M. WARZECHA

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NUMERICAL AND PHYSICAL MODELLING OF STEEL FLOW IN A ONE-STRAND CONTINUOUS CASTING TUNDISH

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The article presents the results of numerical and water model studies of a steel flow in a one-strand continuous casting tundish. The flow field measurements are obtained at a 1:3 scale water model of the tundish with the Laser-Doppler Anemometry (LDA) method, during steady-state casting. The LDA-measurements are performed using the Reynolds-similarity criterion. Numerical simulations of the three-dimensional turbulent fluid flow in a tundish are carried out with the finite-volume commercial code FLUENT. Mathematical model, validated with experimental results, is used to simulate liquid steel flow through a 1:1 scale industrial facility – a 16 t tundish.

Key words: tundish, continuous casting, numerical modeling, physical modeling

Numeričko i fizikalno modeliranje protjecanja čelika u međuloncu uređaja za kontinuirano lijevanje s jednom žilom. U radu se prikazuju studije numeričkog i vodenog modela protjecanja čelika u međuloncu konti lijeva s jednom žilom. Mjerenja polja protjecanja provedena su na vodenom modelu međulonca u mjerilu 1:3 pomoću Laser-Doppler Anemometrijske (LDA) metode, tokom stacionarnog lijevanja. LDA mjerenja provedena su korištenjem Reynoldsovog kriterija sličnosti. Numeričke simulacije trodimenzionalnog turbulentnog toka u međuloncu provedene su pomoću komercijalnog programa konačnog volumena FLUENT. Matematički model, potvrđen eksperimentalnim rezultatima, korišten je za simulaciju protjecanja tekućeg čelika u međuloncu industrijskog kapaciteta 16 t, u mjerilu 1:1.

Ključne riječi: međulonac, kontinuirano lijevanje, numeričko modeliranje, fizikalno modeliranje

INTRODUCTION

Constantly increasing customers demands for the production of high and very high-quality steels, promote the intensive technological development of their production. Since the dominating method of global steel production is continuous casting, the tundish has become very important metallurgical unit. Nowadays, tundish is not only a storage vessel which guaranty the continuous casting of steel, but it become an additional metallurgical stage where other operation are performed. These operations are for example control of melt temperature, composition and melt flow control to promote non metallic inclusion separation. The melt flow is the key factor to control the inclusions flotation.

Investigations of steel flow or inclusions separation process at the industrial plant are nearly impossible because of the high temperature and a lack of optical accessibility. For this reason the investigations are performed with physical modelling and numerical simulations. Investigations with water models are already well known and widely applied [1-4]. Water can be used to model liquid steel because the kinematic viscosities of both fluids are similar ($\nu_{st.1536°C}$ = 8,26·10^{-7} m^2/s, $\nu_{w.20°C}$ = 10,0·10^{-7} m^2/s). So far tundish water models were used for qualify as well as quantify investigations. Flow visualisation and measurements of the residence time distributions, transient zone, influence of different flow control devices on steel flow, or particle separation are the examples. Physical models are often combined with mathematical model since the accuracy of the numerical simulation in describing investigated phenomena is validated with water model experimental results.

A large number of tundish flow and particle separation studies have been performed with using mathematical modelling as well [5-7]. An extensive development of numerical studies is an effect of dynamic development of the computers computational power parallel with development of computational codes. In mathematical modelling, the fluid flow is described by the Reynolds Averaged Navier-Stokes equations (RANS) and turbulence model.

The results of physical and numerical modelling presented in this article are carried out to investigate the steel flow in a one-strand tundish for steady-state casting conditions. First, Laser-Doppler Anemometry (LDA) measurements of the flow field of a 1:3-scale water model of the tundish are carried out. Then, the results are used to validate the numerical model used to predict an isothermal water flow in a tundish model. Properly validated numerical model is used for modelling steel flow in the industrial plant tundish.

