LIQUID STEEL HYDRODYNAMIC STRUCTURES IN THE THREE STRAND TUNDISH WITH A MODIFIED LADLE SHROUD BASED ON THE RESIDENCE TIME DISTRIBUTION CURVES

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Abstract

This work shows the numerical simulation results of liquid steel flow in three strand tundish designed for the continuous bloom casting process. The authors proposed the modification of ladle shroud by expanding-compressing-expanding system at the end of ladle shroud. The considered ladle shroud modification consisted on the decrease momentum of the liquid steel feeding stream. The aim of the research was checked the influence of ladle shroud immersion depth in liquid steel on hydrodynamic structures in the three strand tundish based on the E and F-type residence time distribution curves. Furthermore, the flow and temperature fields of liquid steel were considered too. The research results allowed to assess the appropriate the modified ladle shroud depth in a liquid steel according to the amount of active and stagnant liquid steel flow volume. The transition zone during the sequential casting process was established for every research cases. Also, the factor of asymmetrical liquid steel flow in the tundish was checked based on the residence time distribution curves. The computer calculations were performed in the Ansys-Fluent computer program.

Keywords: Continuous steel casting, tundish, ladle shroud, numerical simulation, liquid steel flow

1. INTRODUCTION

A tundish is practically the last device (while continuous steel casting process) in which a liquid steel resides enough much time in order to perform treatments directed to improve the liquid metal quality. Nowadays, the liquid steel is transferred from a steel ladle to the tundish via a ladle shroud, which is an isolator between the liquid metal and a surrounding atmosphere. Furthermore, the application of ladle shroud allows to cover the liquid steel by a tundish powder. Recently, the ladle shroud was found as flow control device in works [1-3]. The change of ladle shroud immersion depth in liquid steel [4], the bending of ladle shroud [5] and the modification of ladle shroud location in the tundish [6] influence on the liquid steel flow hydrodynamic structure. Therefore, it started to looking for the appropriate ladle shroud conditions while continuous steel casting process. It caused the invention of a new ladle shroud shapes which allow to improve the tundish working conditions. A widening of the ladle shroud diameter is a well-known way for the lowering of the liquid steel stream momentum [2]. Also, the compressing and decompressing of the liquid steel feeding stream inhibit its flow velocity [3]. Furthermore, the integration of a vacuum chamber and the ladle shroud were tested in work [7]. The ladle shroud can be used to the intensification of the swirling liquid steel flow in the swirling chamber by its bending [8]. According to the literature review, the flow control devices such as dam, subflux turbulence control, argon curtain etc. should be tested for the individual tundish geometry beacause it isn't exist an universal solution for every tundishes. Therefore, the ladle shroud modification should be examined for the individual tundish too.

The performance of examination in industrial conditions is related to difficulties such as a continuity of casting process, an opacity of liquid steel or high costs. Therefore, Computer Fluid Dynamic techniques (CFD) are used to simulate the liquid steel flow hydrodynamic structure in the tundish. The numerical simulations of the liquid steel flow in the three strand tundish were performed in this work. Authors were performed an analysis of the use a modified ladle shroud based on the Residence Time Distribution (RTD) curves.

2. CHARACTERISTIC OF EXAMINED OBJECT AND RESEARCH MEHODOLOGY

The considered object was the three-strand tundish designed for continuous bloom casting process, which was characterized by 30 Mg of nominal capacity. The object was wedge type tundish because of the expansion of walls towards the outlet zone. Furthermore, the outlet zone was characterized by a lower bottom of the tundish. Also, the dam was installed before a lowering the tundish bottom. Liquid steel was flowing into the tundish by the ladle shroud. Generally, the authors considered four variants using the conventional ladle shroud and the modified ladle shroud. Each ladle shroud were tested at two immersion depths in the liquid steel (0.1 and 0.4 m). Whereas, the modification of ladle shroud consisted on the expansion and compression and expansion again of the liquid steel feeding stream. In this work, the individual research variant was being described as follows: case 1 - the use of conventional ladle shroud (CLS) immersed in liquid steel at a depth of 0.1 m, case 2 - the use of conventional ladle shroud immersed in liquid steel at a depth of 0.4 m, case 3 - the use of modified ladle shroud (MLS) immersed in liquid steel at a depth of 0.1 m and case 4 - the use modified ladle shroud immersed in liquid steel at a depth of 0.4 m. **Figure 1** shows the tundish variant with the conventional and modified ladle shroud immersed in liquid steel at depth of 0.1 m. The numeration of the tundish outlets presented on the **Figure 1** take effect during the describing of the research results.

