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INFLUENCE OF DESIGN PARAMETERS OF TUNDISH AND TECHNOLOGICAL PARAMETERS OF STEEL CONTINUOUS CASTING ON THE HYDRODYNAMICS OF THE LIQUID STEEL FLOW

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Hydrodynamic conditions occurring in the tundish are strictly connected with the equipment of its working zone. On such conditions influence also many factors such as: the amount of steel present in the working zone, the velocity of steel casting. In order to study these relationships the CFD simulation and physical modelling were applied. Research was carried out for the following parameters: different velocity of steel casting, bare tundish and tundish with turbulence inhibitor (kind of working zone equipment) and the amount of liquid steel in tundish equal 5,5 Mg and 7,5 Mg.

Key words: steel, casting, tundish, turbulence inhibitor, residence time distribution (RTD) curve

INTRODUCTION

Continuous casting (CC) of steel belongs to the group of progressive technologies. That means the necessity of perpetual development and improvement. It concerns especially the optimization of liquid steel flow through tundish [1-4]. A tundish in CC process plays really important role. Its correct working influences the quality of obtained cast strands considering their chemical homogeneity, metallurgical purity and demanded primary structure of cast strand [5].

Key-factor of operations conducted in a tundish is identification and control of liquid metal flow. Understanding the structure of such flow has basic meaning. To control appropriately the movement of liquid steel can influence the improvement of steel flow pattern in a tundish. That is why, in working zone of a tundish different kinds of control flow device are applied [1, 2]. They are translated into the individual for every type of a tundish view of flow structure, distribution of temperature and conditions of steel mixing. Another factors such as: amount of steel present in working zone [6, 7] (the bigger amount of liquid metal causes the elongation of time that steel staying in a tundish), velocity of steel casting [8, 9] influence also the hydrodynamic conditions.

Article presents the continuation of research presented in work [10]. The aim of such research was to point out that the equipment of working zone of the object, amount of steel staying in the working zone and the velocity of steel casting influence the process of forming the hydrodynamic conditions occurring in the examine tundish. For such evaluation the Residence Time Distribution (RTD) characteristics were used. They enable to determine the kinetics of steel mixing and the percentage participation of particular flow areas for examined cases. The obtained results can be helpful in conducting correctly the technological process of steel continuous casting; and as a consequence the quality of obtained cast strands.

T. Merder: Silesian University of Technology, Institute of Metals Technology, Katowice, Poland

RESEARCH METHODOLOGY

Examined object

Figure 1 presents the geometry of studied tundish. Table 1 shows the basic dimensions of the real object and water model of the tundish at the 1:2 scale. The flow control device – turbulence inhibitor (TI), which was applied in the tundish, was designed as a result of earlier modelling research [4].

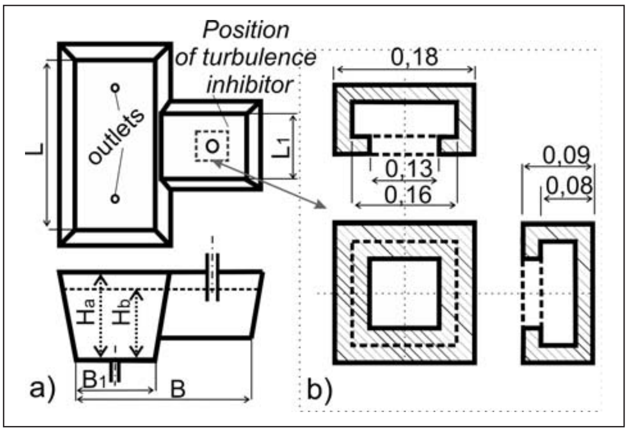

Figure 1 Geometric of the a) tundish model, b) turbulence inhibitors

Table 1 **Dimensions of the 7,5 Mg tundish and the 1:2 water model**

Parameter	Sym-bol	Tundish	
		Scale 1:1	Water model scale 1:2
Volume of tundish at filling level H_a / m^3	V	1,07	0,125
Tundish length / m	L	2,30	1,150
	L_1	0,69	0,345
Tundish width / m	B	1,14	0,570
	B_1	0,60	0,300
Filling level / m	H_a	0,60	0,300
	H_b	0,44*	0,22*

* filling level - 5,5 Mg.

