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A. CWUDZIŃSKI*,#

NUMERICAL AND PHYSICAL SIMULATION OF LIQUID STEEL BEHAVIOUR IN ONE STRAND TUNDISH WITH SUBFLUX TURBULENCE CONTROLLER

SYMULACJA NUMERYCZNA I FIZYCZNA ZACHOWANIA SIĘ CIEKŁEJ STALI W JEDNO-WYLEWOWEJ KADZI POŚREDNIEJ Z PODSTRUMIENIOWYM REGULATOREM TURBULENCJI

This paper presents the results of computer simulations (Ansys-Fluent) and laboratory experiments (physical water model) carried out to describe the motion of steel flow in the tundish. The facility under investigation is a single-nozzle slab tundish. The internal geometry of consider object was changed by flow control device i.e. subflux turbulence controller (STC). In order to obtain a complete hydrodynamic picture in the tundish furniture variants tested, the computer simulations were performed for both isothermal and non-isothermal conditions. From the performed computer simulations and laboratory experiments (physical modeling) it can be found that, the non-isothermal conditions occurring during continuous steel casting will definitely influence the hydrodynamic pattern forming in the tundishes with STC.

Keywords: tundish, steel flow, numerical simulation, physical modeling

Praca przedstawia wyniki symulacji komputerowej (program Ansys-Fluent) i eksperymentów laboratoryjnych (fizyczny model wodny) opisujące ruch ciekłej stali w kadzi pośredniej. Badanym obiektem jest jedno-wylewowa kadź pośrednia przeznaczona do odlewania wlewków płaskich. Geometria wewnętrzna kadzi pośredniej była zmieniona poprzez zastosowanie urządzenia sterującego przepływem w formie podstrumieniowego regulatora turbulencji. Celem otrzymania kompletnego obrazu struktury hydrodynamicznej powstającej w poszczególnych wariantach kadzi pośredniej symulacje komputerowe wykonano dla warunków izotermicznych i nieizotermicznych. Na podstawie wykonanych symulacji komputerowych i eksperymentów laboratoryjnych (modelowanie fizyczne), stwierdzono, że warunki nieizotermiczne powstające podczas ciągłego odlewania stali będą zdecydowanie oddziaływać na strukturę hydrodynamiczną w kadziach pośrednich z podstrumieniowym regulatorem turbulencji.

1. Introduction

The continuous steel casting (CSC) process enables the effective production of continuous slabs, blooms and billets. The effectiveness of the CSC process is defined by the amount of cast steel free from any external and internal defects in relation to the incurred costs. The CSC technology is a complex method of casting steel semi-finished products due to a considerable number of factors affecting the steel at the individual stages of the technological sequence [1-5]. The continuous steel casting machine consists of a tundish, a mould and a secondary cooling zone. During its residence in the tundish, the liquid steel interacts with the refractory lining of the tundish and the flow control devices and the tundish powder. Therefore, the refractory lining is expected to have adequate leaching resistance, while the powder is expected to exhibit the efficient assimilation of non-metallic inclusions. Both the refractory lining and the tundish powder should provide thermal insulation for the liquid steel. In the case of the primary and secondary cooling zones, where the liquid steel solidifies, the quality of the continuous casting is determined chiefly by the thermal conditions. The quantity of heat and the way in which it is taken away from the liquid steel determines the structure of the continuous casting. On the other hand, the effective liquid steel cooling process is limited by: the chemical composition of the mould powder, the size of the air gap, the construction of the mould, the format of the castings being cast, the casting speed, the chemical composition of the steel being cast, the number of mould oscillations or the type of air-water nozzles employed in the secondary cooling zone. In view of the above, many research centres conduct both model studies (numerical and physical simulations), as well as industrial tests [6-11]. This paper presents research results describing the subflux turbulence controller (STC) on the hydrodynamic pattern formed in the one-strand tundish during continuous casting of slabs.