M. Warzecha, Department of Metals Extraction and Recirculation, Czestochowa University of Technology, Czestochowa, Poland

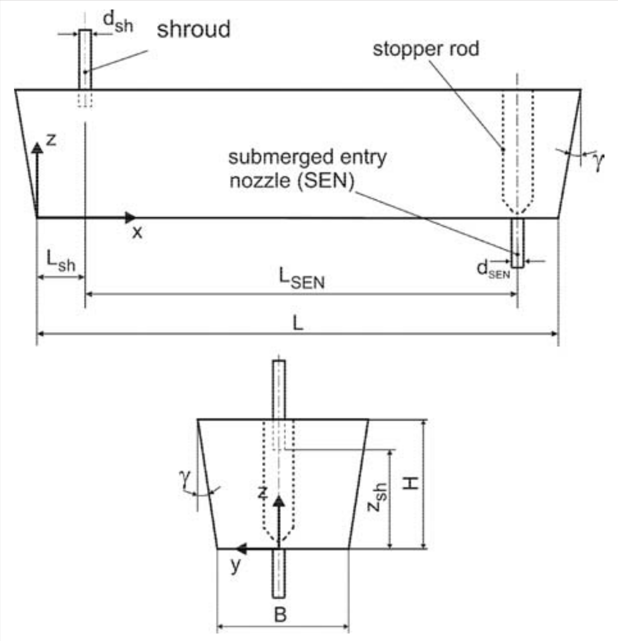

Figure 1 Illustration of the shape and dimensions of the tundish

INVESTIGATED TUNDISH

The investigated object is a one-strand tundish characterized by a molten steel mass flow rate more than 136 Mg/h.

The nominal capacity of the tundish is 16 Mg of liquid steel. Tundish is symmetrical relative to the longitundial plane.

The dimensions of the original tundish and its water model are shown in Figure 1 and summarized in Table 1.

WATER MODEL EXPERIMENT

The results of experimental measurements done with water model are the basis for the validation of a numerical model. For the investigated object, a 1:3-scaled tundish water model is used. This model can be operated with either an open or closed circuit. For fluid flow measurements, model is operated with closed circuit. In this case, water flow out of the tundish through the SENs, past the pump, flow meter, and flow back into the tundish through the shroud.

For measuring the fluid flow field, LDA method is used. LDA is a laser optical technique with a high spatial and temporal resolution that gives information about flow velocity and turbulence. For measurements, the 3D-LDA system consists of a 5W-Ar-ion laser with a 6-beam Fiber Optic flow, based on a 3D-traversal was used. More detailed information about used equipment can be found elsewhere [8].

For fluid-dynamic similarity, the Reynolds similarity is used. The Reynolds number describes the dynamic flow behavior, comparing the ratio of inertia to friction forces. Using the kinematic viscosity ν of the fluid and the hydraulic diameter d_{hyd} of the cross section of the tundish, the volumetric flow rate in the water model is derived as follows:

$$\dot{V}_w = \dot{V}_{st} \cdot \frac{d_{hyd,w}}{d_{hyd,st}} \frac{\nu_w}{\nu_{st}} \tag{1}$$

where the indices *w* and *st* refer to water and steel. Regarding the Reynolds similarity criteria, the volumetric flow rate, at the shroud, increases in a reduced model. This leads to the occurrence of strong surface waves at the inlet range and, in turn, to a formation of air bubbles which affect the measurements negatively. Therefore investigations with a reduced volume flow rate are carried out. The fluid-dynamic data are given in Table 2.

Table 1 **Dimensions of the 16 Mg tundish and the 1:3 scale water model**

	Symbol/ unit	tundish	
		1:1	model (1:3)
volume of tundish at filling level H	V / m^3	2,275	0,084
tundish length	L_1 / m	3,140	1,047
tundish width	B_1 / m	0,780	0,26
inclination of the side walls	γ / °	7	7
filling level for steady-state casting	H / m	0,8	0,266
shroud-bottom distance	z_{sh} / m	0,6	0,2
shroud position	L_{sh} / m	0,335	0,122
shroud diameter	d_{sh} / m	0,068	0,023
SEN position	L_{SEN}/ m	2,885	0,962
SEN diameter	d_{SEN} / m	0,070	0,023

MATHEMATICAL MODELING

General equations

Numerical simulations are carried out on the basis of the Reynolds averaged Navier-Stokes (RANS) equations for incompressible fluid. The liquid phase is described by the equations in the Euler formulation. Since the fluid flow in the continuous casting tundish is considered to be turbulent, the realizable k-*ε* model from Shih et al. [9] is combined with the RANS equations. Former investigations [10-12] showed that this model describes well steady-state flow field in the tundish.

