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NUMERICAL INVESTIGATION OF THE HYDRODYNAMIC CONDITIONS IN A MULTI-STRAND CC TUNDISH WITH CLOSED OUTLETS

NUMERYCZNE BADANIA HYDRODYNAMIKI PRZEPŁYWU W WIELOWYLEWOWEJ KADZI POŚREDNIEJ Z ZAMKNIĘTYMI WYLEWAMI

In industrial conditions there are situations when the CC machine works under emergency. It can be result of mechanical or electrical causes, breakout of billet or problem with supplying new parts of liquid steel to the CC machine. As a consequence one or two outlets of the tundish should be closed. However, closing one of the outlets influences the hydrodynamic and thermal conditions occurring in the tundish. Thus, the important information is which of the outlets should be closed to conduct further continuous casting process correctly.

The following research was conducted to analyze the influence of liquid steel flow behaviour in the multi-strand tundish when all outlets do not work. Such problem was solved by means of numerical methods based on Navier-Stokes equations (k-ε standard turbulence model). Numerical simulations were done using the educational version of CFD program (Computational Fluid Dynamics) – ANSYSFluent. As a result forecasted velocity fields and RTD curves (Residence Time Distribution) were obtained. RTD characteristics were used to determine kinetics of liquid steel mixing and also to calculate parts of particular flow areas for studied cases.

Keywords: numerical modeling, Residence Time Distribution, tundish, closing strand

W warunkach przemysłowych zdarzają się sytuacje, kiedy maszyna COS pracuje w stanie awaryjnym. Wynikać to może z powodu usterek mechanicznych lub elektrycznych, przerwania wlewka ciągłego lub być wywołane dostarczeniem nowej partii ciekłej stali na stanowisko COS. Prowadzi to do zamknięcia jednego lub dwóch wylewów w kadzi pośredniej. Zamknięcie któregokolwiek z wylewów wpływa na warunki hydrodynamiczne i termiczne panujące wewnątrz kadzi. Istotną informacją jest więc to, które z otworów wylewowych powinny być zamknięte, aby proces ciągłego odlewania przebiegał prawidłowo.

Niniejsze badania mają na celu analizę wpływu zachowania przepływu ciekłej stali w wielowylewowej kadzi pośredniej, kiedy nie pracują wszystkie otwory wylewowe. Tak postawiony problem rozwiązywano metodami numerycznymi opartymi na równaniach Naviera-Stokesa przy użyciu modelu turbulencji standard k-ε. Symulacje numeryczne przeprowadzono z wykorzystaniem edukacyjnej wersji programu CFD (Computational Fluid Dynamics) – ANSYSFluent. W wyniku obliczeń numerycznych otrzymano prognozowane rozkłady pól prędkości i krzywe RTD (Residence Time Distribution). Opracowane charakterystyki RTD posłużyły do określenie kinetyki mieszania stali, oraz wyliczenia udziałów poszczególnych stref przepływu dla rozpatrywanych przypadków.

1. Introduction

Tundish as an element of CC machine plays an important role in the technological process of steel casting. In continuous casting process, tundish is used as an intermediate reservoir placed between ladle and mould, receiving the molten steel from the ladle and distributing it to the continuous casting moulds. In addition to its conventional role (as a reservoir and distributor), tundish is also used as a reactor producing clean steel and assuring smooth operation. Continuous casting tundishes normally have multiple outlets through which steel is continuously fed to the respective moulds at the constant rate. In case of strand breakout or non-availability of molten steel, a particular strand is closed, which helps increasing the casting duration of the liquid steel in the ladle. Closing the outlet in multi-strand tundish alters the flow behaviour inside the tundish and hence the effectiveness of tundish with regard to its residence time distribution (RTD) behaviour is liable to be changed.

An understanding of the change in tundish working by closing one or two outlets is very important for the steelmakers, especially to decide which of the outlets should be closed in order to have better RTD characteristics of the tundish [1].