* CZESTOCHOWA UNIVERSITY OF TECHNOLOGY, FACULTY OF PRODUCTION ENGINEERING AND MATERIALS TECHNOLOGY, DEPARTMENT OF METALS EXTRACTION AND RECIRCULATION, 19 ARMII KRAJOWEJ AVE, 42-200 CZESTOCHOWA, POLAND
# Corresponding author: cwudzinski@wip.pcz.pl

2. Characterization of the test facility

The facility under investigation is a single-nozzle tundish designed for casting concast slabs (fig.1a). The nominal capacity of the tundish is 30 Mg. Currently, the tundish is furnished with a low dam installed before the bottom step in the stopper rod system area. The height of the low dam is 0.12 m. The dam incorporates two 0.14×0.05 m overflow windows arranged symmetrically relative to the tundish axis. On the pouring zone side, the tundish is furnished with an overflow trough that protects the tundish against overfilling. The tundish shape resembles a wedge narrowing towards the pouring zone. The submerged entry nozzle discharge orifice and the ladle shroud pouring gate are located in the tundish axis at a distance of 2.915 m from each other. The inner diameters of the openings supplying liquid steel to the tundish and to the mould are identical, being equal to 0.07 m. For the validation of the numerical model and verification of the hydrodynamic conditions occurring in the examined tundish furniture variants, obtained from the computer simulations, a physical model of the tundish was employed (fig.1b). The tundish model was made on a scale of 2:5. The tundish model's nominal capacity is 210 litres. Figures 1c-f show the tundish furniture variants on a scale of 1:1, which are intended for numerical simulation. A tundish with subflux turbulence controller (STC) in the form of virtual models was prepared for numerical simulations using the Gambit 2.4 software program.

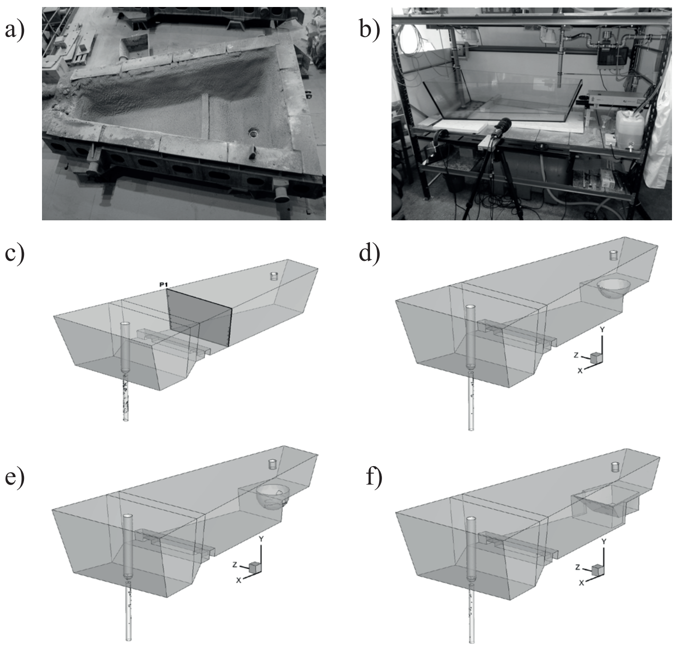

Fig. 1. Test facility: a) industrial tundish, b) physical model of tundish, c) virtual model of tundish with low dam and measurement plane (P1), d) virtual model of tundish with STC no. 1, e) virtual model of tundish with STC no. 2, f) virtual model of tundish with STC no. 3

3. Testing methodology

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

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

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

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

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

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

$$\rho = 8300 - 0.7105T \tag{6}$$

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

where: C_i - concentration of the tracer (kg), $\overline{\overline{\tau}}$ - stress tensor (Pa), $\overline{\overline{\tau}}_{eff}$ - effective stress tensor (Pa), k_{eff} – effective thermal conductivity (W/m×K), I - unit tensor, μ - viscosity (kg/m×s), D_i - diffusion coefficient of the tracer (m^2/s), ρ - density (kg/m^3), ρ_0 - initial density (kg/m^3), u - velocity of the steel flow (m/s), t - time (s), E - energy (J), g - gravitational acceleration (m/s^2), p - pressure (Pa), T - temperature (K), h – enthalpy (J), Jj - diffusion flux (kg/m^2×s).

