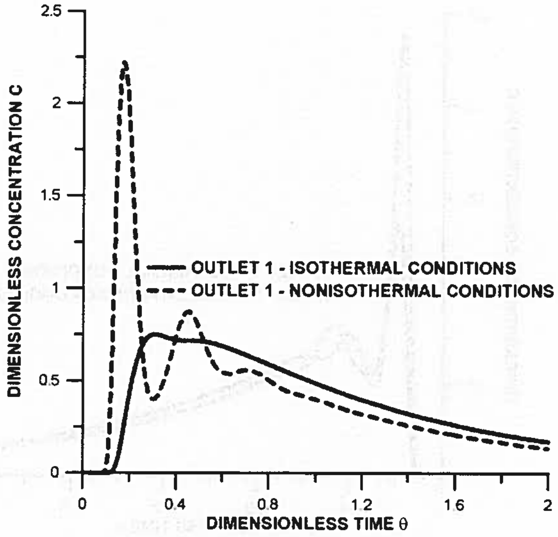

Fig. 14. Residence time distribution for outlet number 1 in the tundish with subflux controller of turbulence (variant 3)

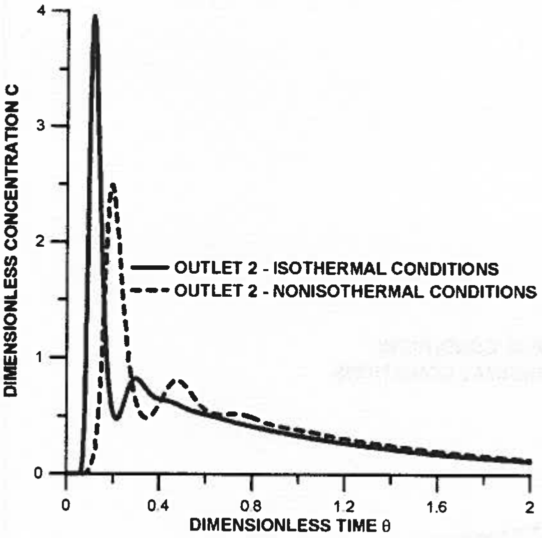

Fig. 15. Residence time distribution for outlet number 2 in the tundish with subflux controller of turbulence (variant 3)

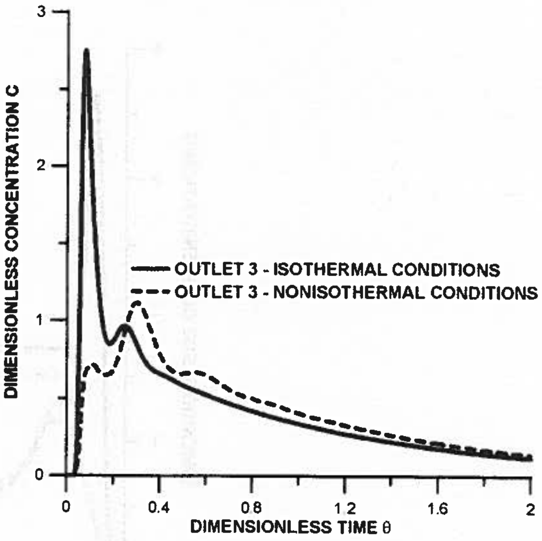

Fig. 16. Residence time distribution for outlet number 3 in the tundish with subflux controller of turbulence (variant 3

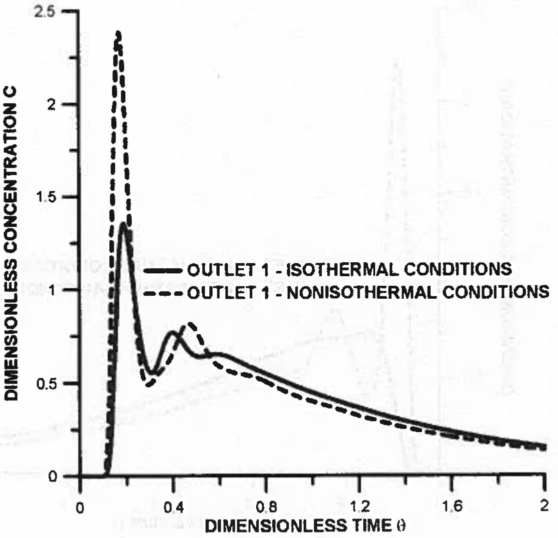

Fig. 17. . Residence time distribution for outlet number 1 in the tundish with subflux controller of turbulence (variant 4)