Some researchers investigated the steel flow phenomena in the industrial tundish [2-4]. The conclusion is: the operating conditions in steel plants such as the massive size of such tundishes and the high temperature cause serious prob-

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lems when carrying out industrial experimental investigations. Consequently, the numerical simulation becomes a reasonable alternative to known better the metal flow inside the tundish. Therefore, a large number of mathematical modeling investigations on heat loss in continuous casting tundish (including its influence on the fluid flow, residence time distribution, temperature distribution, etc.) were written [2-8]. The purpose of fluid flow optimization in the tundish is to achieve the best flow pattern inside the tundish. Many researchers [9-12] have studied the effect of flow modifying agents for fluid flow phenomena and RTD behaviour in multi-strand tundish. The use of flow modifying agents causes a decrease in the dead volume and results in a significant decrease in the range of transient zone and therefore in the quantity of cast steel. Majority of the reported works deals with the tundish flow with all the outlets open all the time.

In the present work, the effect of closing two outlets of the six-strands tundish has been studied numerically. Such effect was studied basing on RTD curves and mixing parameters, namely, mean residence time, mixing time and volume fraction of particular flows: dead volume, dispersed plug and well-mixed volume. The participation of particular flows allowed to determine the ratio of well-mixed volume to dead volume V_m/V_d and ratio of dispersed plug volume to dead volume V_{dp}/V_d.

2. Description of the problem

The investigated object was a six-strand continuous casting tundish of a trough-type. The nominal capacity of the tundish was 15 Mg of liquid steel. The bath height equaled 550 mm; the size of the inlet and outlets diameter was 50 mm and 17 mm respectively. The tundish was equipped with an impact pad. Fig. 1 shows the scheme of analyzed tundish with its major dimensions. The tundish was symmetrical relative to the transverse plane. It is used for the casting billets intended for the production of small cross-section rolled products. The examined object was described in detail in work [12].

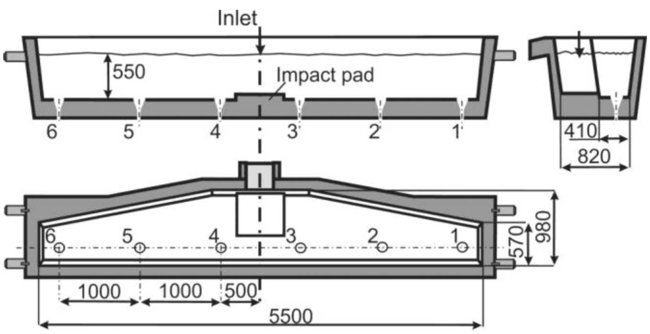

Fig. 1. Geometry of the studied industrial tundish, dimensions in [mm]

Half of the tundish was analyzed because of the symmetry of the inlet plane. Three outlets namely outlet 1 (being far from the inlet), outlet 2 (being in between the 1 outlet and 3 outlet) and outlet 3 (being closest to the inlet) fall on one side of the inlet of the tundish. On other side of the inlet, symmetrically outlet 4, outlet 5 and outlet 6 are in the same position.

Table 1 shows the different cases studied in the work. Case I is a case when all the outlets are open, whereas Case II refers to the case when outlet 1 is closed. In Case III outlet 2 is closed. Finally in Case IV outlet 3 is closed.

The three cases should present the effect of closing different outlets on the flow behavior inside the tundish.

TABLE 1

Different cases and conditions performed for simulation

Case number	Outlet which was closed		
	Outlet 1	**Outlet 2**	**Outlet 3**
I			
II	x		
III		x	
IV			x

3. Numerical modeling

The flow field in the tundish is computed by solving the mass, momentum and energy conservation equation in a boundary fitted coordinate system along with a set of realistic boundary conditions. These equations were presented in detail in works [13, 14]. The species continuity equation is solved in a temporal manner to capture the local variation in the concentration in the tundish. The surface of the liquid in the tundish was considered to be flat and the slag depth was considered to be insignificant. With these two assumptions, the flow field was solved with the help of the k-ε turbulence model [15]. Such model is commonly applied in solving many engineering problems [16-18].

