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MATHEMATICAL MODELING AND INDUSTRIAL EXPERIMENT OF LIQUID STEEL FLOW IN THE THREE OUTLETS CONTINUOUS CASTING BLOOM TUNDISH

EKSPERYMENT PRZEMYSŁOWY I MODELOWANIE MATEMATYCZNE PRZEPŁYWU CIEKŁEJ STALI W KADZI POŚREDNIEJ Z TRZEMA OTWORAMI WYLEWOWYMI

The dynamic development of the continuous steel casting (CSC) process has resulted in the application of this technology to the casting of steel semi-finished products on a mass scale. In the CSC process, before the cooling and solidification of liquid steel commences, the liquid metal dynamically flows through the steelmaking ladle, the tundish and the mould. Therefore, the control of steel flow is the key to the correct process. One of the metallurgical device in which the control of steel flow hydrodynamics is of crucial importance is the tundish. The subject of investigation within the present study was a three-nozzle tundish designed for casting of blooms. The software program Ansys-Fluent® was employed for the analysis of tundish operation. For the verification of the correctness of obtained results, an industrial experiment was carried out. For modification of the hydrodynamic conditions within the working volume of the tundish, two flow control devices were proposed, namely: a dam and a dam with an overflow window. The outcome of performed computer simulations were liquid steel flow fields and residence time distribution curves.

Keywords: continuous casting process, tundish, flow control devices, hydrodynamic conditions, numerical modeling

Dynamiczny rozwój procesu ciągłego odlewania stali spowodował masowe zastosowanie tej technologii do odlewania półwyrobów stalowych. W procesie COS zanim nastąpi proces chłodzenia ciekłej stali i krzepnięcia, metal dynamicznie przepływa przez układ kadź stalownicza, kadź pośrednia a krystalizator. W związku z tym faktem kontrola przepływu stali jest kluczem do poprawnego przebiegu procesu. Jednym z urządzeń metalurgicznych w którym sterowanie hydrodynamiką przepływu stali jest niezwykle ważne jest kadź pośrednia. W niniejszej pracy badanym obiektem była trój wylewowa kadź pośrednia przeznaczona do odlewania wlewków kwadratowych. Do analizy pracy kadzi wykorzystano program komputerowy Ansys-Fluent®. Dla weryfikacji poprawności otrzymanych wyników badań wykonano eksperyment przemysłowy. Do modyfikacji warunków hydrodynamicznych w objętości roboczej kadzi pośredniej zaproponowano dwa rodzaje urządzeń sterujących przepływem: przegrodę i przegrodę z oknem przelewowym. Efektem wykonanych symulacji komputerowych były pola przepływu ciekłej stali oraz krzywe czasu przebywania.

1. Introduction

Nowadays, all steelworks geared to the production of steel slabs, blooms or billets are equipped with a continuous steel casting machine. Only few steel mills make casting of liquid steel by the traditional method to ingot moulds. In this connection, improving the continuous steel casting technology and steelmaking technology remains in the sphere of special interest of research centres and metallurgical equipment manufacturers [1-9]. Depending on the product range and type, CSC machines enable several strands to be cast at a time. Additionally, the regulation of mould walls or a possible quick exchange of complete moulds provide the capability to cast steel in varying sizes and shapes. Moreover, with individual steel grades differing in chemical composition, it is necessary to select the casting speed and the intensity of strand cooling with water. Feeding the moulds with liquid steel is done via the tundish, to which liquid metal is poured from the steelmaking ladle. By maintaining the appropriate level of liquid steel in the tundish, the exchange of the empty ladle and sequential casting of consecutive casts are possible. So, the stabilization and optimization of the pattern of liquid steel flow within the tundish interior favourably influences the operation of the entire CSC plant. One of the methods for influencing the liquid steel flow hydrodynamics is to reconstruct the tundish working space. To this aim, flow control devices are introduced to the tundish working space [10-14]. This paper presents the outcome of computer simulation of steel flow through the wedge-type tundish used for casting of blooms. The correctness of the numerical model was verified by experimental tests carried out in the Steelworks. For the facility under examination, upgrad-

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ing of the working space by installing a new dam was proposed.

