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NUMERICAL ANALYSIS OF LIQUID STEEL FLOW STRUCTURE IN THE ONE STRAND SLAB TUNDISH WITH SUBFLUX TURBULENCE CONTROLLER AND DAM

NUMERYCZNA ANALIZA STRUKTURY PRZEPŁYWU CIEKŁEJ STALI W KADZI POŚREDNIEJ JEDNOWYLEWOWEJ WYPOSAŻONEJ W PODSTRUMIENIOWY REGULATOR TURBULENCJI I PRZEGRODĘ

The paper present the results of computational calculation showing liquid steel flow in the tundish. The one-strand slab tundish is used to casting slabs. The internal work space of tundish was modified by two flow control devices (FCDs). The first device is subflux turbulence controller situated in the pouring tundish zone. The second FCD is a dam with two holes. The dam presently using in the industrial conditions was modified by changing a height. Adapted to internal work space new flow control devices were located in the tundish virtual model. Numerical model and computational grid of tundish was performed in the Gambit application. The visualization of interaction of flow control devices on hydrodynamic conditions was received from numerical simulation. As a results of the computations carried out, liquid steel flow fields, turbulence intensity maps, steel temperature maps and RTD curves (E and F) were obtained. On the distribution of RTD characteristics, percentage contributions of stagnant, plug, ideal mixing flow type, and transition grade zone were calculated.

Keywords: tundish, flow control devices, RTD characteristics, numerical modeling

Artykuł przedstawia wyniki obliczeń komputerowych obrazujacych przepływ ciekłej stali w kadzi pośredniej. Jednowylewowa kadź posrednia jest przeznaczona do odlewania wlewków płaskich. Przestrzeń robocza kadzi pośredniej została zmodyfikowana i zabudowana dwoma urządzeniami sterującymi przepływem ciekłej stali. Pierwszym urządzeniem USP jest podstrumieniowy regulator turbulencji umieszczony w strefie zasilania kadzi pośredniej. Drugim urządzeniem jest przegroda z dwom oknami przelewowymi. Wykorzystywaną obecnie w warunkach przemysłowych przegrodę zmodyfikowano zmieniając jej wysokość. Dostosowane do przestrzeni wewnętrznej kadzi pośredniej nowe urządzenia sterujące przepływem umieszczono w wirtualnych modelach kadzi pośredniej. Modele numeryczne kadzi pośredniej i siatkę obliczeniową wykonano w programie Gambit. Wizualizację oddziaływania nowej zabudowy kadzi na warunki hydrodynamiczne uzyskano na bazie wyników otrzymanych z symulacji komputerowej przepływu ciekłej stali. W wyniku obliczeń komputerowych otrzymano charakterystyki w postaci krzywych RTD (E i F) oraz pól przepływu, intensywnosci trubulencji i temperatury ciekłej stali. Na podstawie rozkładu czasu przebywania stali w kadzi posredniej wyliczono udziały procentowe przepływów: stagnacyjnego, tłokowego, idealnego mieszania oraz zakres strefy przejściowej.

1. Introduction

In the continuous steel casting process, liquid metal cast into the Continuous Steel Casting (CSC) machine's mould solidifies under the action of a cooling medium (water). Thus, a concast slab, a steel semi-finished product is formed, which is ideal for processing at Steel Mill departments dealing with the plastic working of metallic stock. Notwithstanding the dynamic development of composite and polymer materials engineering, the steel material continues to be a major structural component in the building, automotive, aircraft, armament and shipbuilding industries. This fact gives scientific centers grounds for conducting studies on the optimization of steelmaking technologies. The results of those studies enjoy considerable interest and get a good reception by leading global steelmaking corporations. The turn of the 20^{th} and 21^{st} centuries saw many interesting studies on the optimization of the CSC technology. Among those studies, the investigations of the tundish make a major part. In view of the wide range of tundish optimization opportunities, as well as industrially operated tundish types themselves, research activities focusing on the tundish are still topical and being carried out by

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research centers both at home and abroad [1-5]. Studies on tundishes are conducted based on either physical or mathematical modeling. By simulating the actual process conditions prevailing in the production cycle, these studies provide information necessary for making a valuable assessment of the state of a technology being used under actual conditions. In the case of a tundish, information about the directions and intensities of liquid steel flow and the thermal conditions in the tundish working space, as obtained from simulations, are of key importance, as it directly translates into the quality of the concast slab. This paper presents investigation results concerning the analysis of operation of a single-nozzle tundish that is used, among others, in casting of concast slabs.