Table 2 Data for original tundish and water model experiment

	Unit	tundish	
		1:1	model (1:3)
density	kg · m^{-3}	7 038	998,2
viscosity	m^2 · s^{-1}	$8{,}7\times10^{-7}$	$10{,}1\times10^{-7}$
volume flow rate	dm^3 · s^{-1}	5,4	1,0
inlet velocity	m · s^{-1}	1,49	2,407
mean residence time	s	421	84
Reynolds number	-	10 350	5 172

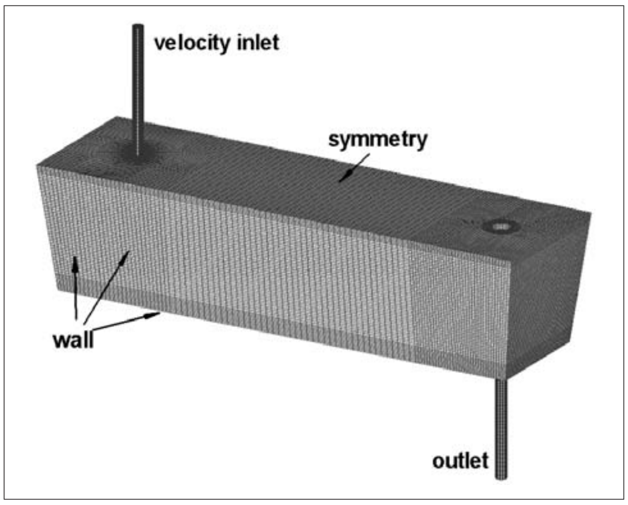

Figure 2 Structured mesh with boundary conditions used for the simulations

Initial and boundary conditions

At the inlet shroud, the velocity of the incoming fluid is set (see Table 2) with a turbulent intensity of 3 percent. All walls and the bottom of the tundish have stationary wall boundary condition for the velocity components and the turbulence quantities using Launder and Spalding's standard wall function [13]. During experiments performed with the water model, it can be seen that water surface is relatively calm for the investigated volumetric flow rate and remain almost flat, with exception of small inlet zone. Therefore, no special model for the free surface is needed. Water surface is assumed to be flat and is modeled with a symmetry boundary condition.

For tundish model, a block-structured computational mesh with 450,000 computational cells is used. Mesh together with boundary conditions is shown in Figure 2.

The other parameters and boundary conditions used for the simulations of the fluid flow in the tundish model are listed in Table 2.

RESULTS AND DISCUSSION

The presented investigations are focused on steady-state casting conditions.

The flow field structure in the tundish is measured with LDA equipment at different tundish cross sections. The measurements results, together with numerical simulation predictions, for chosen tundish cross-sections, are shown in Figures 3 and 4.

Figures 3 and 4 show the measured and calculated fluid flow structure in the water model tundish. At the investigated cross-sections, the flow is dominated with a vortex induced between the shroud jet and the side walls of the tundish. The jet hit the bottom and reflects upward, generating strong, circulated flow pattern. Closer to the SEN, the centre of these vortexes are moving upward. This can be seen in measured and calculated flow patterns. Vortexes predicted by the numerical model are approximately at the same positions as those measured with 3D LDA. In Figures 3 and 4 one can observe good accuracy between measured and calculated results.