In non-isothermal computation, polynomial density model was employed, which is described by equation 6. 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. The wall condition with zero tangential stress was assumed on the free steel table surface. User defined scalar (UDS) transport equation and Species model were used to calculation the motion of the tracer in the liquid steel. For the description of the turbulence of steel flow through the tundish, the Realizable k-ε turbulence model were adopted. In the Realizable k-ε turbulence model constants take on the following values: C_2=1.9, σ_k=1.0, σ_ε=1.2 [11]. Physical quantities of liquid steel as follows: viscosity 0.007 kg/m·s, heat capacity of steel 750 J/kg·K, thermal conductivity of steel 41 W/m·K. At the inlet tundish, liquid steel inflow of 1.316 m/s was assumed with turbulence kinetic energy 0.0173 m^2/s^2 and energy of dissipation rate of kinetic energy 0.065137 m^2/s^3. The initial liquid steel velocity corresponded to the sequence of continuous casting of 1.5×0.225 m concast slabs at a speed of 0.9 m/min. The initial liquid steel temperature in the non-isothermal computer simulation was 1823 K. The system of equations forming the mathematical model of steel flow was solved by the method of control volumes by employing discretization of the second order upwind using the sequential solver. The Semi-Implicit Method for Pressure-Linked Equations-Consistent (SIMPLEC) algorithm was used for the description of the coupling of the pressure and velocity fields in the model being solved. The controlled level of residues was at a level of at least 10^{-3}. The condition to comply with the impassable y+ parameter values (30÷60) indicating the correct choice of the grid in the wall boundary layers was also respected. According to the similarity criteria, the medium simulating the liquid steel was water, which, at a temperature of 20°C, has the identical kinematic viscosity to that of liquid steel. Studies on the water model were conducted while satisfying the Froude criterion, which ensured that the similarity between the inertial forces and the gravity forces occurring in the physical model and those prevailing in the metallurgical plant tundish was maintained. Within the conducted "IuventusPlus" project, the physical tundish model was additionally equipped with a 2DPIV (2D Particle Image Velocimetry) vector flow field recording and analysis system supplied by Lavision. For the analysis of the vector flow field the DaVis 8 software program with the 2DPIV module was employed. Seeding in the form of 10 mL glass balls of a density of 1100 kg/m^3 (± 50 kg/m^3) and an average diameter from 9 to 13 mm was introduced to the water flowing through the physical model of tundish. The job of the seeding was to fill up the flow fields "cut" with the light knife in the working space of the model. After attaining a steady flow field in the working space of the physical tundish model, the laser was activated, whose beam passing through the optical system formed a light plane in which glass ball motion trajectories were recorded. The employed glass balls flowed following the flow directions that formed in the examined water stream field. Then the camera was started, which was furnished with a filter adapted to the wavelength emitted by the laser, eliminating any environmental interference during recording. In the next stage of analysis, the recorded glass ball motion was transformed into the vector field form using the 2DPIV module.

4. Isothermal simulation and model validation

The numerical model was verified using the PIV method which was used during simulation in the physical tundish model. The plane situated in the central tundish plane reduced down to the dimensions of 0.525×0.4 m, was chosen for experimental studies. The measurement plane was situated at a height of 0.2625 m above the tundish bottom level and 0.0375 m beneath the liquid steel surface. Whereas, in the case of its position relative to the FCD, it was located before the dam, as seen from the poring zone side, and immediately after the STC installation area, as seen in the stopper rod system direction. The analysis of the flow pattern in the dam tundish, as shown in Figures 2a-b, confirms the good agreement between the results obtained by both examination methods. In both cases, a descending behaviour of the liquid steel and water streams was obtained. Figure 2c-d shows vector flow fields in the tundish with STC no. 1. In the measurement region, the reverse stream coming back from the dam region flows up to the pouring zone and then, in the upper part of the liquid steel volume, flows back to the tundish nozzle. Also in this case, the PIV examination has shown that at the interface of individual streams making up the flow pattern clashing with one another, small sites of liquid steel circulation may form in a given region of the liquid steel volume. In the tundish furniture variant with STC no. 2 (fig.2e-f), both the mathematical model and the physical model predict the occurrence of a liquid steel circulation region between the streams heading for the stopper rod zone and the streams flowing from the bottom towards the free surface. So, computer simulations done using the Realizable k-e model may also predict the formation of small, localized and atypical liquid steel circulation patterns. In the last tundish furniture variant, the facility was equipped with STC no. 3. In the central plane, within the range of recording of the vector flow field, the liquid steel streams flow towards the tundish bottom. A similar pattern for water flow was obtained from the physical model (fig.2g-h).