2. Characterization of the test facility and testing methodology

The test facility was three-outlets wedge-type tundish. The tundish is used to continuous casting blooms. Figure 1 shows draft of consider variants of tundish and numeration of tundish outlets. The considered tundish variants held 25 Mg of liquid metal, each. Liquid steel flows into the tundish via the ceramic ladle shroud. The internal diameter of the ladle shroud is 70 mm. The internal diameter of tundish outlets amounts 32 mm. The tundish is equipped with a slide gate system of regulation of steel flow into the moulds. The continuous steel casting machine is furnished with a set of three copper moulds to which blooms are cast. In the simulation studies, the process of casting 280×280 mm blooms was considered. Actually in the tundish is installed low dam. The liquid metal level in the tundish feed zone is 700 mm, while in the nozzle zone it is 920 mm. Figure 1b illustrates a 550 mm high and 200 mm wide dam proposed as a flow control device [15]. The dam was installed at a distance of 1260 mm from the rear wall edge. In the described tundish equipment variant, steel material (tundish skulls) in the amount of 4.5 Mg would remain in the tundish at the end of the casting process, constituting the Steelworks' own scrap. Therefore, an overflow window was provided in the designed dam to assure the flow of the liquid steel at the lower tundish part (Fig. 1c). The overflow window will enable the maximal, safe (minimizing the casting powder carryover to the CSC mould) emptying of the tundish in the final phase of the casting sequence.

The virtual model of the tundish being currently operated at the Steelworks and that of the tundish with the dams were made in the software program Gambit®. The virtual tundish models were built of 500,000 tetrahedral elements. Computer simulation of the liquid steel flow through the facility under examination was performed within the Ansys-Fluent® program. On the tundish inlet were assumed following initial boundary conditions for steel: velocity inlet 0.76 m/s, kinetic energy of turbulence 0.005776 m^2/s^2 and energy of dissipation rate of kinetic energy 0.012542 m^2/s^3. The wall boundary condition was defined on the surfaces describing the walls and bottom of the facility examined. On the free steel table surface, the wall boundary condition with zero shear stresses was used. The remaining boundary conditions assure the flow of liquid steel through the volume of the virtual model. In the computer simulation of liquid steel casting, the terrestrial gravity force was considered. For recording the hydrodynamic conditions in the tundish, a virtual tracer as described by the user-defined scalar (UDS) was used. The virtual tracer was added in to the liquid steel by ladle shroud. Variation in tracer concentration was recorded at individual tundish nozzles. A tracer concentration value signal red out during casting made up an information set, based on which C and F type steel residence time distribution (RTD) curves were plotted. The computer simulation was made using a double-precision segregated solver. The Simplec algorithm was used for the description of the relationship between pressure and flowing metal velocity. Computations were made using a computation server equipped with an AMD Opteron 2.01 GHz processor and an operating memory of 4 GBRAM. Physical quantities, such as density, viscosity, heat capacity, thermal conductivity and the coefficient of thermal expansion of liquid steel are as follows: ρ =7010, μ =0.007, C_p =750, k=41, β =0.0001. For the non-isothermal conditions of steel flow through 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 [16-24]. For all considered variants of non-isothermal simulations it was assumed that the temperature of steel flowing to the tundish was 1550°C.