The flow is considered to be steady and incompressible. Tracer dispersion has been carried out for different studied cases. Surface of tundish is assumed to be flat and velocity at the inlet was given at 2.4 m/s when all the outlets were open. This correspond to the parameters of casting the cast strands (0.16×0.16 m) with the casting velocity 1.7 m/min. For the cases with any of the outlet closed, the incoming velocity is reduced accordingly so that uniformity in casting speed is maintained. The walls were set to a no slip condition and turbulent quantities were set from a log wall function for the k-ε turbulence model. It was assumed at the inlet the turbulence intensity of 5%. Fig. 2 shows the boundary conditions used in the computations.

To evaluate the distribution of the tracer concentration in the steel during the casting process, two types of boundary conditions were set at the inlet:

– at the moment t = 0, a one-off tracer addition was X_{tr} = 0.0006 of mass fraction (Dirac‘s function),
– the tracer concentration was uniform and normalized (C=1) in the whole period of measurement (Heaviside’s function).

Thermal boundary conditions include heat losses in terms of constant heat flux values, as shown in Table 2 [5,19] through the all the side and bottom walls and surface of fluid in the tundish. The physical properties of liquid steel (BSt500S) used in these simulations are reported in Table 3. The physical properties of liquid steel (BSt500S) used in these simulations are reported in Table 3. They were calculated basing Iidy i Guthrie'e [20] data and the chemical composition of BSt500S steel.

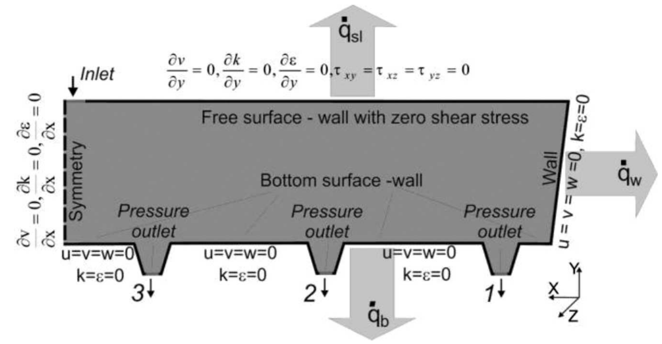

Fig. 2. Boundary conditions used in calculations

TABLE 2
Heat losses from the tundish applied in the mathematical model [5,19]

Free surface [7] $[\mathrm{kW \cdot m^{-2}}]$	Bottom wall [7] $[\mathrm{kW \cdot m^{-2}}]$	Wall [1] $[\mathrm{kW \cdot m^{-2}}]$
15	1.4	2.6

TABLE 3
Physical properties of liquid steel (BSt500S) used in the mathematical model

Grade of steel	Temperature, T, [K]	Density, ρ, $[\mathrm{kg \cdot m^{-3}}]$	Viscosity, μ, $[\mathrm{kg \cdot m^{-1}\ s^{-1}}]$	Specific heat, C_p, $[\mathrm{J \cdot kg^{-1} \cdot K^{-1}}]$	Thermal conductivity, λ, $[\mathrm{W \cdot m^{-1} \cdot K^{-1}}]$
BSt500S	1828	6947	$4.49 \cdot 10^{-3}$	830.8	40.5

To simulate the unsteady state conditions the flow and thermal fields under steady state conditions were employed as initial conditions in all cases.

The analyzed system is 3D. The computational space discretization was made with use of the computational mesh consisting of 460 000 control volumes. The mesh was denser in the inlet and outlets regions.

The SIMPLE numerical algorithm was used to solve those equations. During iteration, the convergence was assumed to reach a point where all the normalized residuals are smaller than 10^{-6}. Computations were carried out for the transient casting conditions. The time intervals of the recorded concentration were constant in the entire testing range, being equal to 0.5 seconds. The range in which continuous recording was performed was 3500 seconds. The mathematical simulations were run on a 2 x INTEL CORE i7 processor computer.