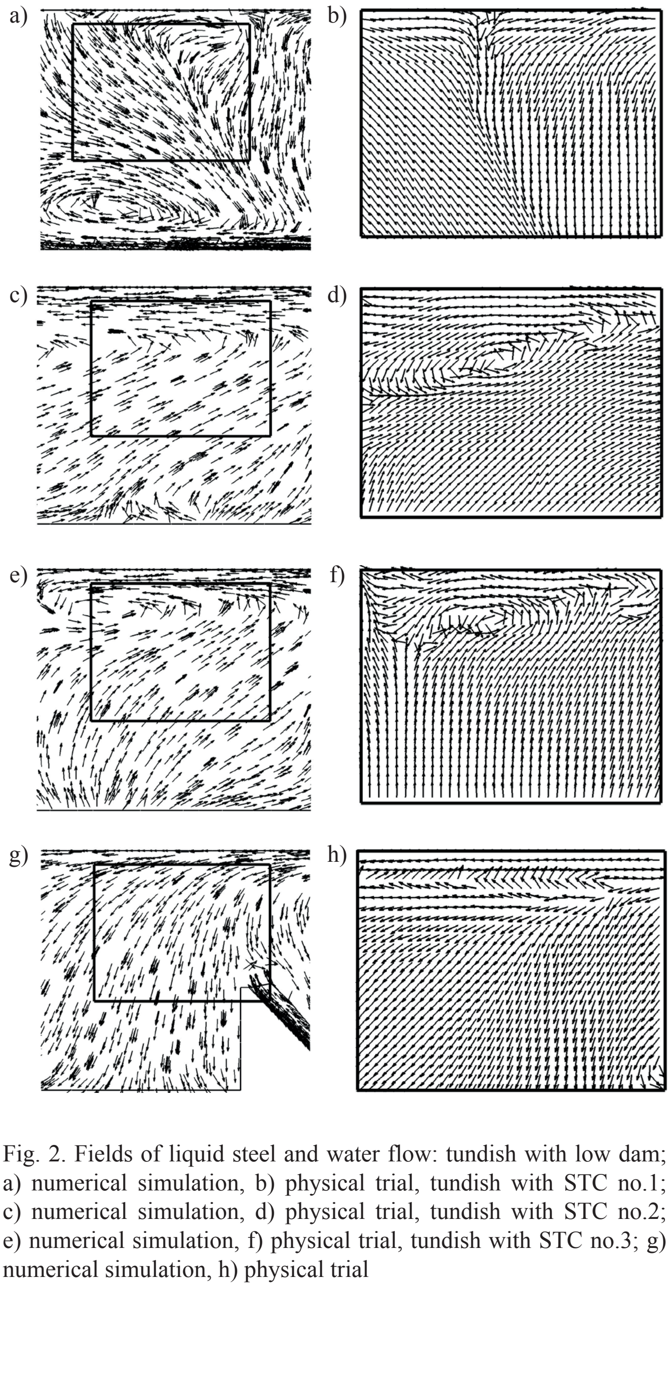

Fig. 2. Fields of liquid steel and water flow: tundish with low dam; a) numerical simulation, b) physical trial, tundish with STC no.1; c) numerical simulation, d) physical trial, tundish with STC no.2; e) numerical simulation, f) physical trial, tundish with STC no.3; g) numerical simulation, h) physical trial

For the complete verification of the correctness of the results obtained from the computer simulations, complementary laboratory experiments were carried out for all of the tundish furniture variants examined in the study. In the experiments done using the physical model, the residence time curves were determined. Figure 3 shows E–type RTD curves obtained from numerical and physical simulations. The presented characteristics confirm the good agreement between the results describing the hydrodynamic state of the examined facility according to the numerical simulations and the pattern recorded during the physical modelling. However, in some tundish furniture variants, a shift of the peaks of the E RTD curves obtained from the computer simulations relative to RTD characteristics recorded in the physical model was obtained [12]. In this connection, additional computer simulations were performed, in which the "Species" model was used for determining the RTD characteristics. Based on the analysis of the shape of the RTD curves and the position of their peaks, it has been found that the "Species" model shows hydrodynamic conditions similar to those of the physical model, which occur in the tundish working space. The both numerical models are characterized by some deviations from the results obtained from the laboratory experiment. However, they complement one another and confirm the usefulness of the employed software for the analysis of the hydrodynamic pattern that forms in the actual industrial facility.