Table 2 **Research program**

	Code number	Description			
		Real conditions		Water model	
		Capacity / Mg	Casting speed / m/min	Capacity / m^3	Flow rate / l/min
Bare tundish	75BT12	7,5	1	0,125	12
	75BT14		1,2		14,5
	75BT24		2		24
	55BT12	5,5	1	0,092	12
	55BT14		1,2		14,5
	55BT24		2		24
Turbulence inhibitor	75TI12	7,5	1	0,125	12
	75TI14		1,2		14,5
	75TI24		2		24
	55TI12	5,5	1	0,092	12
	55TI14		1,2		14,5
	55TI24		2		24

Research program

The following parameters were studied: equipment of working zone (bare tundish and tundish with turbulence inhibitor), the velocity of steel casting, and the amount of liquid steel in tundish. In terms of water heights in the model tundish, 0,22 m and 0,3 m are equivalent to 7,5 and 5,5 Mg of liquid steel in the tundish as it is represented in Figure 1. The velocities of steel casting were assumed on the basis of real conditions of continuous casting process (Table 2) and equal 1 m/min ($1,13 \cdot 10^{-3}$ m^3/s), 1,2 m/min ($1,36 \cdot 10^{-3}$ m^3/s) and 2 m/min ($2,27 \cdot 10^{-3}$ m^3/s). Using the Froude`s number as the main scaling up creation [11,12] these flow rates are equivalent, in the water model, to 12, 14,5 and 24 l/min, respectively. Table 2 presents the description of the realized program of modelling research (physical and CFD) with the share of all applied variables.

Water model

Studies were carried out on the physical model of the CSC plant. It is a segmented water model and was constructed according to the conditions of the theory of similarity. The plexiglas tundish model (Figure 1) was made in a scale of 0,5, in accordance with the geometrical similarity criterion. Flow rates of water at the inlet and outlet streams were measured by means of flow meters previously calibrated and controlled through glove and on/off valves located at the inlet and at the outlets of the water model. As a tracer in the model, a water solution of NaCl was used. To identify F-type curve, the method of step input function (Heaviside`s) on the inlet was applied. The tracer was introduced in such a way during the whole time of measurement. To identify curve RTD (E-type), a method of impulse input function (Dirac`s) on the outlet was applied. The tracer (water solution of NaCl) was introduced to the system on a one-off basis in the amount of 0,02 m^3.

In both cases the change of marker concentration (NaCl) was registered continuously using conductometers, right behind the outlets from the tundish model. From these experimental data the RTD curves were obtained, employing the usual dimensionless variables for concentration.

Numerical modelling

Computer simulation of the liquid steel flow and alloy addition behavior in turbulent motion conditions was done using the commercial computational fluid dynamics program. The basic mathematical model equations describing the phenomena under examination are present in references [2, 4, 13].

The 3D domain of this model tundish is divided into 350 000 cells, making a finer mesh in the zone of the incoming and outgoing liquid jet in order to visualize in more details the effects of velocity, turbulence gradients. At the inlet the mean vertical velocity was assumed to be uniform through their cross-sections and the other two mean velocity components were assumed to be zero. To evaluate the distribution of tracer concentration in the steel during the casting process, two types of boundary conditions were set at the inlet. The first one for E-type was at the moment t = 0, and a one-off tracer addition was X_{tr} = 0,001 of mass fraction (Dirac`s function). The second one for F-type was the tracer concentration; it was uniform and normalized (C=1) in the whole period of measurement (Heaviside's function).

Velocity fields at steady state were first calculated and later they were employed to solve the mass transfer equation. The non-lineal system of partial differential equations was discretized using the finite volume technique in a computational domain and solved with the help of boundary conditions using ANSYSFluent program.