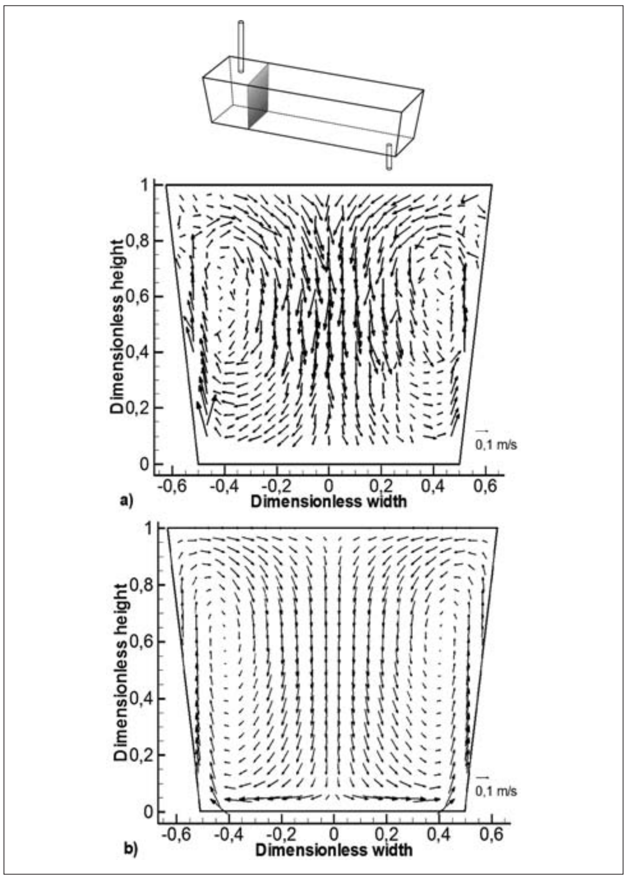

Figure 3 Velocity distribution at the plane x/L=0,2: a) measured with LDA, b) mathematically predicted

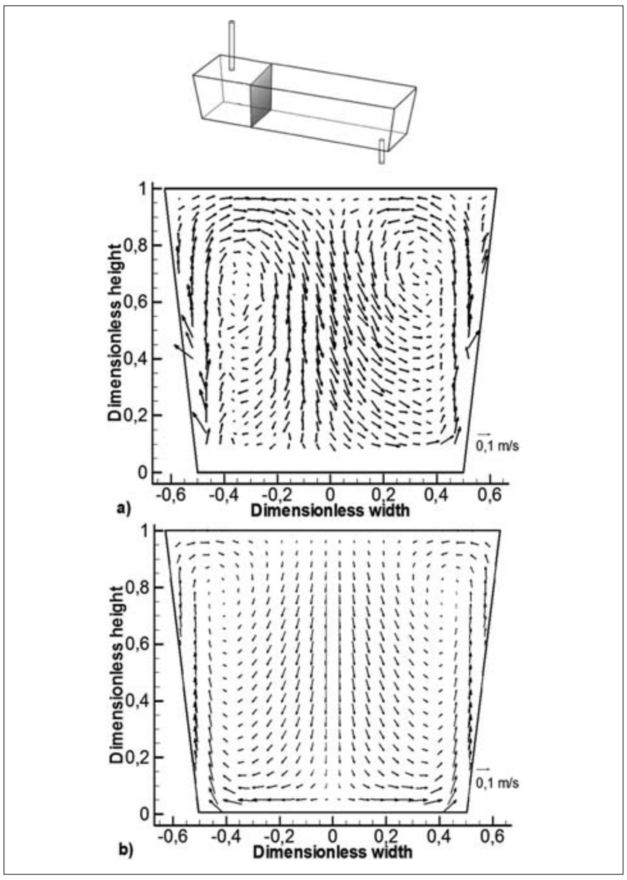

Figure 4 Velocity distribution at the plane x/L=0,3: a) measured with LDA, b) mathematically predicted