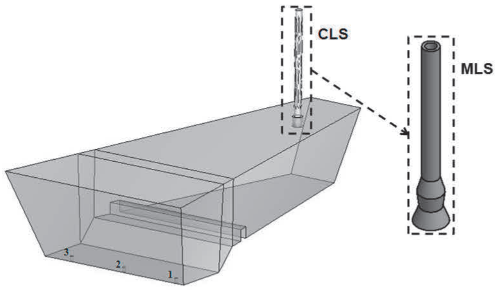

Figure 1 The virtual model of the tundish with the considered ladle shrouds

The 3d virtual objects were performed in the Gambit computer program using the bottom-up and Boolean method. The virtual tundishes were divided by a computational grid which consisted with control elements in the range of 200000-221000 (depends of the research case). Then, the boundary conditions were attributed on the individual tundish walls. The performed tundishes were exported to the Ansys-Fluent computer program, where the numerical simulations of liquid steel flow were done in the considered objects. The mathematical model which describe the liquid steel hydrodynamic structure equipped with the Realizable k-ε turbulence model was used in the calculations [9]. The numerical simulations imitated the continuous bloom casting process with dimensions of 0.28 × 0.28 m. The following parameters were established at the ladle shroud beginning: liquid steel temperature 1823 K, velocity 0.76 ms^{-1}, turbulence kinetic energy 0.005776 m^2s^{-2}, turbulence kinetic dissipation 0.012542 m^2s^{-3}. The phenomenon of heat transfer between tundish and surrounding atmosphere was taken into account by attributing on the individual tundish walls heat loses, which were described in details in work [10]. Whereas, the upper tundish surface imitated the liquid steel/tundish powder boundary. Moreover, the used in calculations the physicochemical properties of liquid steel were described in work [4].

The analysis of the liquid steel flow hydrodynamic structure consisted on the examination and the visual assessment of fields of liquid steel flow and temperature on a vertical plane being the tundish symmetry (which passed through the ladle shroud and tundish outlet number 2). Furthermore, the turbulence intensity of liquid steel was investigated on the tundish bottom under the ladle shroud. The turbulence intensity was counted by the relation of the turbulence kinetic energy and the velocity flow of liquid steel [10].

Then, the analysis of the tundish working conditions were performed based on the residence time distribution E and F type curves. The generation of E curve was consisted on the pulse introducing the marker into the ladle shroud and recoding the marker concentration in the individual tundish outlets. A time and a marker concentration were converted into dimensionless values using equations described in works [11,12]. Also, the results from E type curve allowed to estimate the liquid steel flow volumes (plug, ideal mixing and stagnant flow volume) in the individual tundish outlets using the dependence described in details in work [12]. Then, the F curve were generated which allowed to the determination of the transition zone during sequential casting process. The performance of F curve was consisted on the introducing of marker into ladle shroud (with continuous signal) and recording the change of marker concentration in the tundish outlets. The transition zone can be changed according to the production specification of the considered steel plant. In this work the transition zone was established in the range from 0.2 to 0.8 dimensionless marker concentration. Moreover, the analysis of residence time distributions allowed to estimate the level of the liquid steel flow asymmetry in the tundish working space.

