NUMERICAL ANALYSIS OF STEEL FLOW IN A FOUR-STRAND TUNDISH: EFFECT OF SPHERICAL IMPACT PAD GEOMETRY AND LADLE SHROUD MISALIGNMENT

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Abstract

Hydrodynamic conditions in the tundish play a crucial role in ensuring the quality of liquid steel and the effectiveness of refining processes during continuous casting. The present study focuses on the numerical comparison of flow characteristics in a four-strand tundish under various geometric configurations of impact pads and positional deviations of the ladle shroud. The calculations were performed using Computational Fluid Dynamics (CFD) in Ansys Fluent, employing the realizable k-ε turbulence model and particle tracking methods to determine residence time distributions. Simulated setups included impact pads of the Spherical K4 type and a standard impact pad, with modifications to their geometry and positional deviations of the ladle shroud from the reference axis. The analysis demonstrated that the standard impact pad results in longer residence times, enhancing the homogenization of liquid steel, however, this benefit is counterbalanced by the development of more dominant piston-type flow and a higher tendency toward red eye formation under misaligned shroud conditions. In contrast, configurations incorporating the Spherical K4 pad demonstrated a more uniform velocity field and higher flow stability under varying ladle shroud positions. These findings highlight the importance of impact pad design in maintaining stable flow behavior, particularly under non-ideal ladle shroud alignment, minimizing uneven refractory wear, mainly in the slag line region near the ladle shroud, and reducing dead flow zones.

Keywords: CFD simulation, tundish, spherical impact pad, ladle shroud misalignment, steel flow

1. INTRODUCTION

In continuous casting, the tundish plays a critical role in distributing and controlling the flow of liquid steel, ensuring product quality, minimizing inclusions, and optimizing refining reactions at the slag-metal interface. Achieving stable and uniform flow conditions is particularly challenging when the flow is influenced by variations in impact pad geometry and deviations in ladle shroud positioning, both of which can significantly affect the hydrodynamic behavior of the liquid steel. Impact pads are widely used to control the initial momentum of the incoming liquid steel stream and to promote favorable flow patterns within the tundish. Their geometry significantly affects residence time distribution (RTD), dead zone formation, and flow stability. Previous studies have demonstrated that optimized impact pad designs can improve inclusion removal and temperature homogenization, reducing the risk of steel quality deterioration [1,2].

Numerical and physical modeling approaches are essential tools for investigating tundish flow behavior under various operational and design scenarios. These methods enable the evaluation of different configurations without interrupting industrial production, allowing researchers to compare the efficiency of flow control devices such as impact pads and dams [1,3,4]. While recent studies have highlighted the importance of combining CFD simulations, water model experiments, and industrial trials to validate tundish design improvements, this work focuses specifically on the numerical analysis based on CFD methods [4,5].

Additionally, research has shown that tundish flow behavior is highly sensitive to asymmetric conditions, such as ladle shroud misalignments or non-isothermal effects, which can lead to unstable flow patterns and reduced process control [6]. This highlights the need for comprehensive numerical studies that consider both ideal and non-ideal operating conditions. The present study focuses on the numerical analysis of flow behavior in a four-strand tundish, evaluating the effects of different impact pad geometries and ladle shroud misalignments. Specifically, the study compares a standard flat impact pad with a Spherical K4 impact pad, which features a three-dimensional geometry designed to enhance flow distribution. The aim is to assess how these designs perform under various misalignment scenarios using CFD simulations with the realizable k-ε turbulence model and particle tracking methods to analyze RTD behavior. The findings are expected to contribute to improved tundish operation by identifying configurations that maintain stable and uniform flow, even under non-ideal ladle shroud alignment.

2. MATERIALS AND METHODS

Tundish Geometry and Configurations

The analyzed tundish **Figure 1** represents an industrial four-strand design with an operating volume of 7.794 m^3, typically used for continuous casting sequences involving approximately 65 tons of liquid steel cast over 35 minutes. Based on similarity criteria and the physical properties of steel, the calculated volumetric flow rate for the simulations was 30.92 $kg\cdot s^{-1}$, corresponding to an average flow velocity of 0.878 $m\cdot s^{-1}$, assuming a steel density of 7020 $kg\cdot m^{-3}$.