2. Characterization of the Test Facility and Testing Methodology

The facility under investigation was a wedge-shape tundish with a stopper rod system used for the control of steel feed to the mould. The nominal capacity of the tundish is about 30 Mg. Liquid steel flows into the CSC machine's mould through the submerged entry nozzle. The liquid steel column in the stopper rod system region is 0.92 m high, whereas elsewhere within the tundish working space, 0.7 m high. Figure 1a gives a general view of the tundish prepared for the continuous steel casting process. The tundish is equipped with a low dam with two overflow windows. Figures 1 and 3 present virtual tundish models with the tundish working space being modified by installing **f**low **c**ontrol **d**evices (FCD). To modify the working space, a **s**ubflux **t**urbulence **c**ontroller (STC) and a dam have been used. The designed STC is a cube with dimensions making the controller compatible with the tundish working space in the tundish feed zone. With a view to its purpose, which is to inhibit the turbulent flow within the tundish feed zone, the STC has been installed in the axis of the liquid steel stream flowing out from the ceramic ladle shroud mounted at the steelmaking ladle bottom. Another modification was a change in the design dimensions of the currently used dam by increasing its height. In virtual tundish models, a 0.35 m-high and a 0.5 m-high dams were installed (each of them being provided with overflow windows). The location of installation of the modified dam remained the same as that of the dam being currently in use.

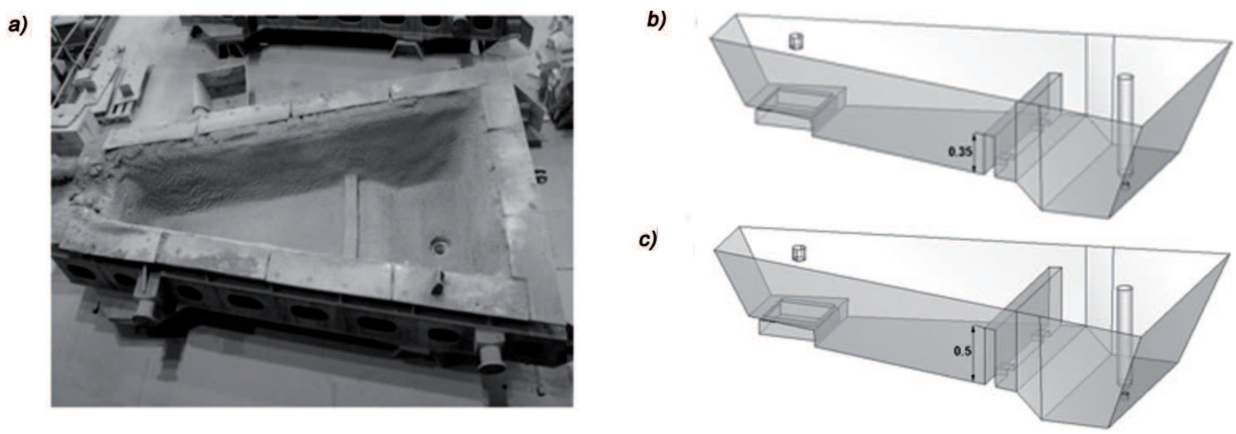

Fig. 1. One-strand slab tundish: a) view of industrial tundish, b) virtual tundish model with STC and medium dam, c) virtual tundish model with STC and high dam