3. RESEARCH RESULTS

The visual assessment consisted on the analysis of the liquid steel flow and temperature fields. **Figure 2** presents fields of the liquid steel flow in the case 1 and 3. The two circulation stream were generated by the feeding stream along of the tundish bottom in all considered cases. However, the circulation streams between the left wall and tundish bottom were different shapes among of cases. Particularly in the case 3, a large impact of the circulation stream was visible (from the tundish bottom to the liquid steel/tundish powder boundary). The modified ladle shroud decreased the momentum of the liquid steel feeding stream in view of nearby location of the circulation stream from the right side of the ladle shroud. Furthermore, a horizontal circulation stream was noted over the left corner of the dam in the case 2, 3 and 4. Also, the circulation stream was noticed in the outlet tundish zone in the cases with the modified ladle shroud. Moreover, the backflows were visible in the all research cases which headed to the circulation stream located to the right side of the feeding stream. Generally, the liquid steel flow structure was a falling-horizontal in the cases with the conventional ladle shroud, whereas the hydrodynamic structure was a horizontal in the cases 3 and 4. Furthermore, the change of the ladle shroud immersion depth in liquid steel impacts slightly on the liquid metal flow fields. **Figure 3** shows fields of the liquid steel temperature in the case 1 and 3. In general, the construction modification and change of the ladle shroud immersion depth in liquid steel didn't influence on the thermal homogenization in the considered tundish according to a similar liquid steel temperature close to the tundish outlet (about 1816 K). However, the higher temperature drops of liquid steel were visible close to the tundish bottom (on the left side of the dam) in cases with the modified ladle shroud.

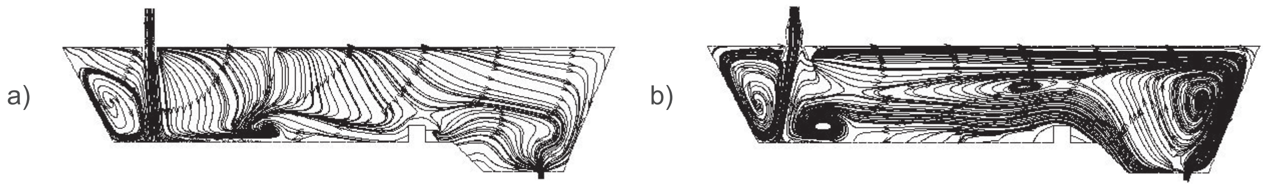

Figure 2 Fields of the liquid steel flow: a) case 1, b) case 3

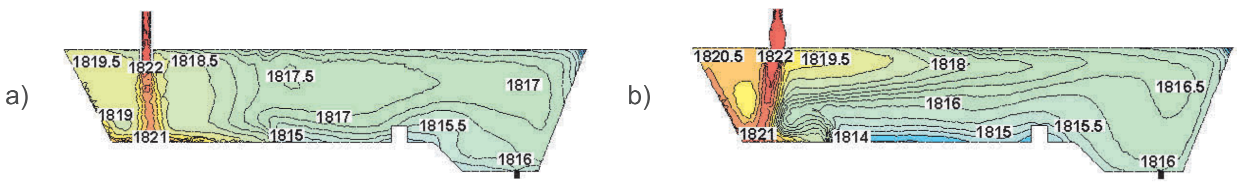

Figure 3 Fields of the liquid steel temperature: a) case 1, b) case 3

Then, the analysis of the liquid steel turbulence intensity was performed in the feeding zone in the tundish bottom (**Figure 4**). The comparison of **Figures 4a** and **4b** or **4c** and **4d** shows that a deeper immersion of the ladle shroud increase the liquid steel turbulence intensity in the tundish bottom, which can affect the wear of the object refractory lining. Furthermore, the modification of ladle shroud decrease the turbulence intensity of the feeding stream. Nevertheless, the proposed ladle shroud changes the direction of the feeding stream what was visible in **Figure 4c** and **4d** (the higher turbulence intensity was noted along upper part of the figures).