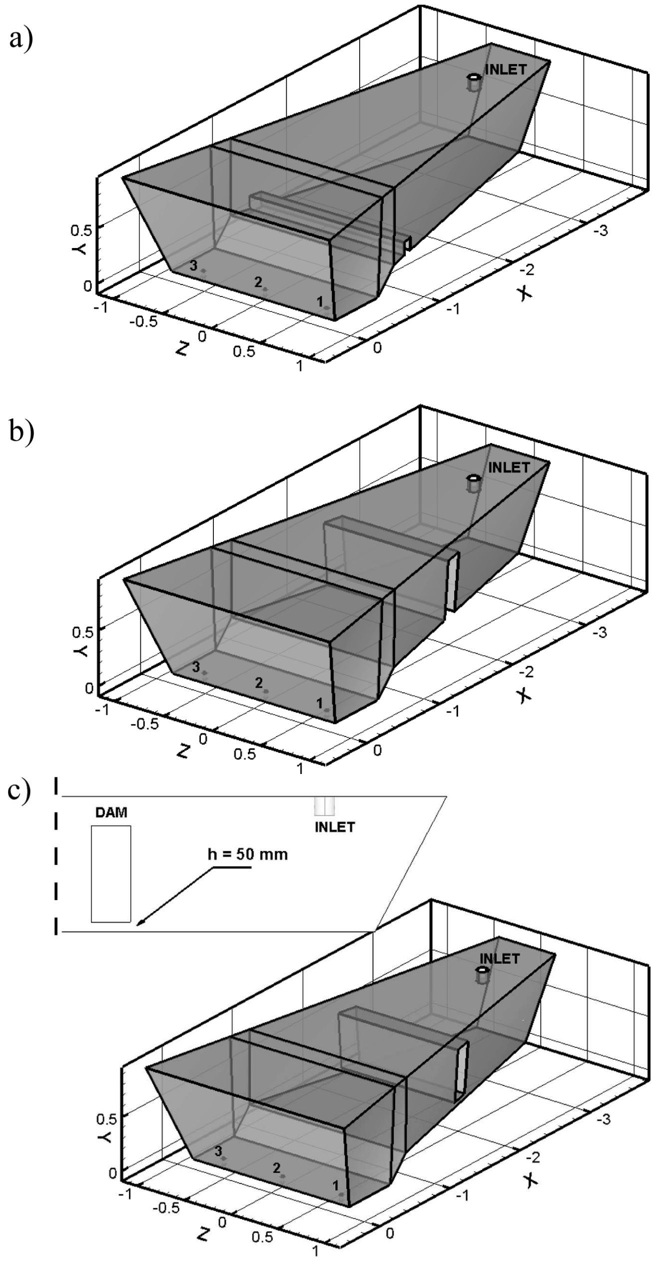

Fig. 1. Wedge-type bloom tundish (a) actually working in the steel plant (b) tundish with dam (c) tundish with modified dam

The basic mathematical model equations describing the phenomena under examination are as follows:

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

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

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

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

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

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

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

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-ε 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. An active flow zone (dispersed plug flow and well mixed volume flow) and a stagnant flow zone (dead volume flow) are distinguished within the volume of steel flowing through the tundish. From the point of view of tundish operation, the first of the zones needs to be the largest possible, as it assures the optimal conditions for the chemical and thermal homogenization of steel being cast. Moreover, the control of the liquid steel flow direction intensifies the carrying away of non-metallic inclusions present in the steel towards the refining and insulating powder [25]. The extent of the both zones is estimated based on the shape of the C-type RTD curve. For the quantitative analysis of tundish operation, the model proposed by Sahai and Emi, described in detail in paper [26], was employed. For the quantitative evaluation of particular flow volumes in the tundishes examined, formulas 9-13 [27-28] were used:

$$\frac{V_{stagnant}}{V} = 1 - \frac{Q_a}{Q}\cdot\bar{\theta}_C \tag{8}$$

$$\frac{V_{plug}}{V} = \frac{\theta_{\max} + \theta_{\min}}{2} \tag{9}$$

$$\frac{V_{idealmixing}}{V} = 1 - \frac{V_{stagnant}}{V} - \frac{V_{plug}}{V} \tag{10}$$

$$\frac{Q_a}{Q} = \sum_{\theta=0}^{2} C_i\Delta\theta \tag{11}$$

$$\bar{\theta}_C = \frac{\sum_{\theta=0}^{2} C_i\theta_t}{\sum_{\theta=0}^{2} C_i} \tag{12}$$

Based on the distribution of the F-type RTD curve, it is possible to describe the transient zone occurring in sequential casting of consecutive steel grades differing in chemical composition. According to Clark's model, this zone lies between the values 0.2 and 0.8 of the dimensionless tracer recorded at the tundish nozzle [29]. The smaller extent of the above-mentioned zone, the less steel is classified as a material intermediate between the steel grades being cast.