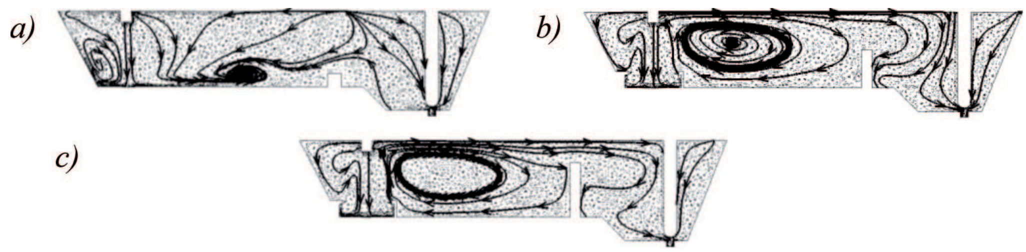

Fig. 2. Liquid steel flow in the central plane: a) tundish with low dam b) tundish with STC and medium dam, c) tundish with STC and high dam

Numerical simulation of liquid steel flow concerned a sequence of casting 225×1500 size concast slabs at a speed of 0.9 m/min. The computations were performed within the Ansys-Fluent® software program. The mathematical model of the flow of liquid steel and a tracer substance under turbulent motion conditions is described in detail in study [6]. Computational grids making up the computational domain of the virtual models for particular tundish equipment variants were built of tetrahedral elements. The velocity, temperature, turbulence kinetic energy and the energy of dissipation of liquid steel turbulence kinetic energy at the tundish inlet zone were, respectively: 1.31 m/s, 1827 K, 0.017161 m^2/s^2 and 0.064231 m^2/s^3. The physicochemical properties of liquid steel, including its density, viscosity, heat capacity, thermal conductivity and coefficient of thermal expansion were assumed with the following values: 7010 kg/m^3, 0.007 Pa·s, 750 J/kg·K, 41 W/m·K and 0.0001 K^{-1}. The ideal thermal insulation of the liquid metal within the free surface region was assumed for the numerical simulation. On the other surfaces describing the tundish walls and bottom, the heat loss flux was 2600 W/m^2. On the surfaces of the FCD and the ceramic ladle shroud, on the other hand, heat losses were assumed to be at a level of 1750 W/m^2. The use of a virtual tracer allowed the variations in tracer concentration within the tundish working space to be recorded at the tundish nozzle. The research method enables residence time distribution curves of the E and F types to be recorded. Based on the obtained E-type time curve distributions, it is possible to determine the quantities that quantitatively define the hydrodynamic conditions in the tundish [7-8]. Thus, the extent of stagnant, dispersed plug and ideal mixing volume flows can be determined. In this method, Sahai and Emi have defined the dead volume flow as the region under the curve occurring above the dimensionless time 2τ. Whereas, the dispersed plug flow is the sum of the dimensionless time that has elapsed since the first concentration increase until the point of reaching the maximum tracer concentration divided by two. The dispersed plug flow is the most advantageous for non-metallic inclusions (NMI) to freely flow out from the liquid steel, whereas the dead volume flow may lead to liquid steel temperature drops to below the level permissible for a given steel grade. The F curve, on the other hand, is necessary for determining the transient zone that characterizes the hydrodynamic conditions occurring in the tundish during consecutive casting of steel grades differing in chemical composition. In the transient zone, there is part of the liquid metal having a chemical composition intermediate between those of the steel grades being cast. This material is difficult for classification and subsequent working in the Rolling Mill's departments. The model presented in the paper [9] assumes also that the transient zone lies between the values 0.2 and 0.8 of the dimensionless trace substance concentration in the system under examination. Also in studies [10-11], the authors have stated that the transient zone is contained in the range from 0.2 to 0.8 of the dimensionless concentration F; however, they suggest that, in the case of casting concast slabs, this zone may even extend from 0.1 to 0.9 of the dimensionless concentration F. The extent of the transient zone may also undergo additional modifications, e.g. from 0.1 to 0.6 or from 0.4 to 0.9 of the dimensionless concentration F, depending on the steel grades being cast.