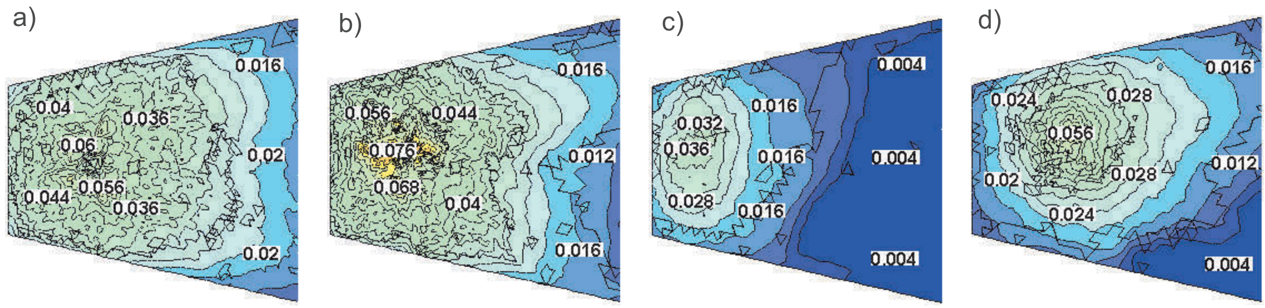

Figure 4 Fields of the liquid steel turbulence intensity in the feeding stream zone in the tundish bottom: a) case 1, b) case 2, c) case 3, d) case 4

Figure 5 represents the RTD E curves on the individual tundish outlet. In general, the shapes of the E curve from case 1 and case 2 were almost the same. However, in the cases with the modified ladle shroud the E curve shape were slightly different. In the tundish outlet 1 and 2, the highest marker concentration was different between case 3 and case 4. Furthermore, in the tundish outlet 3 can be seen the recirculation flow according to decreasing and increasing the marker concentration in time range from 0.2 to 0.6 in the cases with the modified ladle shroud. The RTD F curve of the individual tundish outlet are presented in **Figure 6**. The shape of the F curves were similar between variants with the conventional ladle shroud. Nevertheless, like in the E curve analysis, the change of the modified ladle shroud immersion depth in liquid steel influence on the marker behavior in the tundish working space. The biggest differences can be seen in the tundish outlet 2 and 3 in time range from 0.2 to 1.2. Furthermore, the cases with the use of the conventional ladle shroud were characterized by a shorter transition zone during sequential casting process. Then, the quantity analysis was performed, what was showed in **Table 1**. The active flow volume, stagnant flow volume and the transition zone were indicated on the individual tundish outlet. Also, the relations between average (from three tundish outlet) active and stagnant flow volume were presented. Then, the average transition zones were counted for the each research case and the asymmetry factor were indicated (the highest difference in the transition zone between the three tundish outlets). The analysis showed that the cases with the conventional ladle shroud were characterized by a higher range of the active flow volume, a shorter transition zone and a lower liquid steel flow asymmetry than cases 3 and 4.

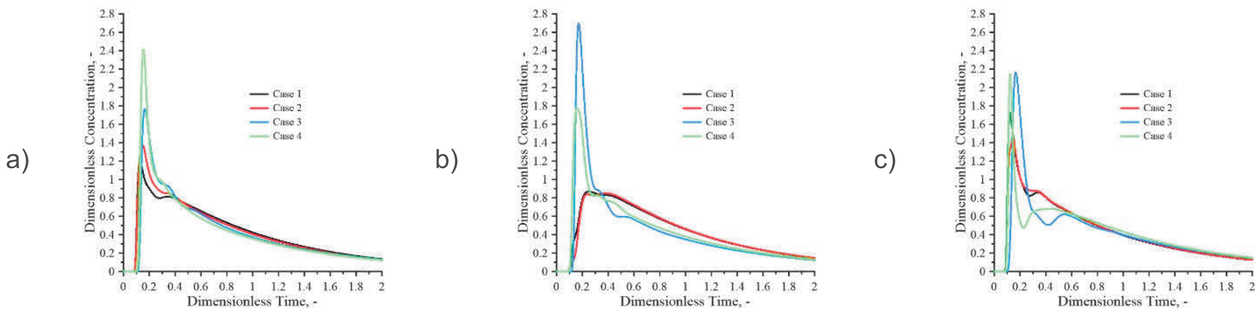

Figure 5 E curves of the cases under consideration:
a) tundish outlet 1, b) tundish outlet 2, c) tundish outlet 3