3. Industrial experiment

To verify the correctness of the computation results, an industrial experiment was carried out. During the successive casting of two steel grades differing in chemical composition, variation in the concentration of selected chemical elements was recorded. The industrial experiment was completed during two casting sequences: no.17830 [30] and no. 17831. During the first 5-heat casting sequence, the experiment was done between heats 2 and 3. Within the second 6-heat sequence, on the other hand, the experiment was done between heats 4 and 5. The industrial experiment involved taking of liquid steel samples by the operator and, after their solidification, making the chemical analysis of the steel on a quantometer. The metal samples were taken from the tundish. The measurement was made in the upper region of the metal volume above nozzle no. 1, at a depth of approx. 100 mm under the tundish powder. Knowing the initial concentrations of chemical elements, as recorded at the ladle furnace stand prior to the casting process, and the values recorded during the casting sequence, the process of liquid steel mixing in the actual industrial tundish was described. During the casting sequences under consideration, three 280×280 mm blooms were cast at a time at an average casting speed of 0.725 m/min and an average tundish liquid steel temperature of 1525°C. Figure 2 shows the results of the computer simulation and the industrial experiment, respectively. During the ladle treatment of the liquid steel, no modification to the chemical composition of the steel grades being cast was made. Because of this fact, the difference between the selected steel grades in the concentration of a majority of chemical elements was small enough as to allow them to be used as tracer elements. In the first casting sequence, as the tracer elements, Si, C, Mn and Cr were chosen, while in the second casting sequence, Mn and Cu. Unfortunately, of this group of elements, only Cu is a stable element, not undergoing oxidation during the steelmaking process. The mixing curves shown in Fig. 2 exhibit good agreement with the industrial experiment. In summary, the obtained results indicate that the numerical steel flow model is sufficient for the description of the hydrodynamic conditions occurring in the actual industrial plant. The resulted discrepancies might be due to the high affinity of Si, Mn, Cr and C to oxygen, or the simplicity of the mathematical model. The mathematical model employed in the computations does not consider, for instance, the fluctuations in the tundish steel level, or the change in casting speed during the actual casting process.

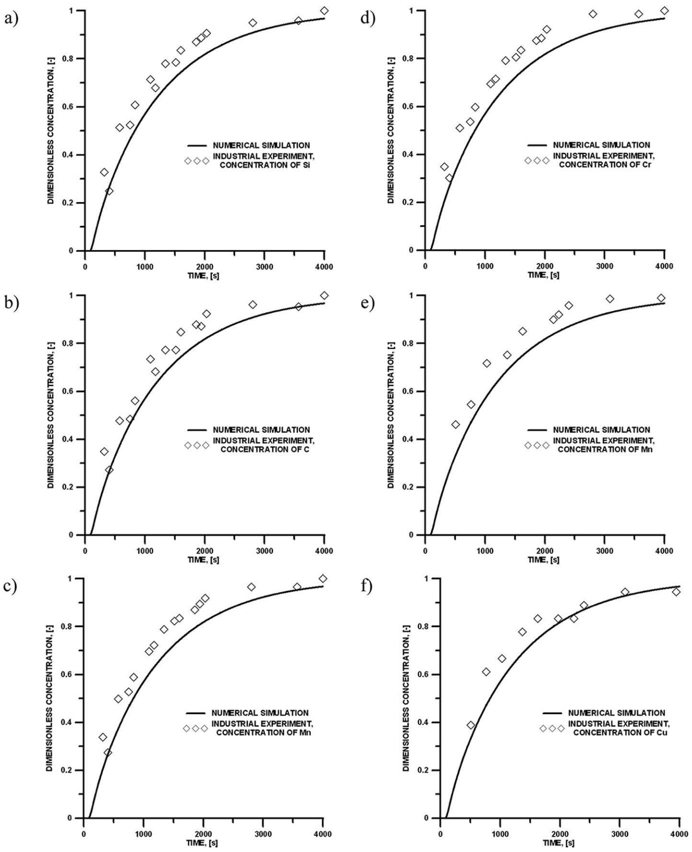

Fig. 2. Results of numerical simulation and industrial experiment. Mixing curve calculated by numerical simulation and concentration of chemical element measured during continuous casting sequence no. 17830 and 17831: (a) comparison with Si concentration during CS no. 17830 (b) comparison with C concentration during CS no. 17830 (c) comparison with Mn concentration during CS no. 17830 (d) comparison with Cr concentration during CS no. 17830, (e) comparison with Mn concentration CS during no. 17831, (f) comparison with Cu concentration during CS no. 17831