4. Results and discussion

The set of partial differential equations was solved with the help of the mentioned boundary conditions using finite volume technique using educational version of the CFD software ANSYSFluent [21].

4.1. Analysis of steel flow

Simulations based on mathematical model allowed to obtain forecasted 3D distributions of velocity vectors for all studied cases. Taking into account the ease of matching and clarity of presented characteristics comparison they were shown on the identical plane (coming through the outlets). Analysing the forecasted velocity fields (Fig. 3) the similar structure of liquid steel flow and circulation is observed for all cases. However, the profile of velocity in Cases II to IV is lower than in Case I.

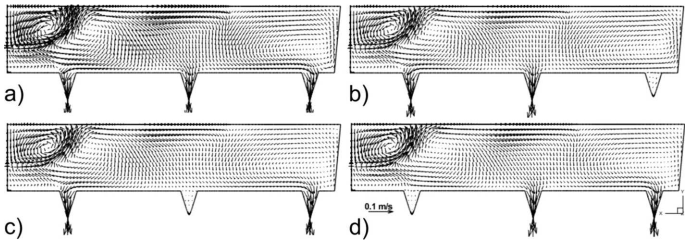

Fig. 3. Velocity vectors at outlet plane for: a) Case I, b) Case II, c) Case III, d) Case IV

In the examined tundish (independently on considered case) two areas are created: near-inlet and off-inlet. They are characterized by different structure of steel movement. In near-inlet area circulation with substantial participation of ascending component is generated. In the off-inlet area the small participation of ascending jets is observed. In this part of tundish there are areas with the significant slowing down of flowing steel, especially in the end of the tundish and in the centers of swirls. Such areas are practically stagnant ones. The highest participation of such areas can be seen for Case II. Additionally, the considerable velocities at the interfacial surface: metal-slag are also observed, this can cause the metal surface uncover.

Special structure of the flowing liquid steel can be observed in the area of outlet 2. In the central part of tundish liquid steel directs into tundish bottom in the area of outlet 2.

4.2. Analysis of Residence Time Distribution curves

The F-type curve. To plot the F curves, changes of tracer concentration in the steel flowing out were monitored continuously on the tundish nozzle cross sections. To compare these curves, the results are given in a dimensionless form. The dimensionless tracer concentration values were obtained directly from a simulation, whereas their corresponding dimensionless time magnitudes were calculated from the relationship [5]:

$$\Theta = t_i / \tau \tag{1}$$

where theoretical mean residence time is defined in the following form:

$$\tau = V/Q_V \tag{2}$$

whereas real (actual) mean residence time in such form:

$$t_r = \sum C_{avi} t_i \Big/ \sum C_{avi} (\text{i = elapsed time}) \tag{3}$$

where: V – volume of the tundish, Q_V – volumetric rate of the flow, C_{avi} – average concentration of the tracer at outlet, t_i – specified time.

Dimensionless mixing time characteristics (the F-type curve) for the analyzed cases were obtained from this transformation. They are presented on Fig. 4. Analysis of the results presented on Fig. 4a, especially in the rage Θ =0.15 to Θ =2.5 saw that there are significant differences between particular curves for outlets in Case I. In the same range for Case II to Case IV (Fig. 4b to 4d) these differences are small, this suggests that this outlets are characterized by similar working conditions. In the range between Θ =0 to reaching time Θ =0.15 the character of curves growing for particular outlets is the same independently from the analyzed case. It can be also stated that in all examined cases the dominant is the participation of well-mixing volume.