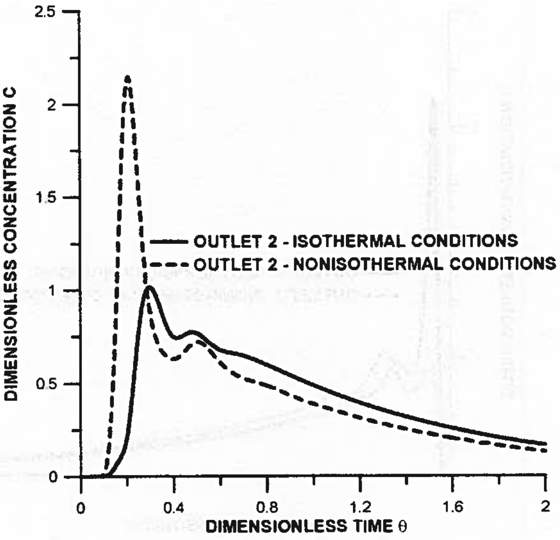

Fig. 18. . Residence time distribution for outlet number 2 in the tundish with subflux controller of turbulence (variant 4)

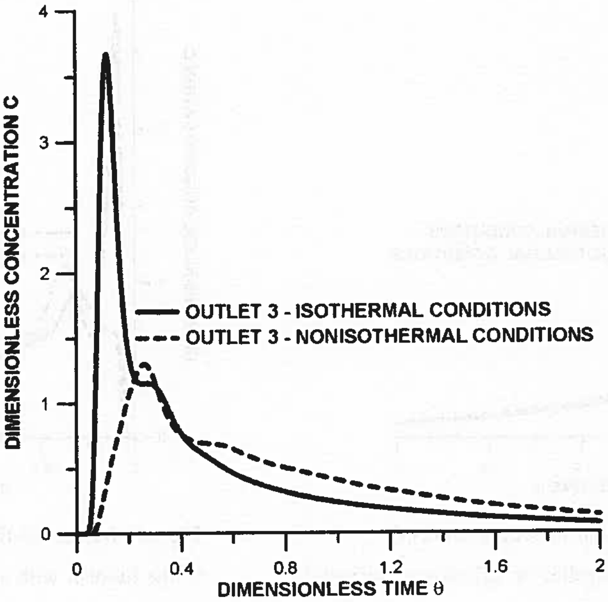

Fig. 19. Residence time distribution for outlet number 3 in the tundish with subflux controller of turbulence (variant 4)

$$Bu = \frac{Gr}{\mathrm{Re}^2} = \frac{g\beta\Delta TL}{u_{ave}^2} \tag{8}$$

The buoyancy number, Bu, describes the effect of natural convection on the modification of the fluid flow structure and expresses the ratio of the buoyancy forces to the inertial forces acting upon the fluid. The Bu number value above 5 means that the liquid metal flowing through the tundish will be affected by natural convection, whereas the value of the number Bu < 1 will indicate the effect of forced convection on the steel motion. Table 1 given the values of the dimensionless number Bu for the tundish furnishing variants, computed on the assumption that ΔT = 5K, L = 0.78 m. The lowest Bu number value occurs for the tundish without the regulator. For the other cases, the Bu number exceeds 5 in value. This explains why the significant differences in RTD characteristics between the isothermal and non-isothermal tundish states occur in Figures 8-19.

TABLE 1

Bouyancy number Bu for considered tundish

Tundish variants	u_{ave} [m/s]	Bu
Bare tundish	0,043	2,06
Tundish with controller (variant 1)	0,026	5,65
Tundish with controller (variant 2)	0,027	5,24
Tundish with controller (variant 3)	0,025	6,12
Tundish with controller (variant 4)	0,022	7,9

When assessing the spatial velocity field it can be noticed that the flow of steel in the tundish is highly diversified and, according to the theory of flows, the following volumes can be distinguished: stagnant flow, plug flow, and ideal mixing flow. Hence, the assessment of the particular flow magnitudes for each tundish gains especial significance. For the correct influence of tundish geometry and applied flow control devices on the motion of steel is determined by the least possible share of stagnant volume. The magnitude of that volume defines the range of tundish regions, where the fluid resides at least two times the average time of fluid residence in the facility. For the quantitative evaluation of particular flow volumes in the tundishes examined, formulas 9-13 [32-33] were used:

$$\frac{V_{dead}}{V} = 1 - \frac{Q_a}{Q} \cdot \overline{\theta}_C \tag{9}$$

$$\frac{V_{plug}}{V} = \frac{\theta_{\max} + \theta_{\min}}{2} \tag{10}$$

$$\frac{V_{idealmixing}}{V} = 1 - \frac{V_{dead}}{V} - \frac{V_{plug}}{V} \tag{11}$$

$$\frac{Q_a}{Q} = \sum_{\theta=0}^{2} C_i \Delta\theta \tag{12}$$

$$\overline{\theta}_C = \frac{\sum_{\theta=0}^{2} C_i \theta_t}{\sum_{\theta=0}^{2} C_i} \tag{13}$$

TABLE 2

Steel flow characteristics for tundish outlet 1 without and with different variants of subflux controller of turbulence

