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NUMERICAL MODELING OF STEEL FLOW IN THE SIX-STRAND TUNDISH WITH DIFFERENT FLOW CONTROL DEVICES

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Numerical modelling have been extensively used to study the fluid flow phenomena taking place in continuous casting tundish. The paper presents the results of steel flow researches done on tundishs with a capacity of 22 Mg, with different flow control devices. The tundish is a "trough"-type designed for the continuous casting of slabs intended for small cross-section rolled products. In effect of mathematical calculations liquid steel velocity, turbulence intensity, turbulent kinetic energy and temperature distributions have been obtained. Calculations were passed by commercial computer program FLUENT.

Key words: steel, tundish, impact pad device, numerical modeling; fluid dynamics, mixing time.

Numeričko modeliranje protjecanja metala u međuloncu sa šest žila pomoću različitih uređaja za kontrolu protjecanja. Numeričko modeliranje široko se primjenjuje za proučavanje fenomena protjecanja fluida koji se odvija u međuloncu uređaja za kontinuirano lijevanje. U članku su prezentirani rezultati istraživanja protjecanja čelika u međuloncima kapaciteta 22 Mg, s različitim uređajima za kontrolu protjecanja. Međulonac je "koritastog" tipa, a namijenjen je za kontinuirano lijevanje slabova za valjane proizvode malog poprečnog presjeka. Matematičkim proračunima dobije se brzina tekućeg čelika, intenzitet turbulencije, turbulentna kinetička energija i temperaturna raspodjela. Proračuni su provedeni na komercijalnom računalnom programu FLUENT.

Ključne riječi: čelik, međulonac, uređaji sa štitnikom od udaraca, numeričko modeliranje, dinamika fluida, vrijeme miješanja

INTRODUCTION

Modern steel making processes are based on electrical arc furnaces (EAF) or converters, secondary metallurgy and CSC equipment. Steel casting processes are carried on as the continuous ones, which today are the dominating methods in global quantities of steel production. These methods make possible production of the continuous castings of predetermined profiles and dimensions, and therefore to reduce significantly the product manufacturing costs.

The component of equipment, which significantly influences the course of the continuous steel casting process, is called the tundish. A stabilized flow of steel in the tundish greatly affects the process characteristics related to quality, performance and economical issues. Today the main direction of research works concerning the tundishs refers to the refinement processes of the non-metallic inclusions, to lessening the transient zone in the continuous castings and to equalizing the temperatures of the steel being cast.

In the work presented here we show the results of numerical simulations [1] illustrating steel motion in the tundish equipped with different flow control devices arrangements.

TUNDISH DESCRIPTION

The object of the study is a "trough"-type tundish designed for the continuous casting of slabs intended for small cross-section rolled products. The tundish is symmetrical relative to the lateral plane and has six outlet nozzles. The nominal capacity of the tundish is 22 Mg of liquid steel. Figure 1 shows scheme together with the most important dimensions of tundish geometry with impact pad device a) and low dams b).

CONDITIONS OF NUMERICAL COMPUTATIONS

The mathematical model used for the simulation of liquid steel flow in the tundish incorporates differential equations [1] of flow continuity, momentum and energy conservation. Additionally an equation describing the

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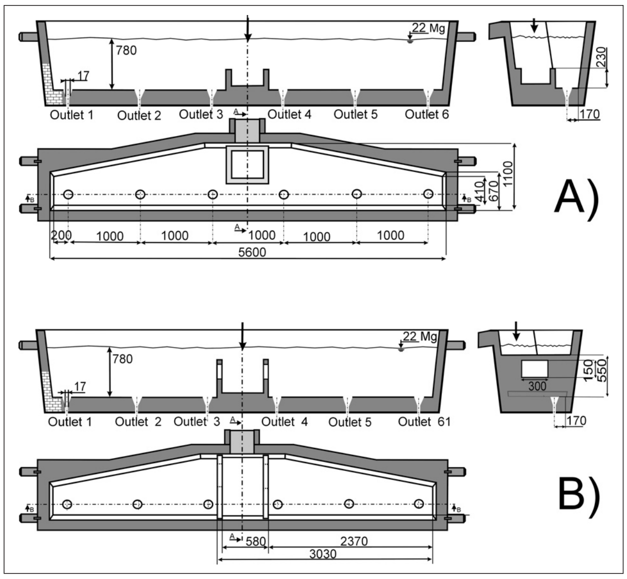