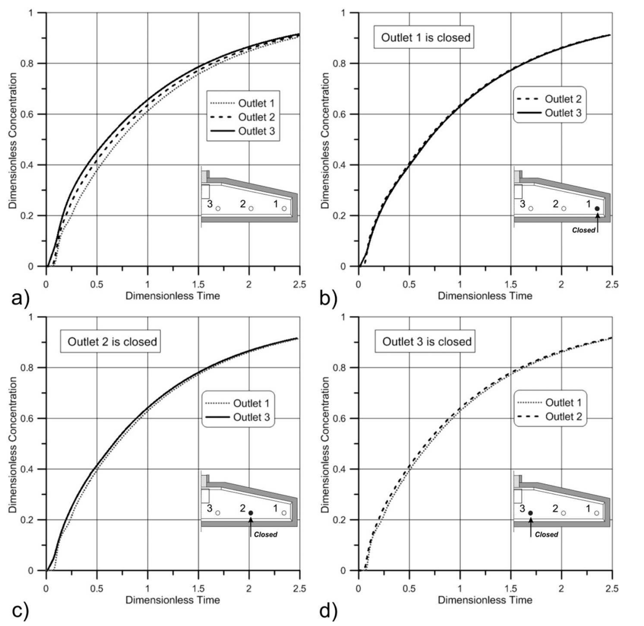

Fig. 4. Dimensionless mixing time characteristic (F-type curve) for: a) Case I, b) Case II, c) Case III, d) Case IV

Assuming that the value 0 on the axis of ordinates of the presented curves (Fig. 4) represents the current grade of cast steel, the size of the transient zone extent (kinetics of steel mixing) can be determined. This value is assumed for the dimensionless concentration in range of 0.2 to 0.8. The smallest values of Δt, the better conditions are in the tundish for sequential casting of different steel grades. Table 4 presents obtained results. The increase of Δt for cases II to IV (with closing some outlets) is clearly seen. This is caused by the decreasing the flow rate of liquid steel for inlet. In the same time it is also decreased between working outlets (Case II to Case IV).

If the transient zone extent for a given tundish is known, then it is possible to determine the mass of the cast steel deviating with its chemical composition and material properties from the specifications applicable to that steel grade. The calculated steel masses for individual plants are shown in the last column of Table 4.

The E-type curve. The F-type curves discussed previously, even though they serve their purpose for the evaluation of flow, are sensitive for assessing the flows that occur in the tundishes. For the evaluation of flow in tundishes, residence time distribution characteristics (E-type) are the best. A detailed justification for using the characteristics of this type can be found in the literature [5,10]. By examining these curves, the macroscopic pattern of flow in a plant under study can be evaluated. As mentioned, three regions of liquid steel flow are distinguished in the tundish, namely a dispersed plug flow zone, in which the liquid steel flows in a stable manner; a well-mixed volume flow zone, where the flow is turbulent and a complete mixing of the steel occurs; and the dead volume (stagnant) flow zone, in which the movement of the steel bath is negligible. Fig. 5a shows residence time distribution (E – type) curve for case I (all outlets are open) and Fig. 5b to 5d show RTD curve for case II, case III and case IV. Curves for those cases differ considerably for particular outlets. Especially in the initial phase that means from Θ =0 till reaching time Θ =0.4. However, apart from this range differences between particular outlets are insignificant. There is high participation of bypass (short circuit) flow for outlet 2 (Case I to IV). It is seen in the form of the biggest peak for this outlet. The appearance of the bypass flow means an adverse feature of the tundish, as it is unfavorable to the flotation of the nonmetallic inclusions (because of short residence time), which affect the quality of the billets.

TABLE 4

Kinetics of steel mixing results (transient zone – Δt)

Case	Transient Zone [s]				Mass of the cast steel [Mg]
	Outlet 1	Outlet 2	Outlet 3	Average	
I	730	724	707	720	*21.75*
II	–	994	999	996.5	*21.70*
III	971	–	972	971.5	*21.15*
IV	975	976	–	975.5	*21.24*