4. Computation results

Based on the computer simulation results, maps of liquid steel flow within the tundish and characteristics describing the hydrodynamic condition in the form of residence time distribution curves were developed. The simulation study results presented in the paper [31] describe the flow of liquid steel in the tundish being currently operated under industrial conditions that will be the reference in the assessment of the effect of the proposed modernization of the tundish internal space. Figure 3 shows the maps of liquid steel flow in the plane passing through the feed zone and the nozzle zone in the central tundish part. Figure 3a illustrates the tundish being currently in use in industrial conditions. Three regions of liquid steel circulation can be seen in Figure 3a. The first circulation region occurs in the mid-region between the feed zone and the low dam, immediately at the bottom. The second region can be noticed in the vicinity of the dam. In either case this is the effect of the mutual interaction of two streams: the feeding stream and the return stream flowing from the nozzle zone. The third circulation region is located above the nozzle region and results from the effect of the main steel stream on the side tundish wall and its partial return towards the free surface. A definitely descending behaviour of the main liquid steel streams is observed in the tundish. The tundish working space modified by using the designed dams is characterized by a liquid steel circulation zone before the dam on the feed zone and an ascending stream zone after the dam towards the nozzles. In the tundish with the high dam (Fig. 3b), the backward stream is cut off by the dam and does not reach the feed zone. The overflow window provided in the dam allows again the backward stream to penetrate into feed zone, thus intensifying the process of metal circulation within the tundish feed zone (Fig. 3c).

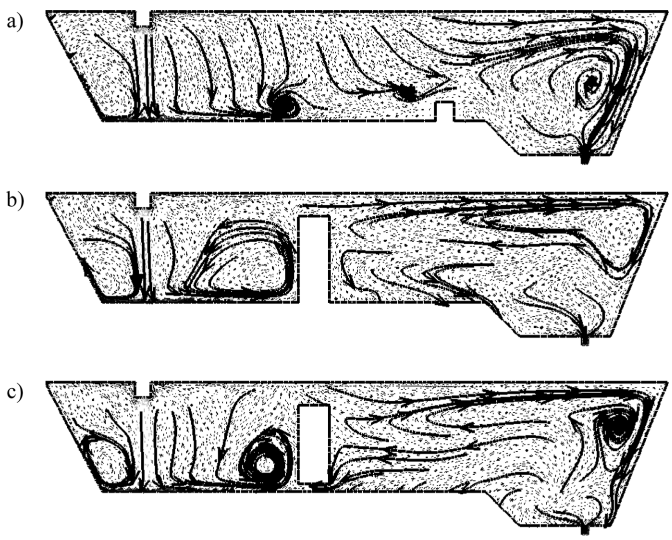

Fig. 3. Liquid steel flow in the central plane (a) in the tundish actually working in the steel plant (b) in the tundish with dam (c) in the tundish with modified dam