RESULTS AND DISCUSSION

Validation with experiment

Figures 2 and 3 present the results of experimental and CFD research for the chosen cases. Comparison is without doubt because the RTD characteristics (obtained from CFD and water modelling) are directly measured characteristics of liquids flowing through the studied reactor [14]. Basing on comparison presented in Figures 2 and 3 it can be stated that there is agreement between results obtained from physical modelling and CFD calculation. The elaborated research program is quite good and can be used in further analysis of studied problem.

Analysis RTD Curves

RTD characteristics contain cumulated information about the hydrodynamic conditions of steel flow through a tundish. They enable to determinate the quality of the

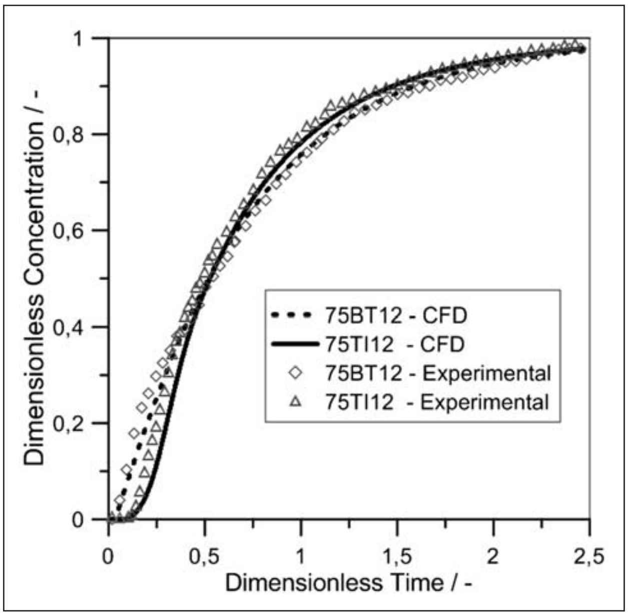

Figure 2 Example of RTD characteristic (F-type curve) obtained from water model and CFD for tundish 7,5 Mg

object taking into consideration the steel mixing and possibilities to intensify the refining processes.

F-type curves give qualitative idea about the influence of hydrodynamic conditions occurring in the tundish on the kinetics of liquid steel mixing. Even after the superficial analysis of obtained F-type curves (Figure 2) it can be seen that the kinetics of steel mixing in the tundish equipped with TI is considerably better than in bare tundish (BT). Increase of the steel casting velocities influences positively on the kinetics of steel mixing in examined cases. Practically it means that equipping the working zone of the tundish with TI is favourable for the casting process in the aspect of transition zone during the sequence casting of different grades of steel.

F-type curves help to determine the mixing kinetics; however they are not much sensitive. E-type curves give considerably more information about the hydrodynamic conditions occurring in tundish. Analyzing such curves it is also possible to estimate the macroscopic character of the flow in studied object.

Analyzing Figure 3 it can be observed short minimum residence times and low peak concentrations in bare tundish. It suggested that in such tundish the participation of well-mixed flow is substantial whereas the participation of plug flow is low. In the same time for the tundish equipped with TI such time is longer and peak concentrations higher. It indicated that the participation of well-mixed flow is decreased, while the participation of plug flow is increased. Practically, it means that the fluid flows with less turbulence and mixing processes is lower which causes, in principle, higher opportunities for inclusion flotation and longer contact times between the liquid steel and a refining-covering slag. For cases of 75BT (Figure 3b) the minimum residence time is even shorter than for case 55BT (tundish 5,5 Mg). It means that bypass flow appears; it is the mostly seen when the velocity of steel casting is the highest (75BT24). This means that the main stream of fluid goes directly to the outlets without having any interaction with the rest of the fluid in the tundish forming a