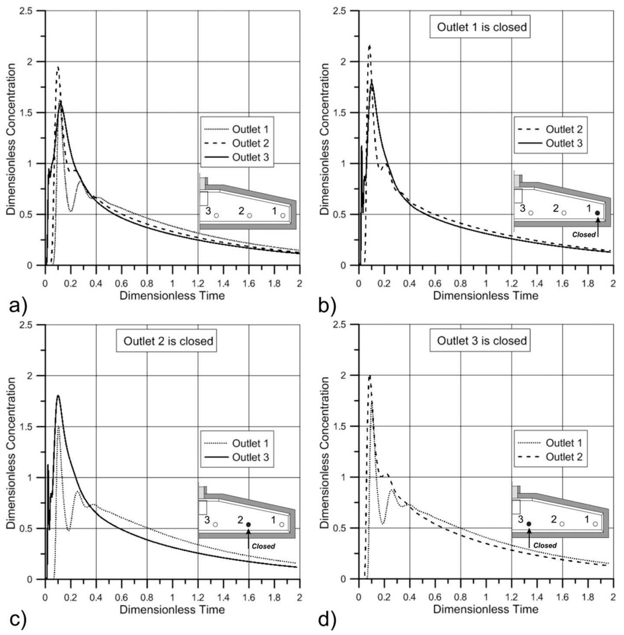

Fig. 5. RTD curves (E – type) for: a) Case I, b) Case II, c) Case III, d) Case IV

Applying mathematical relationship (4 to 6) basing on the obtained E-type RTD curves the participations of flow (dispersed plug flow volume (V_{dp}), well mixed flow volume (V_m) and dead flow volume (V_d)) [10] were calculated for the analyzed cases. Table 5 presents obtained results.

$$V_d = 1 - \frac{\dot{V}_a}{\dot{V}}\Theta_c \tag{4}$$

$$V_{dp} = \frac{\left(\Theta_{\min} + \Theta_{peak}\right)}{2} \tag{5}$$

$$V_m = 1 - V_d - V_{dp} \tag{6}$$

$$\frac{\dot{V}_a}{\dot{V}} = \sum_{\Theta=0}^{2} C_i \Delta\Theta \tag{7}$$

$$\Theta_c = \sum_{\Theta=0}^{2} C_i \Delta\Theta \Big/ \sum_{\Theta=0}^{2} C_i \tag{8}$$

where: C_i – concentration of the tracer, V_{dp} – dispersed plug flow volume, V_m – well mixed flow volume, V_d – dead flow volume, θ – dimensionless time, θ_c – dimensionless mean residence time up to θ =2, θ_{min} - minimal dimensionless time, θ_{peak} – peak dimensionless time, $\dot{V}_a$ – volumetric flow rate trough the active region of a tundish, $\dot{V}$ – total volumetric flow rate trough a tundish.

Occurring in equation (5) dimensionless time θ_{min} and θ_{peak} were determined from E-type curve individually for each outlet. Minimal dimensionless time (θ_{min}) is a time that starts from the tracer addition till the first change of tracer concentration. Whereas peak dimensionless time (θ_{peak}) is a time corresponding to the maximal tracer concentration at the outlet.

Presented in Table 5 flows participations in analyzed cases differ substantially for particular outlets. For outlet 3 which is the most danger for unfavourably casting conditions, small dispersed plug flow is identified and in the same time the big dead volume flow. The participation of dispersed plug flow for cases II to IV is decreased taking into account the Case I, which is unbeneficial. On the other hand, positive is fact that the participation of well-mixed volume flow was increased and dead flow is smaller on the working outlets.

If the tundish works correctly, the relative small difference would be observed between average resident times of steel for particular outlets. This cause that there are the same chances on the realization of the spontaneous refining processes in cast steel, which in the same time guarantees almost identical metallurgical quality of cast strands. This can be observed for Case II (outlet 1 is closed), whereas for Cases III and IV) differences in times between working outlets are rather beneficial.

Table 5 presents also average values of average percentage participation of particular kinds of flows for studied cases. In Cases II to IV the participation of well-mixed flow was increased. Also dead flow was smaller, only for Case II (when outlet 1 was closed) it was observed the increase of dead flow by reducing the dispersed plug flow. To sum up, closing some outlets influences the values of flow participation on the particular outlets, and in consequence in the whole volume of tundish.