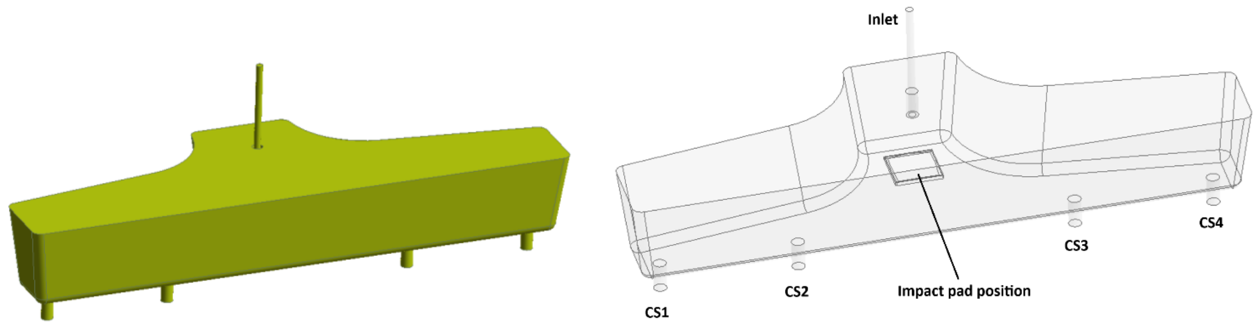

Figure 1 Geometrical representation of the internal fluid volume (Left) and the external structural volume (Right) with visualization of the basic positioning of all investigated impact pads in the tundish.

Two different impact pad configurations **Figure 2** were considered to evaluate their influence on flow behavior. The first configuration employed a standard impact pad, designed to redirect the incoming liquid steel stream vertically downward. The second configuration used a Spherical K4 impact pad, featuring a three-dimensional geometry intended to enhance energy dissipation and promote more uniform flow distribution throughout the tundish volume. In addition to these impact pad geometries, the influence of ladle shroud misalignment was analyzed. Several positional deviations were simulated, including a lateral displacement of 200 mm left from the tundish centerline and tilting of the ladle shroud by 4.7°, in backward direction. Combined positional and angular deviations were also tested to represent realistic operational conditions.

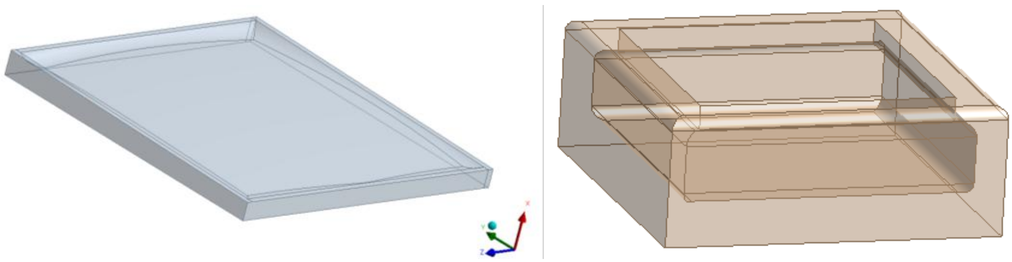

Figure 2 Geometrical models of the evaluated impact pads: Spherical K4 impact pad (left) and standard impact pad (right).

Computational Fluid Dynamics (CFD) Simulation Setup

The numerical simulations were performed using Ansys Fluent, the software developed by ANSYS, Canonsburg, PA, USA, applying the realizable k-ε turbulence model to capture turbulent flow characteristics. The computational domain was discretized using a polyhedral mesh with 204,100 elements. The mesh quality was assessed based on skewness and orthogonality criteria, achieving an average skewness of 0.2318 and a maximum orthogonality of 0.99237, which confirmed the suitability of the mesh for accurate numerical analysis.

The Reynolds number, calculated in equation (1) for the circular cross-section of the ladle shroud inlet, reached a value of Re = 682,935, confirming fully turbulent flow conditions. Based on this, the realizable k-ε turbulence model was selected as appropriate for capturing the complex turbulent structures typical of industrial tundish operations. Turbulence intensity at the inlet was determined as 2.98 %, derived from the calculated Reynolds number, while the outlet was modeled as a pressure boundary with a turbulence intensity of 5 %. A tracer was injected into the flow for 10 seconds to evaluate residence time distributions using particle tracking methods. Both steady-state and transient simulations were performed. The transient analysis involved 8,000 time steps with a time step size of 0.1 s (max. iterations 20), allowing detailed tracking of tracer particle transport and flow development over time.

$$I = 0.16 * Re^{\left(-\frac{1}{8}\right)} * 100 \qquad (1)$$

where:

I - turbulence intensity (%),

Re - Reynolds number (-)

Evaluation Criteria

The hydrodynamic behavior of each configuration was evaluated by analyzing velocity vector fields, which provided insight into flow direction, stability, and the formation of recirculation zones. Concentration contours of tracer particles were used to identify stagnant regions with low flow activity, which are undesirable for effective mixing and temperature homogenization. Residence time distributions (RTD) were calculated based on particle tracking data and expressed as C-curves for each casting strand. These curves allowed for the determination of minimum and maximum residence times, offering a quantitative comparison of flow efficiency between the tested configurations. Additional qualitative evaluation focused on identifying flow patterns indicative of piston-type flow, which can lead to short-circuiting and reduced mixing efficiency, and the formation of red eye phenomena, associated with high-velocity regions near the ladle shroud and increased refractory wear. These observations were critical for assessing the practical performance of the investigated impact pad geometries and their ability to maintain stable flow under misalignment conditions.