The pattern of liquid steel flow in the tundish is formed by the main feed stream, the sides streams and the reverse streams. Therefore, in order to correctly evaluate the whole of liquid steel motion in the tundish working space, a detailed analysis of the vector field of flow in characteristic locations of the examined facility is needed. Plane no. 1 is distant from the axis of the ladle shroud, 1.4675 m towards the stopper rod system (fig.1c). Figure 4 represents the vector field of liquid steel flow in the plane (P1) in dam tundish and tundishes with STC for isothermal conditions. Initiated in the pouring zone, the circulatory motion from the longitudinal side wall towards the tundish centre evolves in the subsequent regions of the tundish working space. Consequently, a liquid steel movement descending towards the bottom is visible in the central part of the tundish, which is the result of swirling of the steel and the formation of two steel circulation regions between the longitudinal side walls, the bottom and the free surface (fig.4a). In tundish with STC no. 1 main feed stream leaves the controller-affected region and is split into two streams flowing closely to the free surface along the longitudinal side walls, and only upon reaching the stopper rod zone does it fall down towards the tundish nozzle. The remaining side streams fall down progressively towards the bottom over the section from the dam to the STC, initiating the process of forming steel circulation regions. It is the effect of the steel turning back also in the direction transverse to the tundish axis and from the side walls to the central tundish part (fig.4b).