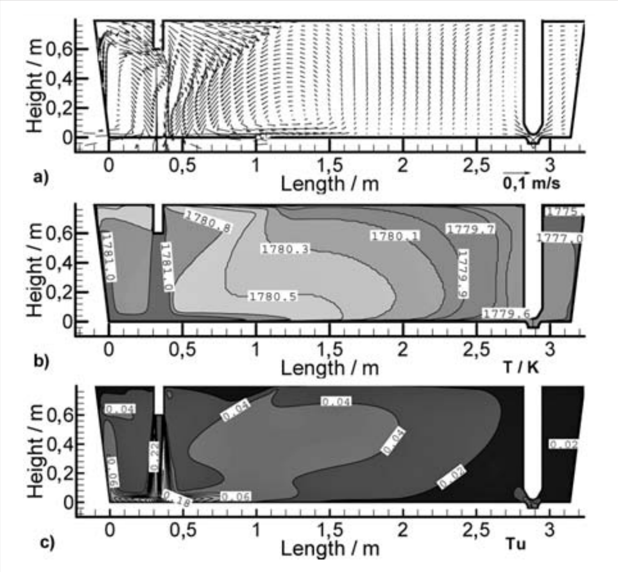

Figure 5 Non-isothermal CFD predictions of the velocity, temperature and turbulence intensity distribution in an original tundish

After validation, numerical model is used to predict the liquid steel flow in a 1:1 scale tundish. Data for steel flow simulations are given in Tabele 2. The inlet temperature of the melt is T = 1 783 K. The heat loses, applied as boundary conditions for the heat transfer equations, are 22 kW $\cdot$ m^{-2} at the slag layer, and 6,7 kW$\cdot$m^{-2} at the side walls and bottom of the tundish. The inflow temperature of the melt is constant.

In Figure 5 the velocity, temperature and turbulence intensity distributions, at the longitudinal symmetry plane of the tundish, predicted with non-isothermal CFD simulations are shown.

Figure 5 shows that melt entering the tundish through the shroud jet, impacts the bottom and is directed to the side walls. When the fluid reaches side walls, flow recirculation is formed and melt is directed upward. This can promote the inclusions flotation to the slag, however the inlet region is characterized with high turbulence and strong waves which can decrease the separation rate of inclusions. Another technical problem is a high erosion of the tundish lining, due to the high power of incoming jet, which produces large exogenous inclusions.

The melt which flows along the bottom of the tundish in the SEN direction, meet the back flow impact (at about 1,5 m length). In this place a circulation flow occurs. Close to the surface, melt which flows in the tundish centre is directed downward.

The distribution of the velocity and the turbulence kinetic energy provide significant information about the casting conditions. Therefore, additionally in the Figure 5c, the local turbulence intensity Tu, defined as

$$Tu = \frac{\sqrt{\frac{1}{2}(u'^2 + v'^2 + w'^2)}}{|\bar{u}|} = \frac{\sqrt{\frac{2}{3}k}}{|\bar{u}|} \qquad (2)$$

is shown. Turbulence intensity is defined as the ratio of the fluctuation velocity to the local flow velocity. Assuming the turbulence is isotropic, the fluctuation velocity is calculated from the turbulent kinetic energy (k). The turbulence has a significant influence on the particle trajectories and, in turn, their separation in the tundish. In regions with higher turbulence intensity, the probability of non-metallic inclusions is higher. On the other hand, an increased average kinetic energy may decrease the agglomeration of the colliding inclusions.

SUMMARY AND CONCLUSIONS

A water model combined with a CFD code FLUENT, are used to simulate the turbulent flow of liquid steel in a one-strand tundish. LDA measurements have been performed to obtain the flow structure in a 1:3 scale tundish water model. The results have been used to validate the numerical simulation of the fluid flow in the tundish. The comparison shows good quantitative and qualitative agreement between physical and numerical models. With this results it is confirmed, that numerical simulations allow modelling the fluid flow with satisfying accuracy. Validated mathematical model is used to predict the flow structure in the industrial tundish. Numerical simulations provide information about the thermal behaviour of the tundish flow.

Future research is carried out to validate the mathematical model for properly describing the phenomena of the non-metallic inclusion separation due to flotation, during steady-state casting.

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Note: The responsible person for English language is C. Grochowina, Czestochowa, Poland