Figure 1. Scheme of tundishs geometry with a) impact pad device, b) low dams

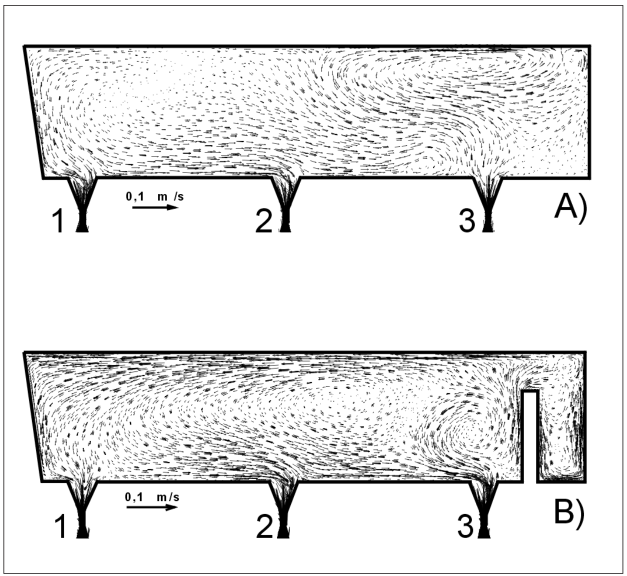

Figure 2. Distributions of the steel velocity vectors a) with impact pad, b) with dam

turbulence of liquid steel motion in the tundish is used. For the modelling of turbulence, the semi-empirical two-equation *k*-*ε* model proposed by Launder and Spalding [2] was employed, which is commonly used in the analysis of engineering problems. This model, in many cases of turbulent flows, gives result close to those of an experiment, with limited computational outlays.

The presented system of equations was solved numerically by the control volumes method in the three-dimensional (3D) space. For the reproduced (real) tundish working space, a hybrid computational grid was generated, which was condensed at the tundish pouring gate and nozzles. The adaptive grid condensing method was additionally used in computations, employing the dimensionless parameter y^+ that resulted in the computational grid having 310000 control volumes.

Appropriate boundary conditions were chosen for the system of differential equations. As the considered spatial system is symmetrical relative to the plane passing through the pouring gate axis, this resulted in the zeroing of the first derivatives in relation to the direction normal to the plane of symmetry.

On the system border corresponding to the pouring gate, the medium (steel) inflow velocity was assumed to be equal to 2,22 m/s, which is equivalent to casting speed in the order of 1,7 m/min with a turbulence intensity of 5 % and steel temperature equal to 1823 K. The velocity of flux outflow from the tundish results from the mass balance. In order to develop concentration characteristics corresponding to normalized conditions, the boundary condition was applied on the pouring gate in the form of a stepwise change of concentration (C = 1).

Calculations of steel flow in the tundish was performed by using the commercial program FLUENT [5]. In the object under study, a hybrid computational grid was generated in the GAMBIT program [6].

RESEARCH RESULTS

As a result of calculations we have obtained spatial distributions of the speed vectors, of the fields of turbulence energies for the predetermined conditions. The researches were done for the whole three-dimensional (3D) space of the object. For the purpose of clear graphical presentation, the obtained results are shown on the plane crossing the tundish nozzles.

The velocity vectors distributions on the plane extending through the tundish's nozzles are illustrated in Figure 2.

When comparing Figures 2a and 2b, distinct variations in the structures of the molten steel flow and circulation can be observed. In the tundish with a dam, the formation of two areas can be observed: the near-runner area, bounded by the flow modifiers, and the out-of-runner one. They clearly differ in separate structures of the steel motion. In the near-runner area the steel circulation is generated (with significant share of the rising component), what can favourably affect the inter-phase release of the non-metallic inclusions. This circulation however, as a result of the slug spreading over the surface, can expose the metal surface, what causes the secondary oxidation of the steel and consequently the increase in quantities of the non-metallic inclusions. Inserting a dam into the tundish brings the steel motion closer to the homogenous condition. It will not be favourable to the non-metallic inclusion removal in the form of coagulation and coalescence, but the role will rise of the gravitational mechanism of the non-metallic inclusion flow out.

In the tundish with dams in their vicinity one can observe the areas, in which the steel motion speed is significantly slower, what results in decreasing the ladle active volume. These areas are not however completely stagnated, and their sizes depend on types of dams.

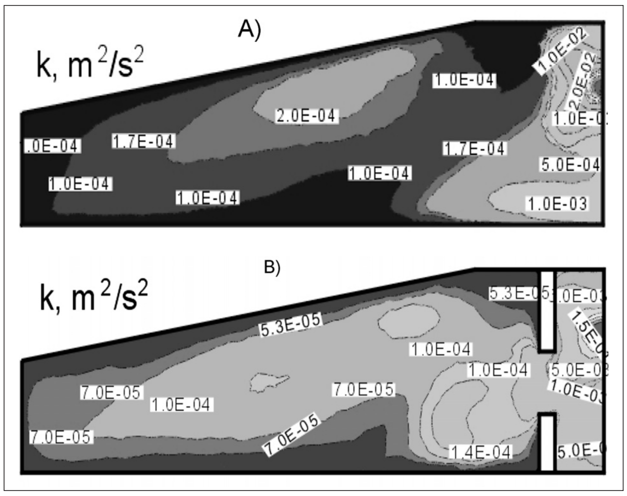

Figure 3. Isolines of steel turbulence kinetic energy a) with impact pad device, b) with dams

In Figure 3 the distribution of the steel turbulence kinetic energy in the plane extending through the half of the tundish height is presented.

