NUMERICAL MODELING OF STEEL FLOW IN A MULTI-STRAND CONTINUOUS CASTING TUNDISH

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Abstract
The tundish is an important unit in a continuous casting device. The flow of the liquid steel in tundishes has a crucial influence on quality of steel, which is nowadays defined by the number and size of non-metallic inclusions. In order to improve the process of removal of inclusions from liquid steel, investigations are being made worldwide to obtain the most favourable shape of the tundish working space to control the flow. The main purpose of research presented in this paper was to analyze the liquid steel flow structure and temperature distribution in the investigated continuous casting tundish. Numerical simulations of liquid steel flow through the tundish were carried out using commercial computational fluid dynamics (CFD) software AnsysFluent. The results of numerical simulation allow to diagnose the tundish with currently working configuration.

Keywords: continuous casting, tundish, numerical modeling

1 Introduction
Modern tundishes play a role of active metallurgical reactor. Because of that it is essencial to understand and describe the liquid steel flow, transfer and thermal phenomena, and non-metallic inclusios transport in liquid steel, occurring during the casting. A lot of researches concern continuous casting are performed with numerical modeling. Numerical studies, as well as experimental tests described in literature, provide plenty of important information when designing and upgrading tundishes. Researches are related to many aspects of the analysis technique of steel casting, including the steel flow and changes of the flow conditions with flow control devices (FCD) [1-5], the residence time distribution [6-8], heat transfer [9-11], and transport and separation of non-metallic inclusions from liquid steel [12-15].
Presented research concerns the diagnose of the liquid steel flow conditions in a currently working tundish. Numerical simulations have been performed for the current tundish working space configuration. Considered simulations conditions are based on industrial plant conditions.

2 Investigated object
The investigated object is a six-strand continuous casting tundish of a channel-shaped type, equipped with two overflow partitions. The tundish is symmetrical relative to the transverse

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plane. The nominal capacity of the tundish is 34-tons of liquid steel. It feeds simultaneously six molds for the production of billets with a cross section of 280 x 300 mm. In its base configuration the tundish is equipped with a pair of dams.

During steady-state casting, with all Submerged Entry Nozzles (SENs) working, the investigated tundish is characterized by a molten steel mass flow of a 138 t/h. The tundish is used for sequence casting with about ten heats. The shape of the tundish together with its basic dimensions are shown in **Fig. 1**. **Table 1** shows the technological operating conditions of the tundish, used also in numerical simulations.

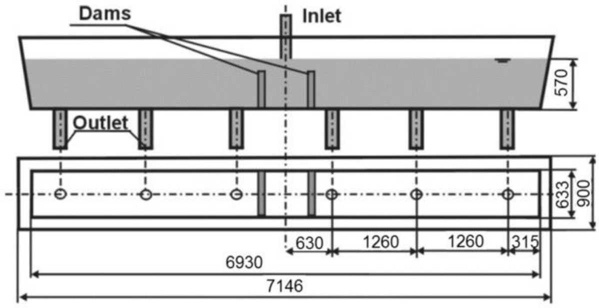

Fig.1 Characteristic dimensions of the investigated tundish

Table 1 Dimensions of the 34 t continuous casting tundish

Parameters	Value	Unit
nominal capacity	34	ton
molten steel level	570	mm
shroud diameter	86	mm
SENs diameter	36	mm
number of tundish nozzles	6	-
casting speed	0.6	m/min
billets	280x300	mm
dam height	300	mm
dam width	100	mm

3 Numerical simulations

The CFD numerical simulations where carried out on the basis of the RANS equations. The liquid phase Navier-Stokes equations for incompressible flow without source terms are as follows.

Continuity equation:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

Momentum conservation equation:

$$\rho \frac{\partial u_i}{\partial t} + \rho u_j \frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu_{eff}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] + \rho g_i \tag{2}$$

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Where: $\mu_{eff} = \mu + \mu_t$ (3)

and where and: $u_{i,j}$ is time-averaged fluid velocities in the ith and jth directions respectively, ρ is liquid density, p is pressure in the fluid, μ is molecular viscosity of liquid, μ_t is turbulent viscosity, μ_{eff} is effective turbulent viscosity, g_i is gravitational acceleration in the ith direction, x_i, x_j are spatial coordinates in the ith and jth directions, i, j denote the three directions in the global Cartesian coordinate system.

Regarding heat transfer, the turbulent energy equation can be written as:

$$\frac{\partial}{\partial t}(\rho h) + \frac{\partial}{\partial x_i}(\rho h u_i) = \frac{\partial}{\partial x_j}\left[\left(k + \frac{c_p \mu_t}{\sigma_t}\right)\frac{\partial T}{\partial x_j}\right] \tag{4}$$

where h is enthalpy, k is thermal conductivity, c_p is heat capacity of liquid water, σ_t is turbulent Prandtl number, T is temperature.

For turbulence modelling, the realizable k-ε model is used. In this model C_μ is a function of the gradients of velocity, whereby mathematical restrictions of the standard k-ε model are avoided. A further modification represents a new differential equation for the dissipation rate ε.

Equation of the turbulent kinetic energy k:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho\varepsilon \tag{5}$$

Equation of the dissipation rate of the turbulent kinetic energy ε:

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_j}(\rho \varepsilon u_j) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + \rho C_1 S\varepsilon - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{\nu\varepsilon}} + C_{1\varepsilon}\frac{\varepsilon}{k} C_{3\varepsilon} G_b \tag{6}$$

where G_k is generation of turbulence kinetic energy due to the mean velocity gradients, G_b is generation of turbulence kinetic energy due to buoyancy, C_1, C_2 and $C_{1\varepsilon}$, $C_{3\varepsilon}$ are constants, σ_k and σ_ε are turbulent Prandtl numbers for k and ε respectively.