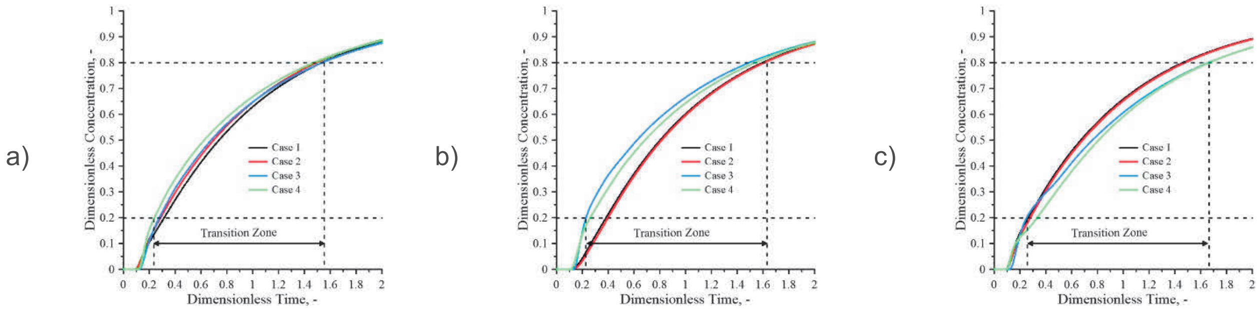

Figure 6 F curves of the cases under consideration: a) tundish outlet 1, b) tundish outlet 2, c) tundish outlet 3

Table 1 The quantity analysis of the RTD curves: AF - active flow volume, PF - plug flow volume, MF - ideal mixing flow volume, SF -stagnant flow volume

Case No.	Tundish outlet No.	AF [%]		SF [%]	$\overline{AF}/\overline{SF}$ [-]	Transition zone [-]	Average transition zone [-]	Asymmetry factor [-]
		PF [%]	MF [%]					
1	1	8.94	56.94	34.12	1.95	1.22	1.21	0.02
	2	15.29	54.43	30.28		1.21		
	3	8.34	54.27	37.39		1.20		
2	1	10.12	53.91	35.97	1.94	1.21	1.21	0.01
	2	21.86	48.69	29.45		1.21		
	3	9.52	53.93	36.55		1.20		
3	1	10.84	50.91	38.25	1.59	1.26	1.31	0.15
	2	11.97	46.98	41.05		1.27		
	3	11.19	52.13	36.68		1.41		
4	1	10.52	49.13	40.35	1.68	1.23	1.28	0.11
	2	11.15	50.80	38.04		1.28		
	3	8.37	57.95	33.68		1.34		

4. CONCLUSIONS

The results of the numerical simulations allowed to indicate the conclusions as follows:

- The use of the modified ladle shroud influence on the liquid steel flow structure and temperature distribution.
- For the considered research cases, the change of the ladle shroud immersion depth in liquid steel has a slight impact on the liquid metal flow and temperature fields.
- The tundish bottom in cases with the modified ladle shroud is less exposed to the erosive affect of the liquid steel feeding stream, whereas by lowering ladle shroud immersion depth in metal that effect can be additional intensified.
- The change of the conventional ladle shroud immersion depth in liquid steel doesn't influence on the hydrodynamic structure according to a similar active flow volume, transition zone and asymmetry factor.

- Cases with the modified ladle shroud were characterized by a lower active flow volumes, a higher transition zones and asymmetrical liquid steel flow in the tundish working space. Whereas, for tundish case 3 and 4 a deeper immersion of the modified ladle shroud in liquid steel increases the active flow volume and decreases the transition zone and the asymmetry metal flow.

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