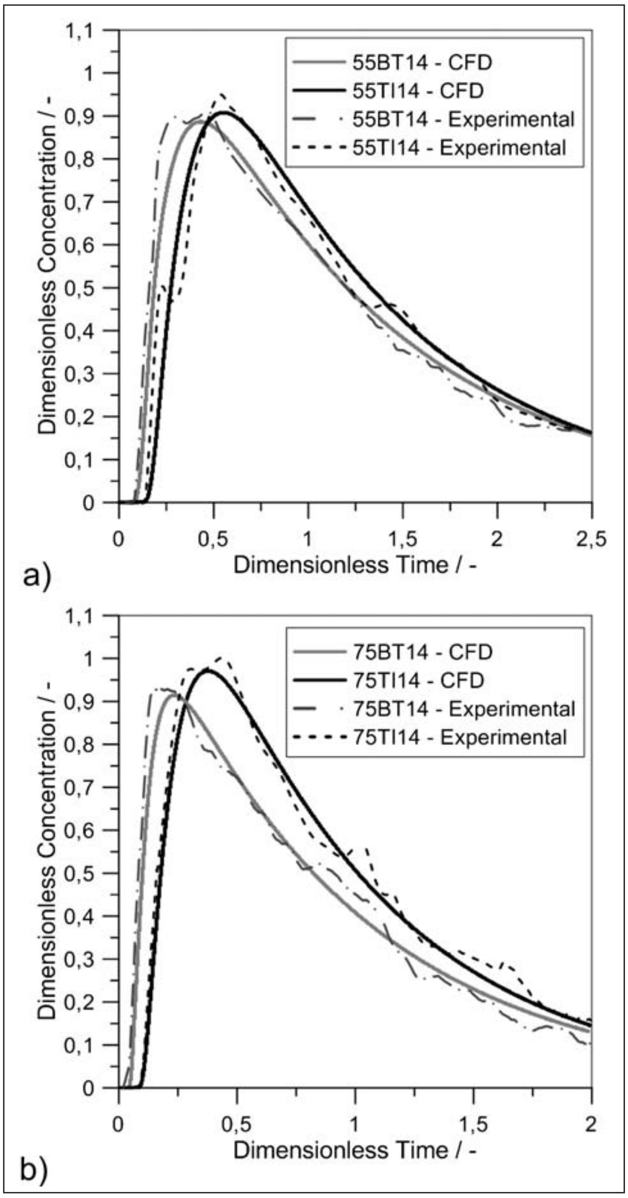

Figure 3 Example of RTD characteristic (E-type curve) obtained from water model and CFD for bare tundish and tundish with TI a) 7,5 Mg b) 5,5 Mg

bypass condition. Under this flow pattern inclusions in steel do not float toward the covering slag since the inertial forces promote their entrainment in the exiting stream.

E-types curves are also used for the estimation of the different kinds of flow in the tundish. For own analysis purposes the mixed model was applied [2,15]. According to this model in the tundish three areas of flow can be found: dispersed plug flow, well-mixed flow and dead flow. The dead area is such an area where the liquid is moving very slowly and the time the marker stays in the liquid is at least twice as long as the average time the tracer stays in the tundish. The dispersed plug can be called an area in chick the liquid steel flows is laminar. The well-mixed area is an area where the flow is turbulent and the total mixing of steel is observed. To determine the participation of particular flows the additional calculations were made. For such purpose the relationships described in works [10,15] were applied. Figure 4 presents the calculated participation of flow for studied cases. Such data represents given equipment of working