Figure 4 present C-type residence time distribution curves. Based on the obtained pattern of tracer concentration variations at the tundish nozzle, the conditions determining the liquid steel movement within the tundish working space can be successfully described. The proposed tundish reconstruction variants have most influenced the steel low hydrodynamics as recorded at nozzle 2. In addition, the use of the high dam with no overflow window has resulted in the curve peak to be shifted from the y axis, which indicates an increase in the volume of the active flow zone. The varying curve shapes recorded at individual nozzles, in particular for the high dam tundish variant, mean a diversification of liquid steel being cast through successive nozzles. Based on Sahai and Emi's model, the percentage shares of active and stagnant flows were computed, as presented in Table 2. The high dam mounted in the tundish resulted in a reduction in dead volume flow, as recorded at nozzle 2, by half compared to the tundish with the low dam. In the case of the overflow window-dam tundish, on the other hand, the volume of dead volume flow was reduced only slightly, i.e. by 1-3%, relative to the dead volume flow as computed for the low dam tundish. The proposed dams enlarge the dispersed plug flow region. In the case of the tundish corresponding to the second tundish equipment variant, the dispersed plug flow extent has increased by 27% and 6%, respectively, for nozzle 2 and for nozzles 1 & 3. The use of the overflow window in the dam causes the dispersed plug flow extent to be already not so large as for the high dam tundish. The both of the proposed dams cause a reduction in the percentage share of well mixed volume flow, especially in the tundish variant with no overflow window.

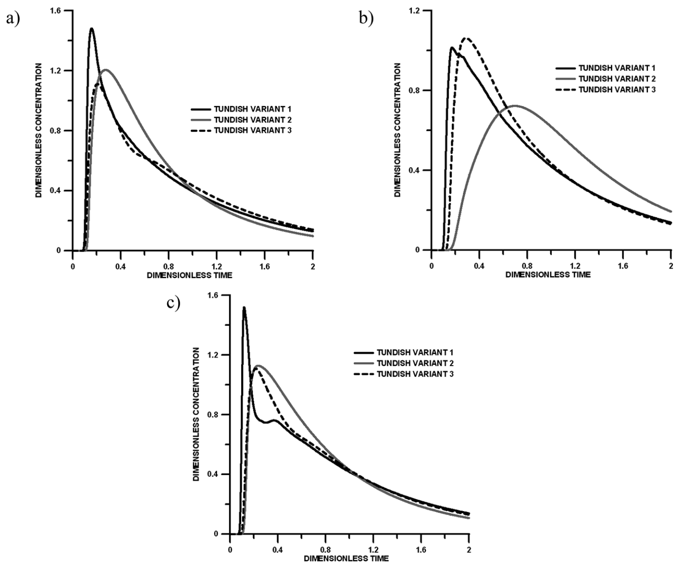

Fig. 4. Residence time distribution curve (a) tundish outlet no. 1 (b) tundish outlet no. 2 (c) tundish outlet no. 3

TABLE 1
Influence of modification of tundish working space on range of active and stagnant flow zone

No. of tundish variant	No. of tundish outlet	Percentage contribution, %		
		Stagnant flow	Plug flow	Ideal mixing flow
1	1	35.8	9.1	55.1
	2	33.4	9.8	56.8
	3	34.7	7	58.3
2	1	35.6	15.4	49
	2	16.5	36.4	47.1
	3	33.9	13.2	52.9
3	1	32.6	11.3	56.1
	2	31.7	15.7	52.6
	3	33.7	12.2	54.1

Figure 5 presents residence time distribution curves of the F type. From the shape of the curves it is noticed that a difference in the pattern of flow between the central nozzle 2 and the outermost nozzles 1 & 3 occurs in the high dam tundish. It is also visible that the variants of the tundish currently used in industrial conditions and the tundish with the overflow window baffle exhibit similar conditions of steel mixing within the tundish working space. Based on Clark's model, the transient zone span, as converted to continuous casting bloom mass, was computed (Table 2). The use of the high dam causes a reduction of the transient zone by 2.7 and 2.8 Mg for the outermost nozzles. The reduction of the transient zone in the high dam tundish amounted to only 1 Mg for central nozzle no. 2. Compared to the base tundish variant, it was noticed that the change of flow hydrodynamics was not favourable, because it diversifies casings as they are cast at the individual strands of the CSC caster. In the case of the overflow window-dam tundish, the reduction in the extent of the transient zone is much smaller than for nozzle no. 1, being only 0.2 Mg.