Tundish variants	Percentage contribution [%]					
	Isothermal conditions			Nonisothermal conditions		
	Volume of dead flow	Volume of plug flow	Volume of mixed flow	Volume of dead flow	Volume of plug flow	Volume of mixed flow
Bare tundish	37,9	5.63	56,47	38,08	5.15	56,77
Tundish with controller (variant 1)	30	9,44	60,56	37,5	8	54,5
Tundish with controller (variant 2)	27,7	14,4	57,9	37,4	8,3	54,3
Tundish with controller (variant 3)	26,8	15,1	58,1	36,7	8,5	54,8
Tundish with controller (variant 4)	31	9	60	36,4	8,5	55,1

Tables 2-4 show the magnitudes of shares of the volumes under consideration for particular tundish inlets, for both isothermal and non-isothermal conditions. Table 2 presents computation results for the first inlet, furthermost from the tundish pouring zone. The obtained results demonstrate that the use of the regulator reduces

TABLE 3

Steel flow characteristics for tundish outlet 2 without and with different variants of subflux controller of turbulence

Tundish variants	Percentage contribution [%]					
	Isothermal conditions			Nonisothermal conditions		
	Volume of dead flow	Volume of plug flow	Volume of mixed flow	Volume of dead flow	Volume of plug flow	Volume of mixed flow
Bare tundish	34.9	10,28	54,82	34,92	9,71	55,37
Tundish with controller (variant 1)	42,6	5,3	52,1	37,4	9	53,6
Tundish with controller (variant 2)	43,8	5,5	50,7	38,2	9,1	52,7
Tundish with controller (variant 3)	44,5	5,6	49,9	37,8	9,6	52,6
Tundish with controller (variant 4)	26,9	14,9	58,2	36,9	10,5	52,6

TABLE 4

Steel flow characteristics for tundish outlet 3 without and with different variants of subflux controller of turbulence

Tundish variants	Percentage contribution [%]					
	Isothermal conditions			Nonisothermal conditions		
	Volume of dead flow	Volume of plug flow	Volume of mixed flow	Volume of dead flow	Volume of plug flow	Volume of mixed flow
Bare tundish	46,42	3,4	53,24	47,64	2,39	49,47
Tundish with controller (variant 1)	45,51	3,6	50,89	37,4	4	58,6
Tundish with controller (variant 2)	45,2	3,4	51,4	37,7	4,1	58,2
Tundish with controller (variant 3)	44,2	3,7	52,1	35,5	5,3	59,2
Tundish with controller (variant 4)	54,43	6	39,57	34,7	12,7	52,6

the share of the stagnant volume and increases the share of the plug and mixing volumes. The results of steel flow computation for inlet 2 under isothermal conditions showed a similar flow behaviour for the tundishes furnished with the regulators in Variants 1-3, while the stagnant, plug and ideal mixing volumes for the tundish with the cylinder-shaped regulator were markedly different. Table 4 gives computation results for inlet 3 situated closest to the tundish pouring zone and the zone of regulator influence on the flow. Simulations both with and without heat exchange showed that the cylinder-shaped subflux regulator had the greatest effect on the modification of flow behaviour in this zone. From the analysis of the results presented in Tables 2-4 it can be seen that the differences in the results obtained for the stagnant, plug and mixing volumes between the simulations with and without heat exchange are pronounced especially in the tundishes furnished with the subflux controller of turbulence. In making the assessment of steel motion in the tundish based on the presented results it can be noticed that the values of particular flow volumes for isothermal and non-isothermal conditions are similar; the values provided in Tables (1-4) indicate that the SCT-type device installed on the tundish has an effect of reducing the stagnant and mixing zone shares and increasing the plug volume share. When making the assessment of the hydrodynamic quality of the facilities it was assumed that the optimal criterion would be the average values from three inlets. On that basis, it was found that the best hydrodynamic conditions occurred in the tundish with the regulator in Variant IV (an increase in the plug flow volume and a decrease in the stagnant flow volume), whereas the facility without the regulator had clearly the worst flow behaviour.

5. Summary

The obtained different distributions of RTD curves and values of particular flow zones for non-isothermal conditions compared to the results of isothermal computation in the tundishes furnished with the subflux controller of turbulence indicate a significant effect of buoyancy forces on the modification of the liquid steel flow field. This fact confirms the value of the number Bu > 5 for those tundish variants. This is associated with the velocity of the steel flow slowing down as a result of steel contact with the regulator in the pouring zone. Lower steel velocities and temperature drops in tundish regions distant from the pouring zone will favour natural convection. The absence of the SCT device in the tundish makes the steel flow to move too fast for the natural convection forces associated with temperature gradients to be able to modify the metal flow direction. The performed computations have proved the advisability of using turbulence regulators for the modification of steel flow in the tundish. It is also worth of pointing out to the fact that minor modifications of the regulator shape have no significant effect on the flow of steel (the regulator in Variants II and III). It is only a significant modification of the regulator geometry (the regulator in Variant IV) that brings about noticeable changes in the shares of particular volumes, especially that of the plug volume. The CFD computer program used for the numerical simulation of steel behaviour in the tundish has proved to be an effective tool enabling the prediction of the effect of flow control devices on the development of characteristic volumes, such as the stagnant, plug and ideal mixing flows.

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