TABLE 5

Residence time distribution parameters and volume participation of flow

Outlet number	**Theoretical mean residence time** (s)	**Real mean residence time** (s)	**Volume Participation**			**Mean Volume Participation** [%]		
			Dead Volume (V_d)	**Dispersed Plug Volume (V_{dp})**	**Well-Mixed Volume (V_m)**	**Dead Volume (V_d)**	**Dispersed Plug Volume (V_{dp})**	**Well-Mixed Volume (V_m)**
Case I								
1	504	546	0.384	0.088	0.528	43.6	7.5	48.9
2		484	0.444	0.070	0.486			
3		451	0.481	0.066	0.453			
Case II								
1	687	x	x	x	x	44.4	5.9	49.7
2		547	0.423	0.062	0.515			
3		508	0.465	0.056	0.479			
Case III								
1	687	743	0.343	0.084	0.573	40.3	7.0	52.7
2		x	x	x	x			
3		597	0.463	0.056	0.481			
Case IV								
1	687	712	0.358	0.081	0.561	39	7.2	53.8
2		627	0.423	0.062	0.515			
3		x	x	x	x			

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 6) can be also used. Ratio V_{dp}/V_d indicated the quiescent region of tundish which promotes the inclusion floatation behaviour inside the tundish, V_m/V_d is indicative of well mixed region which in turn is supposed to provide better homogeneity inside the tundish [5,10].

TABLE 6

Comparison of ratio of different tundish volumes

Case	Overall (V_m / V_d)	Overall (V_{dp} / V_d)
I	1.12	0.17
II	1.12	0.13
III	1.31	0.17
IV	1.38	0.18

In Case II (outlet 1 was closed), the ratio of well-mixed to dead volume is smaller than in other three studied cases. Whereas for case III or IV (outlet 2 or 3 was closed), the ratio of well-mixed to dead volume increased comparing with Case I (all outlets open). That means the conditions of homogenization (equal chemical composition and temperature) are better for Cases III and IV than for Cases I and II. This is beneficial for quality of cast strands (homogenous primary structure of working strands). The ratios of well-mixed to dead volume and dispersed plug to dead volume are the best favourable for Case IV (outlet 3 was closed).

5. Conclusion

Analysis of research results enable to draw the following conclusions:

- Accidental condition of tundish work (Cases II to IV – some outlet closed) negatively influence the structure of liquid steel flow – dead areas in the object are increased. For Case II such areas were noticed to be the biggest.
- The studied cases are characterized by similar parameters taking into account the sequence casting of different grades of steel. The mass of cast steel corresponding the range of transient zone differs insignificantly (max. difference 2.3%).
- For all studied cases only in outlet 2 the bypass flow was observed – it is unfavourable considering possibilities of liquid steel refining in the tundish.
- Althogh the character of liquid steel flow was changed for the cases of accidental work (Cases II to IV) the dominant flow is well-mixed volume flow. Whereas participation of dispersed plug flow was decreased comparing with Case I (all outlets open), which limits the possibilities of liquid steel refining in the tundish.
- Case II is characterized by the most unfavourable participations of flow in comparison with the Case I. Dead volume flow is increasing and at the same time participation of dispersed plug flow is decreasing, which means the parameter plug to dead volume is worst of about 22%.
- For Case IV the improvement of particular flow participation was notices, and at the same time the increase of parameters mixed to dead volume of about 23% and plug to dead volume of about 6% comparing Case I.

Obtained results can be helpful in forecasting fluid flow and mixing of the liquid steel an also the consecutions of accidental work. However in the research the condition of object symmetry was assumed (closing two outlets on both sides of tundish), which in industrial conditions are rather rarely. Thus, the research should be carried out for the whole object analyzing nonsymmetrical closing outlets.

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