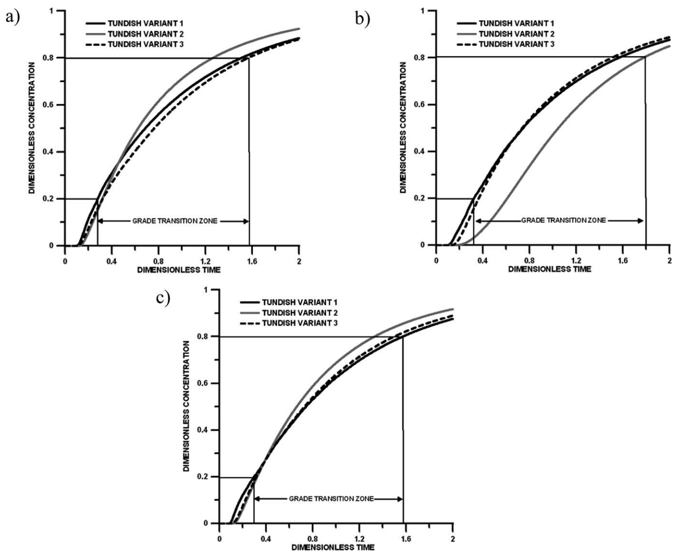

Fig. 5. Grade transition zone characteristic for all variants of presented tundish (a) tundish outlet no. 1 (b) tundish outlet no. 2 (c) tundish outlet no. 3

TABLE 2
Influence of modification of tundish working space on range of grade transition zone

No. of tundish variant	No. of tundish outlet	Range of transition zone, s	Length of casting steel strand, m	Weight of casting steel strand, Mg	Reduction of grade transition zone, Mg
1	1	1560	19.5	10.7	-
	2	1578	19.7	10.8	-
	3	1617	20.2	11.1	-
2	1	1164	14.5	7.9	-2.8
	2	1439	17.9	9.8	-1
	3	1239	15.4	8.4	-2.7
3	1	1538	19.2	10.5	-0.2
	2	1410	17.6	9.6	-1.2
	3	1462	18.2	10	-1

5. Summary

From the performed computer simulations of liquid steel flow, valuable information about tundish operation and the effect of the proposed flow control devices has been obtained:

- The main streams of liquid steel in the tundish currently operated under industrial conditions show a descending pattern;
- In the tundish with the low dam, 1/3 of the volume of steel flowing through the tundish are taken up by dead volume flow;

- The flow control devices proposed for the modification of the tundish working space influence the direction of liquid steel flow;
- The proposed high dam causes an increase in the volume of dispersed plug flow;
- In the tundish with the high dam, a diversification of hydrodynamic conditions as recorded at the individual tundish nozzles is observed;
- The use of the dam provided with an overflow window has caused a unification of the flow pattern at all tundish nozzles;
- The proposed overflow window dam has a slight effect of eliminating the dead volume flow region and reducing the transient zone extent.

The presented results indicate that the modification of the flow pattern in multi-nozzle tundishes is extremely difficult, chiefly in terms of achieving a uniformed pattern of low at all tundish nozzles. So, there is a real need to work out a trade-off between the intensive stimulation of active flow zones and the repeatability of hydrodynamic conditions at all tundish nozzles. Therefore, the use of CFD methods for seeking the optimal design solutions is of great importance to the improvement of the continuous steel casting technology.

Nomenclature

C_i – Concentration of the tracer, dimensionless (-)
C_p – Heat capacity (J/kg·K)
D_i – Diffusion coefficient of the tracer (m^2/s)
g – Gravitational acceleration (m/s^2)
h – Species enthalpy (J/mol)
I – Unit tensor
J_j – Diffusion flux (kg/m^2·s)
k_{eff} – Effective heat capacity (W/m·K)
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)
t – Time (s)
T – Temperature (K)
T_0 – Initial temperature (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 dead plug in the tundish (m^3)
$V_{ideal\,mixing}$ – Volume of mixed region in the tundish (m^3)
ρ– Density (kg/m^3)
ρ_0– Initial density (kg/m^3)
μ– Viscosity (kg/m·s)
β– Coefficient of thermal expansion (1/K)
$\overline{\overline{\tau}}$– Stress tensor (Pa)
$\overline{\overline{\tau}}_{eff}$– Effective stress tensor (Pa)
$\overline{\theta}_C$– 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 (-)

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