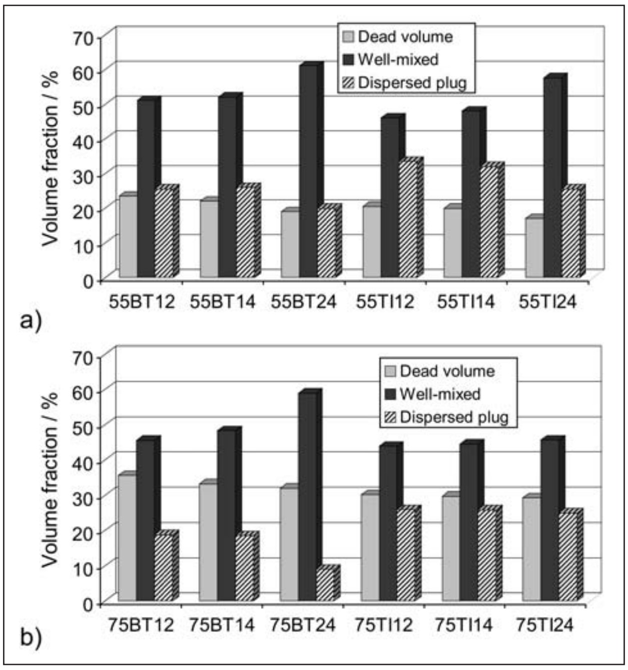

Figure 4 Calculated participations of the flows for the analyzed cases

zone of tundish, capacity of liquid steel in tundish and velocity of the steel casting.

Analyzing the obtained values (Figure 4) it can be fund the confirmation of the features observed in Figure 3. In tundish with TI the participation of well-mixed flow is decreased whereas the participation of plug flow is increased (comparing with bare tundish). Presented values of particular participations of flows show that area of plug flow volume is higher in 5,5 Mg tundish than in 7,5 Mg tundish. Basically, the increase of steel casting velocity causes the decrease of the percentage participation of dead volume flow; and in the same time the increase of well-mixed flow.

To compare analyzed cases the determined ratio of well-mixed volume to dead volume V_M/V_D and ratio of dispersed plug to dead volume V_{DP}/V_D (Table 3) can be also used. Ratio V_M/V_D is indicative of well mixed region which in turn is supposed to provide better homogeneity inside the tundish, V_{DP}/V_D indicated the quiescent region of tundish which promotes the inclusion floatation behaviour inside the tundish [10]. Data in Table 3 shows that in the optional conditions in tundish 5,5 Mg the calculated parameters are better than in tundish 7,5 Mg. Equipping tundish with TI improves the flow pattern, the higher values of V_{DP}/V_D and V_M/V_D for all studied cases of casting velocity were obtained. That means the better conditions fostering the flotation of nonmetallic inclusions and the better homogenization of the liquid steel.

CONCLUSION

Basing on the conducted computer simulations and the laboratory experiments, the following conclusions have been found:

In the bare tundish (7,5 Mg) at the highest steel casting velocity bypass flow occurs. This is very unfavourable phenomena taking into consideration refining possibilities.

Table 3 **Comparison of the different volumes ratios in tundish for the analyzed case**

Parameter	Code number					
	55					
	BT12	BT14	BT24	TI12	TI14	TI24
Overall (V_M / V_D)	2,17	2,36	3,21	2,24	2,40	3,38
Overall (V_{DP} / V_D)	0,5	0,49	0,33	0,73	0,67	0,44
	75					
	BT12	BT14	BT24	TI12	TI14	TI24
Overall (V_M / V_D)	1,28	1,45	1,84	1,45	1,50	1,56
Overall (V_{DP} / V_D)	0,41	0,38	0,15	0,59	0,58	0,55

Equipment of tundish working zone with flow control device (TI) influences favourably the flow fluid pattern. The increase of participation of dispersed plug flow is observed as well as decrease of well-mixed flow for the analyzed casting velocity. In tundish with TI (7,5 Mg) bypass flow did not occur. For all studied cases the increase of casting velocity causes the decrease of percentage participation of dead volume as well as the increase of well-mixed volume flow.

Taking into account the chemical reactor and optional conditions the results obtained in 5,5 Mg tundish are better than in tundish 7,5 Mg. Equipping tundishes with the same size of TI did not change such relations. Efficiency of 5,5 Mg tundish is still better.

To sum up, it can be stated that tundish design is more important than tundish size. In tundish equipped with well designed flow control device the favourable condition for liquid steel refining are observed.

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Note: The responsible translator for English language is P. Nowak, Katowice, Poland