3. Computational results

Based on the obtained computer simulation results, the liquid steel flow direction and intensity fields and the temperature field have been obtained. Figure 2 represents the results for the direction of liquid steel flow in the central tundish part between the feeding and the stopper rod system zones. In the tundish with a low dam, the steel stream descending toward the bottom and reversing from the stopper rod system zone creates a strong rotational motion in the central part of the tundish working space. A different liquid flow pattern occurs in the tundish with an STC and a 0.35 m and 0.5 m-high dams. In the both variants, the STC controls the flow of the feed stream toward the free steel surface and the stopper rod system. In the STC-equipped tundish, there is a region of liquid steel circulation between the STC and the dam extending from the tundish bottom up to the free steel surface. Equipping the tundish with an STC and a dam reduces the turbulent steel flow region (Fig.3). The intensity of flow turbulence is measured on the scale from 0 to 1. In particular, in the 0.5 m-high dam tundish variant, beyond the feed zone, the turbulence intensity decreases to a value of 0.004. The proposed upgrading of the tundish working space does not impairs the thermal conditions prevailing in the tundish (Fig.4). Between the tundish feed zone and the stopper rod system zone, the steel temperature difference amounted to 1 K for the low dam tundish. The influence of the STC on the steel mixing process in combination with the proposed dams intensify the thermal homogenization of the steel by reducing the steel temperature drop during steel residence in the tundish. Figures 5 and 6 present RTDs of the E and F types for the tundish equipment variant under discussion. From the behavior of the curves it can be noticed that the STC and the higher dams reduce the extent of the dead volume flow zone, cause an increase in the dispersed plug flow extent, and intensify the steel mixing process. For performing the quantitative analysis of the hydrodynamic conditions, the models proposed by Sahai and Emi and Clark *et al* were employed.

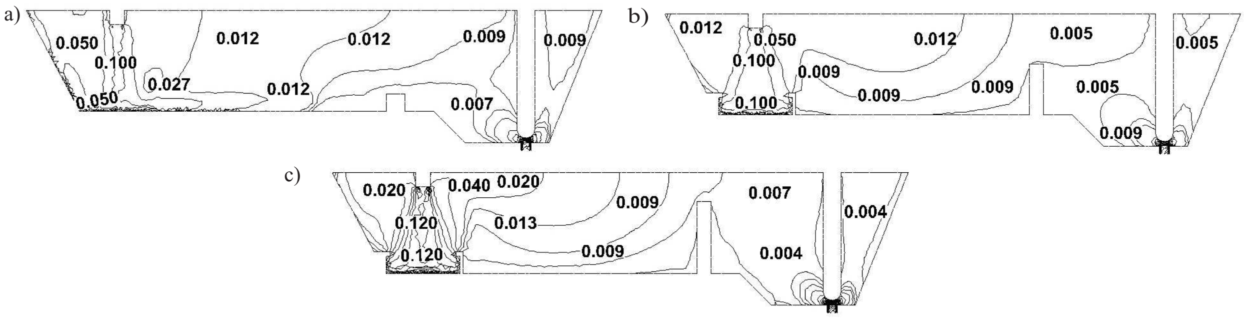

Fig. 3. Turbulent intensity of liquid steel flow in the central plane: a) tundish with low dam b) tundish with STC and medium dam, c) tundish with STC and high dam

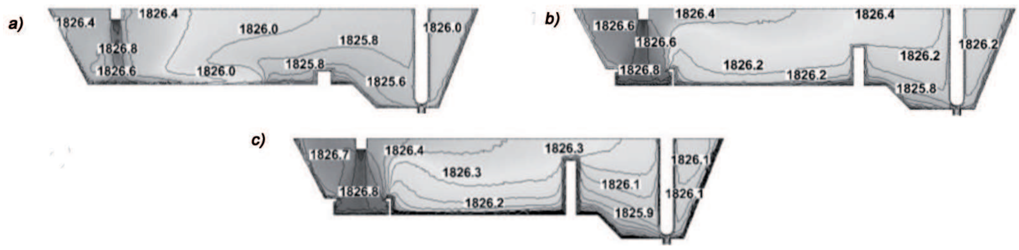

Fig. 4. Temperature of liquid steel in the central plane: a) tundish with low dam b) tundish with STC and medium dam, c) tundish with STC and high dam