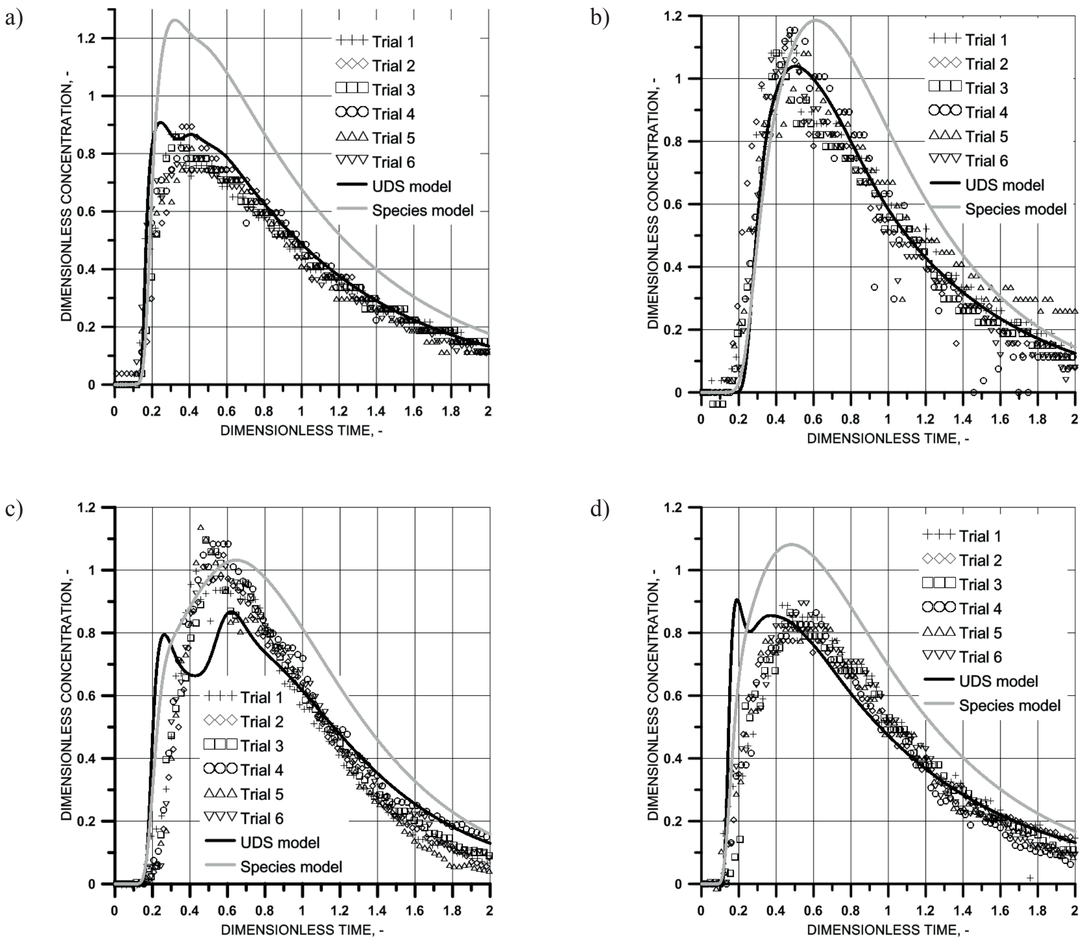

Fig. 3. RTD curve: a) tundish with low dam, b) tundish with STC no.1, c) tundish with STC no.2, d) tundish with STC no.3

In the central part of tundish with STC no. 2, directing of the stream to the free surface is observed. The change of the flow directions from down to up, progressing from the tundish wall towards the longitudinal axis, results in the formation of two liquid steel circulation zones in the vertical transverse planes (fig.4c). By contrast, in the zone between the dam and STC no. 3, part of the side streams descending towards the bottom are separated from the main stream, whereby a steel circulation region forms then in the transverse vertical planes (fig.4d). In this case, the motion takes place from the bottom to the free surface, conversely to that for the tundish with STC no. 1 and 2.

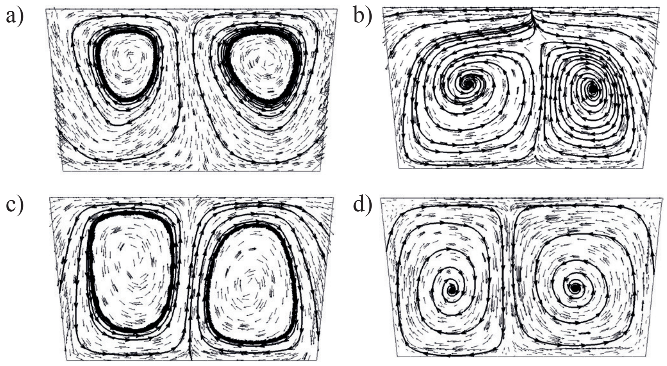

Fig. 4. Fields of liquid steel flow for isothermal conditions on transversal plane no. 1: a) tundish with low dam, b) tundish with STC no. 1, c) tundish with STC no. 2, d) tundish with STC no. 3

5. Nonisothermal simulation

This section reports the results of computer simulation of the liquid steel flow through the tundish under non-isothermal conditions. To illustrate the variations of the temperature and velocity of liquid steel within the tundish working space, a measurement line located at a height of 0.46 m from the tundish bottom was determined. The measurement line is located in the central part of the tundish and encompasses the pouring zone and the stopper rod system's zone. Figure 5 represents the variations of liquid steel temperature and velocity in the tundishes with a dam and a selected subflux turbulence controller. Due to their influence on the feeding stream, the employed STCs have reduced the flow turbulence and the velocity components of the streams circulating in the tundish working space beyond the feed zone. In the tundishes with the proposed STCs, the velocity of liquid steel flow in the examined region beyond the pouring zone does not exceed 0.02 m/s. Through their effect on the directions of liquid steel motion, the STCs modify the thermal conditions in the working space, causing changes in the value of temperature in selected working space regions of tundish. In the zone immediately after the STC, the difference in the value of liquid steel temperature between the tundish dam variant and the tundishes additionally furnished with STC no. 1 and no. 2 amounted to 3.5 K. In contrast, in the stopper rod system zone, in the region under examination, the values of liquid steel temperature in respective tundish variants are similar. Therefore, the reduction of the velocity of liquid steel flow, in conjunction with the occurring local temperature gradients, will have an additional effect of modifying the hydrodynamic pattern in the tundish with the STC.