Presented in Figure 3 distributions of the liquid steel turbulence energy for the investigated ladles significantly differ from each other. It is a result of the flow disturbances caused by the use of different flow modifiers in the working areas of these tundishes. It can be seen that the use of dams causes the areas of increased turbulence to be bounded to the internal modifier area, therefore lowering the flow turbulence in the remaining part of the object. The distribution of velocity vectors and turbulence energy provide a significant knowledge of steel casting conditions, however these characteristics do not explain directly of whether the tundish condition is suitable for nonmetallic inclusion removal or agitation processes in the sequential casting of different steel grades, or not. The answer to this question is provided by RTD (***R****esidence* ***T****ime* ***D****istribution*) curves. Figures 4 and 5 shows RTD characteristics for individual nozzles of the tundishs, calculated based on the distribution of concentration of a single addition of a tracer.

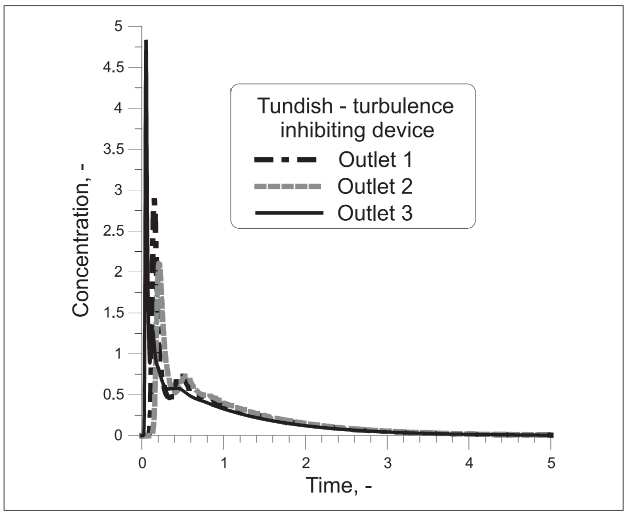

Figure 4. RTD curves for the tundish - with impact pad device

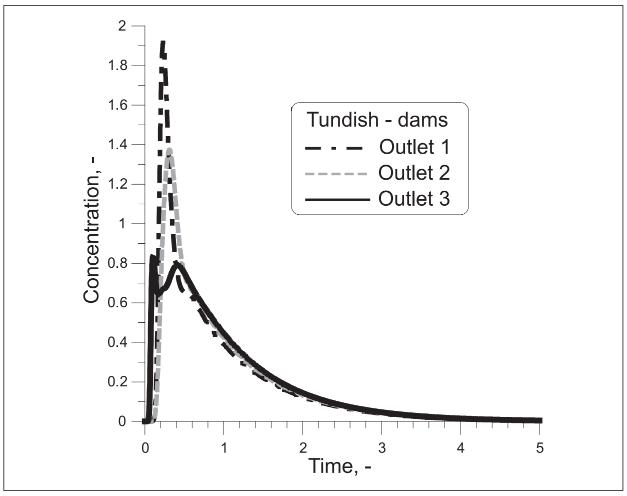

Figure 5. RTD curves for the tundish - with dams

Using an RTD curve developed based on model tests and taking an appropriate theoretical description of liquid flow, individual flow shares or their proportions can be estimated for a particular tundish. The presented Residence Time Distribution (RTD) parameters and volume fraction of flow in the six strand tundish are shown in Table 1.

Table 1. **Residence Time Distribution parameters and volume fraction of flow in the six strand tundish**

Outlet number	Mean residence time (t_{av})/ s	Volume fraction / %		
		Dead volume friction (V_d)	Dispersed plug volume friction (V_{dp})	Well mixed volume friction (V_m)
Tundish – impact pad device				
1	738	0,386	0,127	0,487
2	789	0,345	0,174	0,481
3	651	0,462	0,039	0,499
Tundish - dams				
1	668	0,364	0,179	0,457
2	722	0,327	0,218	0,455
3	745	0,317	0,077	0,606

The volume fractions in the analysed tundish, presented in Table 1, differ significantly in the respective outflow nozzles. The least favourable casting conditions are in the investigated tundish for the nozzle no. 3 and are identified as having very small share of the dispersed plug volume friction and large dead volume friction. For tundish with dams improvements are achieved in casting conditions not only for the nozzle no. 3.