3. RESULTS AND DISCUSSION

The influence of impact pad geometry and ladle shroud misalignment on tundish flow behavior was evaluated based on six selected configurations. Two of these served as reference cases with standard and Spherical K4 impact pads under ideal ladle shroud alignment. The remaining four configurations examined the effects of ladle shroud misalignment, including a 200 mm displacement to the left and a 4.7° backward tilt. Both misalignment scenarios illustrated in **Figure 3** were applied to the standard and Spherical K4 impact pads to assess their sensitivity to non-ideal ladle shroud positioning. An overview of these analyzed configurations is provided in **Table 1**.

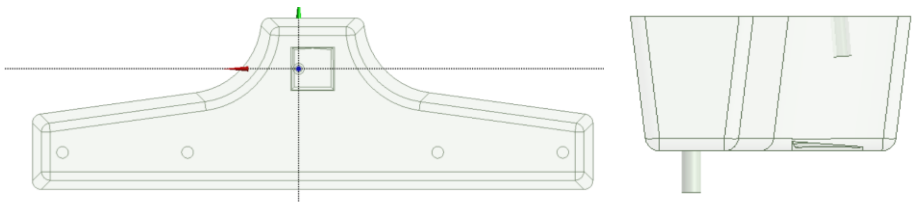

Figure 3 Visualization of the ladle shroud misalignment: 200 mm left displacement (left) and 4.7° backward tilt (right) in the tundish model.

Table 1 Overview of the analyzed tundish configurations with different impact pad types and ladle shroud positions.

Configuration ID	Impact pad type	Ladle shroud position
1	Spherical K4	Centered
2	Standard	Centered
3	Spherical K4	Displaced by 200 mm (left)
4	Standard	Displaced by 200 mm (left)
5	Spherical K4	Tilted by 4.7° (backward)
6	Standard	Tilted by 4.7° (backward)

The first criterion for evaluating the tundish flow behavior was the distribution of the tracer after 400 seconds, which provides insight into the formation of dead zones and overall mixing efficiency. **Figure 4** presents a side-by-side comparison of tracer concentration for all analyzed configurations.

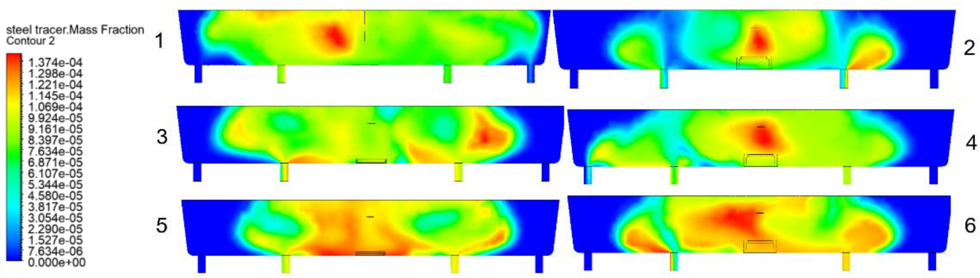

Figure 4 Distribution of tracer concentration at 400 seconds for all analyzed configurations

The comparison of tracer distribution after 400 seconds **Figure 4** shows that the Spherical K4 impact pad **1** provides the most favorable flow behavior, with improved dispersion in the upper region of the tundish, supporting better refining reactions at the slag-metal interface. This configuration also achieves the lowest dead zone volumes. When comparing the effect of 200 mm left displacement, the Spherical K4 **3** shows better flow distribution compared to the standard impact pad **4**, which exhibits larger dead zones near the outlets.

For the 4.7° backward tilt, both impact pads **5** and **6** show similar flow behavior, with no significant advantage observed for either geometry.

The second evaluation criterion focuses on the direction and character of liquid steel flow, which influences the intensity of piston-type flow and the risk of red eye formation. **Figure 5** presents a comparison of velocity vector fields for all analyzed configurations.