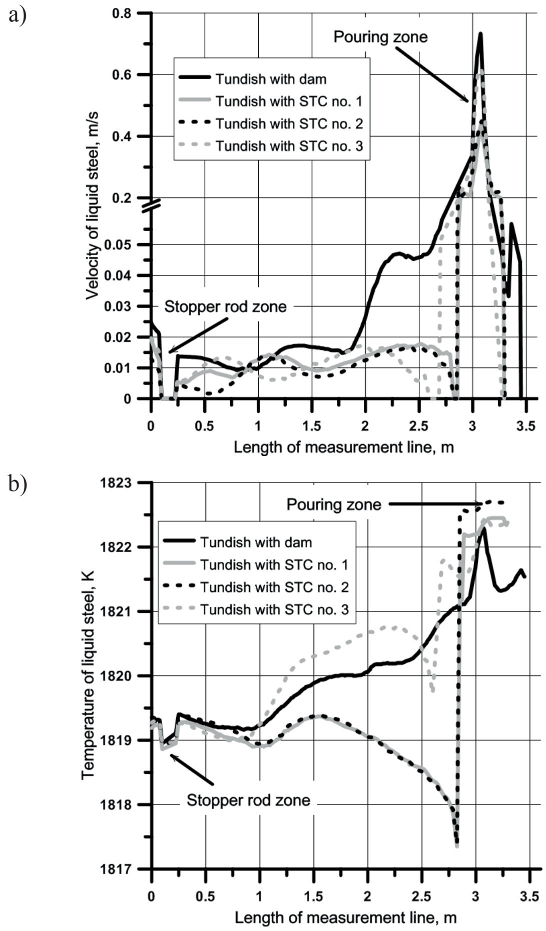

Fig. 5. Measurement line in the internal working space of tundish: a) distribution of liquid steel velocity, b) distribution of liquid steel temperature

The continuous steel casting process is unquestionably a non-isothermal process, in which, due to the continuous flow of heat fluxes between the liquid, solidifying and solidified steels and foreign non-metallic phases, the refractory lining or P-Ni-Cr walls and the environment, temperature gradients come to occur in the material being formed. As has been demonstrated by analysis made in work [13], the non-isothermal conditions may also affect the hydrodynamics of liquid steel flow in the tundish. In view of the above, non-isothermal simulations were carried out for the proposed tundish furniture variants using the Realizable k-e turbulence model recommended for computations [14]. The greatest variety in flow pattern between successive tundish working space furniture variants was observed in the P1 plane. The measurement plane P1 is located at a distance of 1.44 m from the stopper rod system, where a reduction of liquid steel flow velocity was recorded in the tundishes with the STCs. The location of the P1 plane in the dam region enables the observation of the effect of liquid steel temperature and velocity on the formation of steel motion hydrodynamics, whereby, at a distance of 1.46 m from the pouring zone, the inertial forces diminish, while convective forces start predominating. So, steel circulation motions both symmetric (fig.6a) and asymmetric (fig.6b-d) relative to the tundish axis occur in the examined region. In addition, complex steel circulation systems form, which move either in the horizontal (fig.6b-c) or in the horizontal and vertical (fig.6d) plane with respect to the bottom.

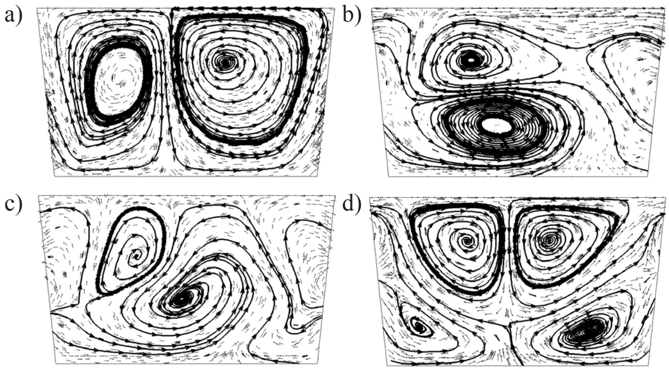

Fig. 6. Fields of liquid steel flow for non-isothermal conditions on transversal plane no. 1: a) tundish with low dam, b) tundish with STC no. 1, c) tundish with STC no. 2, d) tundish with STC no. 3

6. Summary

From the performed computer simulations and laboratory experiments (physical modeling) it can be found that:

- the physical tundish model with a PIV measuring system has enabled the effective validation of the numerical model and provided additional information on the behaviour of liquid steel in the tundish;
- the non-isothermal conditions occurring during continuous steel casting will definitely influence the hydrodynamic pattern forming in the tundish;
- the designed STCs influence not only the direction of liquid steel flow, but also its velocity; therefore, under non-isothermal conditions, the field of liquid steel flow will be additionally modified by the forces of natural convection.

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