For the evaluation of the transition zone during casting different steel grades in a sequence, a characteristics was developed, which is depicted in Figures 6 and 7.

Two different steel grades cast in a single sequence were simulated by the appropriate normalization of marker concentration. In the first steel grade being cast the

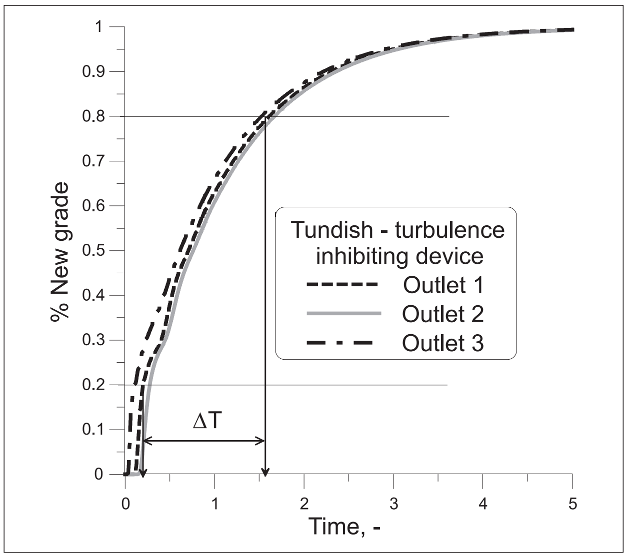

Figure 6. Cumulative transition curves for tree strand of tundish - impact pad device

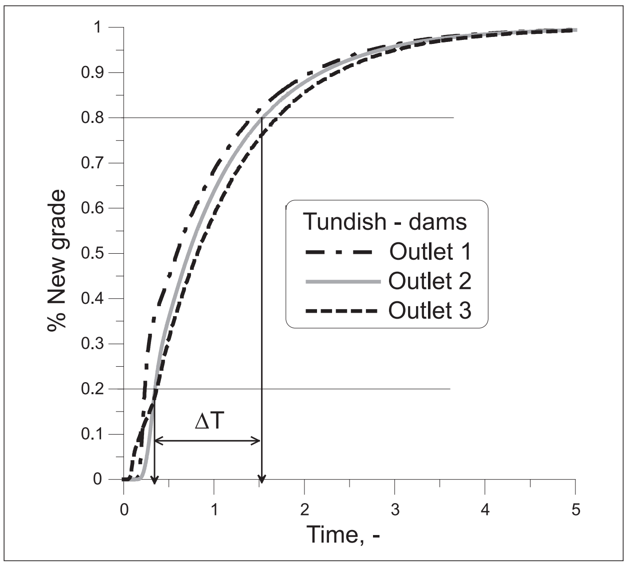

Figure 7. Cumulative transition curves for tree strand of tundish - dams

marker concentration was assumed to be equal to zero [7]. After a certain period of time, the whole liquid in the tundish was replaced with a "new" steel grade that had the marker concentration at the tundish inlet equal to 1.

The Δt values for the respective curves obtained as results of the investigations, relevant to the outflow nozzles no. 1, 2 and 3, correspondingly in the tundish A and B, are shown in Table 2.

From the results being presented one can clearly see the lessening of the transient zone for the proposed modification, provided with dams partitions with the flow-through openings. It indicates the made selection of type of the working area arrangement to be right contrary to tundish with turbulence inhibiting devices. In case of the tundish with dams the mass of this steel cast is reduced by 4,7 Mg in relation to the tundish with the impact pad device.

Table 2. **The transient zone (Δt)**

Tundish	Δt/s				Mass of steel being cast, suitably to the area /Mg
	Nozzle			Average	
	1	2	3		
impact pad	1025	1013	1026	1021	34,8
dams	853	848	945	882	30,1

CONCLUDING REMARKS

After experimental validation, the mathematical model was used for numerical simulations of the steel flow through investigated tundish. Observations collected during the investigations can be summarized in a following manner:

- The use of RANS (R*eynolds* A*veraged* N*avier*-S*tokes*) equations together with the k-ε turbulence model has allowed obtaining the spatial patterns of steel motion during casting in the tundish;
- The steel flow assessment with use of maps of the speed and turbulence intensity vectors makes possible to estimate preliminarily the hydro-metallurgical conditions in the tundish being analysed;
- Introducing the dams clearly and favourably influences the molten steel structure of flow and circulation;
- The least favourable casting conditions exist in the utmost nozzles. They feature the least share of the dispersed plug volume friction and, at the same time, the longest transient zone;
- The use of dams causes a decrease in the dead volume friction share, increasing the dispersed plug volume friction share;
- The use of dams causes a significant decrease in the range of transient zone and therefore in the quantity of steel being cast.

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Note: The responsible translator for English language is T. Merder.