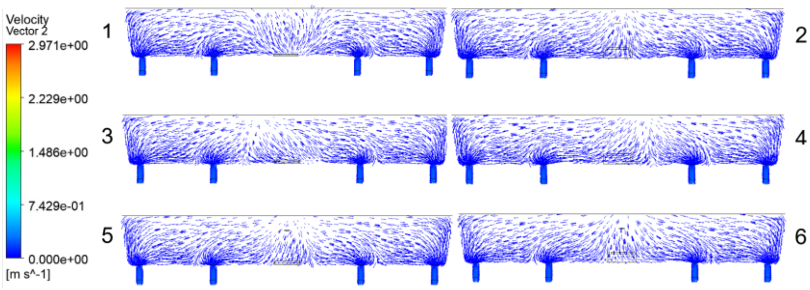

Figure 5 Visualization of the velocity vector fields showing the flow direction and intensity in the tundish for all analyzed configurations.

In the reference configurations, the standard impact pad **2** shows noticeable piston-type flow near the ladle shroud, increasing the risk of red eye formation. In contrast, the Spherical K4 impact pad **1** distributes the flow more evenly into the tundish volume, while both pads demonstrate favorable flow just below the slag layer, supporting effective refining reactions at the slag-metal interface. With the 200 mm left displacement **3** and **4**, the standard impact pad **4** promotes more concentrated flow on the right side, while the Spherical K4 **3** shifts the flow activity toward the left side. In the 4.7° backward tilt configurations **5** and **6** the flow appears more stabilized, with no significant difference between the two impact pad designs.

The third evaluation criterion focuses on the C-curves, representing the residence time distribution (RTD) for each strand. **Figure 6** shows examples of C-curves for configurations 1 (Spherical K4) and 2 (Standard impact pad), with time in seconds on the x-axis and dimensionless concentration on the y-axis.

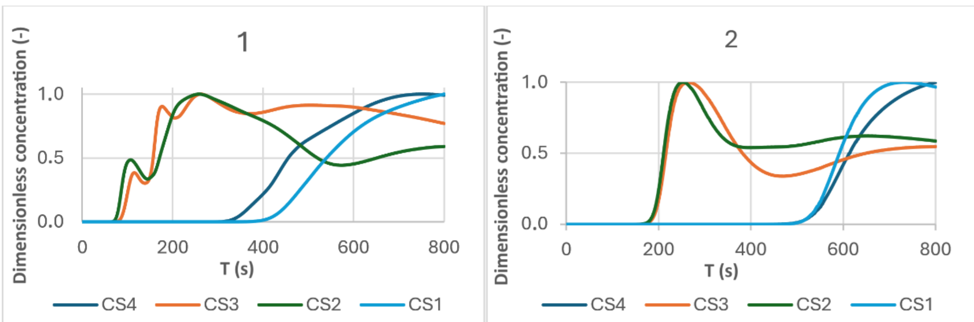

Figure 6 Example and comparison of C-curves for configurations 1 (Spherical K4) and 2 (Standard impact pad) measurements.

Based on the overall comparison of all evaluated configurations, the standard impact pad achieves longer residence times on all casting strands compared to the Spherical K4. However, the Spherical K4 shows clearly visible oscillations in the C-curves, indicating a more complex and less stable flow distribution in the tundish. This behavior results from the combination of tundish geometry and the specific shape of the impact pad. The effect of ladle shroud misalignment is significant across all tested configurations, influencing flow uniformity and residence time distribution. The quantitative results for all configurations are summarized in **Table 2**, presenting the minimum and maximum residence times for all four casting strands.

Table 2 Summary of the minimum (Tmin) and maximum (Tmax) residence times in seconds for all analyzed configurations (1 to 6) and all four casting strands.

Resulting min. and max. residence times								
	Tmin (s)				Tmax (s)			
	CS1	CS2	CS3	CS4	CS1	CS2	CS3	CS4
1	262	49	56	249	800	258	262	752
2	374	120	126	359	731	252	262	800
3	301	91	87	296	781	276	316	725
4	332	93	111	320	800	292	224	472
5	339	98	88	347	752	239	343	800
6	362	94	124	373	800	306	283	627

As mentioned earlier, the results in **Table 2** show that the standard impact pad achieves higher residence times, but with greater variation between strands. In contrast, the Spherical K4 impact pad provides more balanced residence times across the outlets, despite showing more oscillating C-curve profiles, which indicate locally more complex flow behavior. The standard impact pad shows smoother C-curves, but with less uniform distribution between strands.

4. CONCLUSION

The study confirmed that impact pad geometry and ladle shroud position significantly affect tundish flow. The standard impact pad achieved longer residence times and better homogenization but showed stronger piston flow and a higher risk of red eye under misalignment. The Spherical K4 impact pad provided more uniform and stable flow, lower piston flow intensity, and less sensitivity to misalignment. Spherical K4 is recommended for stable flow control, while the standard impact pad is suitable for longer residence time and refining.

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