The model constants are $C_{1\varepsilon} = 1.44$, $C_2 = 1.9$, $\sigma_k = 1.0$, $\sigma_\varepsilon = 1.2$.

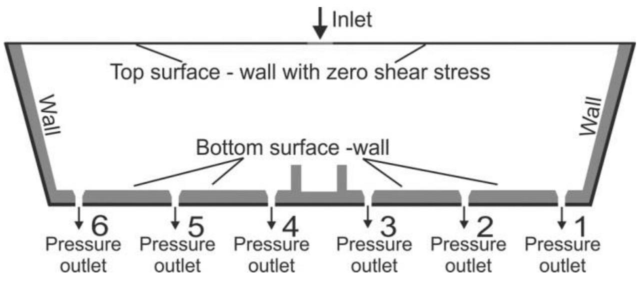

Fig.2 Boundary conditions used in numerical simulations

4 Results and discussion

Numerical simulations have been performed for normal working conditions during steady-state casting. Parameters set for simulations are given in **Table 2**.

Table 2 Operating conditions used for simulations

Parameters	Value	Unit
liquid steel density	7010	kg/m^3
liquid steel dynamic viscosity	0.007	kg/m·s
inlet velocity	2.0	m/s
inlet temperature	1823	K
specific heat	821	J/kg·K
thermal conductivity	30.5	W/m·K
heat flux through side walls/bottom	- 2.6	kW/m^2
heat flux through slag cover	- 16	kW/m^2

Liquid steel flows into the tundish, reach the bottom and thanks to the dams is directed to the free metal surface. It can be clearly seen in **Fig. 3**, where fluid flow topology is shown for the time when liquid steel just flowed into the tundish. With such a flow structure two separate areas in tundish working space can be found. One in the inlet area, which is characterized with high turbulence intensity and fluid velocities, and the other tundish area, which is characterized with much lower turbulence intensity and much lower fluid velocities.

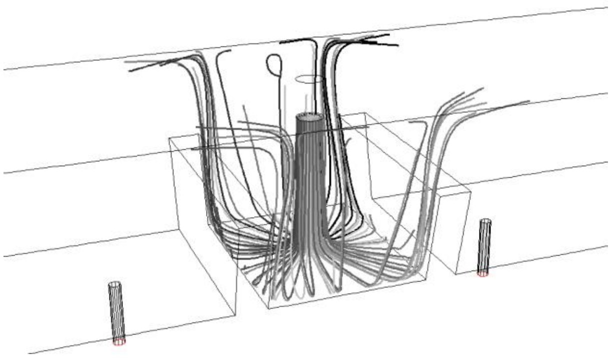

Fig.3 Liquid steel flow topology in the inlet area

Outside the inlet area, liquid steel flows in the vicinity of the free surface (see **Fig.4**). Such a flow topology is very desirable because of the non-metallic inclusions removal process. From one side in the inlet region inclusions have perfect conditions for coagulation and from the other side, outside inlet region they are directed to the surface were the slag layer can absorb them. The question is if they have enough time to reach the slag and to be absorb by the covering slag. Such a simulations have to be performed in the next step.

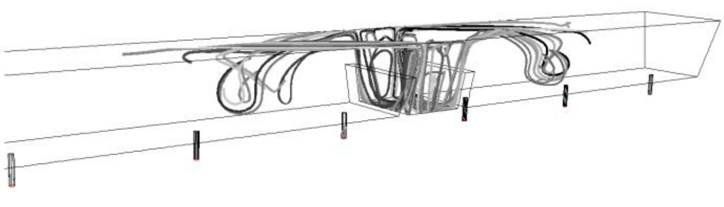

Fig.4 Liquid steel flow topology in the investigated tundish

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The topology of the liquid steel flowing into the tundish is confirmed with the velocity vectors distribution. In **Fig.5**, the uniform liquid steel velocity vectors distribution is shown. One can observe similar fluid flow structure. Fluid directed to the farthest tundish nozzles meets the back flow in the area of nozzles no. 2 and 5. The circulation flow in this area is observed.

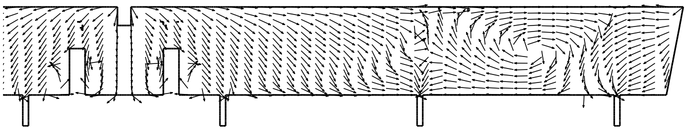

Fig.5 Uniform, liquid steel velocity vectors distribution

Liquid steel temperature distribution predicted numerically for investigated tundish is shown in **Fig.6**. Described earlier flow structure caused by the dams, allows for the movement of warmer fluid in the farther tundish areas, and in turn, liquid steel temperature casted at individual strands is more homogenous. This provides stability of the continuous casting process. The temperature distribution becomes aligned and the maximum temperature difference in the whole tundish reach about 10 K.

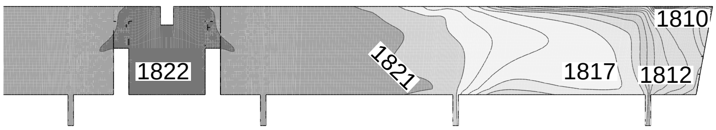

Fig.6 Liquid steel temperature distribution

5 Conclusion

Liquid steel flow in the continuous casting tundish working space can be properly simulated with the computational fluid dynamics (CFD) tool. The numerical simulations of liquid steel flow through the tundish were carried out with commercial CFD software AnsysFluent using k-ε turbulence model.

The presented results concern fluid flow structure and temperature distribution in the investigated tundish. The results of numerical simulation allow to diagnose the tundish with currently working configuration of the working space.

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