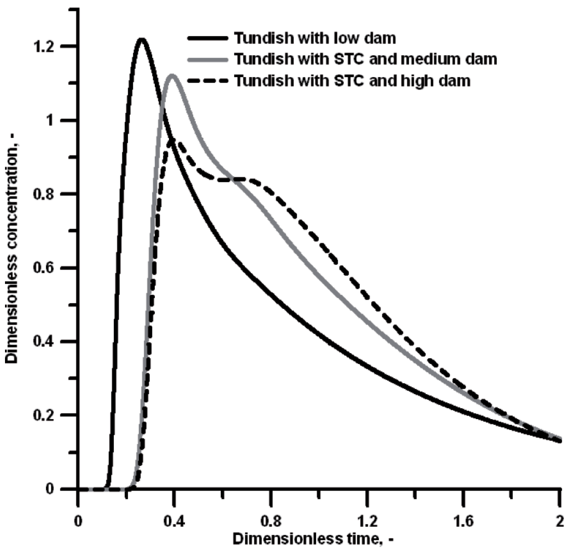

Fig. 5. Liquid steel residence time distribution curve for consider tundishes

The results of the quantitative analysis of the hydrodynamic conditions are given in Tables 1 and 2. The applied arrangement of flow control devices (STC + dam) has reduced the dead volume flow share by 14%. Raising the dam by another 0.15 m has reduced the dead volume flow by further 5% down to a level of 14%. The increase in the share of dispersed plug flow and well-mixed volume flow by, respectively, 9-10% and 6-9%, additionally activates the tundish working space zone in which an active flow occurs. The reduction in the extent of the dead volume flow zones is reflected in the steel mixing processes and in the length of the transient zone, as recorded during the casting process (Table 2). The proposed flow control devices cause a reduction in the transient zone extent by 6.2 and 8 Mg, respectively, for the tundish with the STC and the 0.35 m-high dam and with the STC and the 0.5 m-high dam.

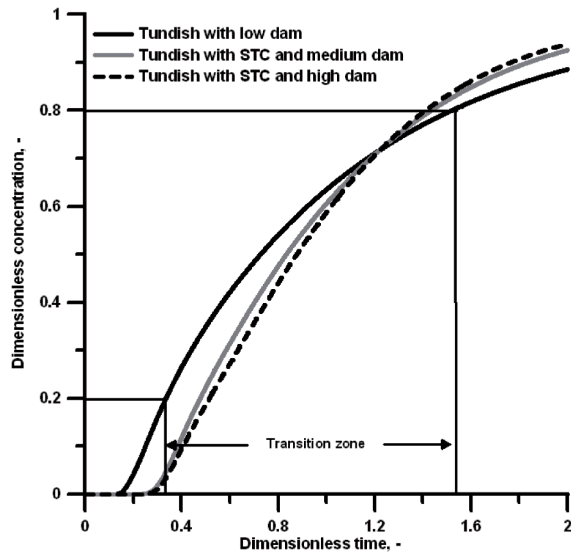

Fig. 6. Liquid steel mixing curve for consider tundishes

TABLE 1
Structure of liquid steel flow system for consider tundishes

No. of tundish	Percentage contribution, %		
	Stagnant flow	Plug flow	Ideal mixing flow
1	33.3	13.2	53.5
2	19	22	59
3	14	23	63

TABLE 2
Characterization of grade transition zone for consider tundishes

No. of tundish	Range of transition zone, s	Length of casting steel strand, m	Weight of casting steel strand, Mg	Reduction of grade transition zone, Mg
1	871	13.06	30.8	
2	695	10.42	24.6	6.2
3	645	9.67	22.8	8

4. Conclusions

Based on the performed computations, a detailed analysis of tundish operation was made. The employed STC combined with the modified-height dam has had a favorable effect on the hydrodynamic conditions occurring in the tundish under investigation. The proposed upgrading of the tundish working space has resulted in:

- a change in the direction of liquid steel flow within the tundish space,
- a reduction in the turbulence of liquid steel flow beyond the tundish feed zone,
- an intensification of the process of thermal homogenization of the liquid steel,
- an increase in the percentage share of the active flow (dispersed plug flow and well-mixed volume flow), and
- a reduction in the extent of the transient zone between the steel grades being cast, differing in chemical composition.

The obtained results demonstrate clearly that the slab continuous casting technology can be effectively improved by implementing the proposed tundish equipment.

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