THERMAL AND FLOW FIELD ANALYSIS IN THE CC MOLD FOR TWO STEEL GRADES USING CFD TOOLS

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Abstract

This study is focused on the numerical analysis of molten steel flow in the CC mold of a continuous casting machine for two different steel grades - ferritic low-carbon stainless steel 409L and normalized structural steel S275N, by EN 10025-3. The aim was to identify the influence of the physical and metallurgical properties of these steels on flow behavior and thermal conditions in the solidification zone. Simulations were realised using Computational Fluid Dynamics (CFD) at two different casting speeds.

Velocity profiles and temperature gradients were analyzed along two reference lines: one positioned at the steel surface and the other along the vertical sidewall of the mold. Based on the temperature gradient, the position of the start of solidification of the casting was determined for steel and process configuration. The results revealed significant differences in hydrodynamic behavior and heat transfer characteristics between the two steel grades, which manifested in variations in the length of the liquid zone and the formation of the primary solid shell. Ferritic stainless steel 409L has higher fluidity and a faster solidification process, whereas S275N showed slower heat dissipation and lower turbulent kinetic energy.

The findings provide a foundation for optimizing the technological parameters of continuous casting processes with regard to the specific behavior of different steel grades.

Keywords: CC mold, CFD, steel, optimizing

1. INTRODUCTION

The flow of molten steel in the mold plays a key role in the solidification process, the removal of inclusions and the quality control of castings. The behaviour of the steel flow, which can be laminar, swirling or turbulent, is influenced by mold geometry, casting speed, steel properties and mold oscillation [1]. Optimal flow should promote uniform temperature distribution, efficient inclusion removal and minimise turbulence, which leads to defects. The molten steel is passed through a tundish shroud where two main flow directions are generated from the shroud - one towards the surface and the other diagonally downwards. The flow is also influenced by the addition of argon, which can change the nature of the liquid steel flow if the quantity is incorrect [2]. Non-uniform heat transport can cause surface defects and disrupt the solidification structure [3]. Therefore, a stable and optimised flow is essential to achieve a quality casting, and CFD numerical simulations are an effective tool for its analysis and optimisation [4].

The present study focuses on the numerical analysis of the behavior of molten steel in a mold during the continuous casting of two different steel grades: low carbon ferritic stainless steel 409L and standard structural steel S275N according to EN 10025-3. The objective of this work is to identify the influence of the physical and metallurgical characteristics of these materials on the hydrodynamics of the flow, thus contributing to the optimization of their casting.

To achieve this, Computational Fluid Dynamics (CFD) was used to provide a detailed simulation of the flow and temperature fields at different casting speeds. The analysis focused on the evaluation of velocity profiles and temperature gradients along reference sections located at the melt surface and at the side wall of the mold. The results of this study [5-7] provide important insights into the influence of the material properties of the cast steels on the continuous casting process and provide a basis for more effective control of the process conditions in order to achieve higher quality castings.

2. METHODOLOGY

The numerical simulations were carried out using Ansys Fluent, a software developed by ANSYS, based in Canonsburg, PA, USA. The calculations were performed on a 3D model (**Figure 1**), which is a physical model of the mold at a scale of 1:1 to the real device.

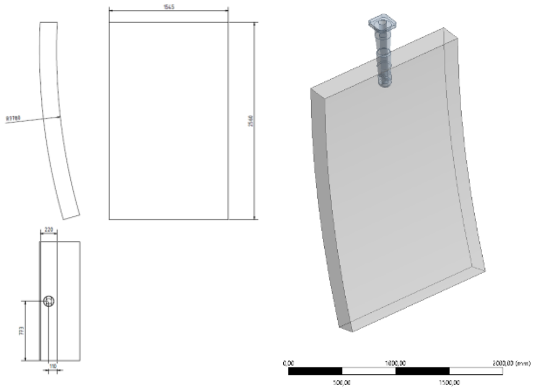


Figure 1 Sample 3D model of the mold

The first area of interest was the upper part of the mold. The basic values of the Reynolds number Re (1) [8] according to the 3D model and the turbulence intensity (2) [9] were calculated to improve the simulations accuracy.

$$Re = \frac{v \cdot \mathrm{d}_h}{\nu} \qquad (1)$$

Where: v – fluid flow velocity (m/s), d_h – hydraulic diameter (m), v – kinematic fluid viscosity (m^2/s)

$$I = 0{,}16 * Re_{dh}^{-\frac{1}{8}} \qquad (2)$$

Type 409LSS and S275N steels were used as simulation flow media. Type 409LSS steel [10] belongs to the group of ferritic unalloyed stainless steels and type S275N steel [11] belongs to the group of unalloyed structural steels. The chemical compositions of the steels are shown in **Table 1**. Physical properties such as specific gravity, specific heat capacity, thermal conductivity and dynamic viscosity have been defined for both steels. At the inlet, the steel temperature was defined to be 1823 K.

Table 1 Chemical composition of steels

Steel	C	Mn	Si	S	P	Cr	Ni	Al	Ti	N	Liquid temperature
	(wt%)										(°C)
409LSS	0.005	0.27	0.54	0.001	0.0224	11.2	0.1	0.003	0.22	0.008	1505-1515
S275N	0.2	1.5	0.5	0.025	0.025	-	-	0.02	-	0.012	1490-1500

The quality of the computational network was assessed using skewness and orthogonality parameters. A network independence analysis was also performed to verify reliability. Three levels of network refinement - gross (823,231 elements), medium (1,602,956 elements) and fine (2,000,369 elements) - were compared by evaluating output variables such as tracer concentration and temperature field distribution. The results showed that although the gross mesh had higher biases, the differences between the medium and fine meshes did not exceed 3%. This confirms that the model is independent of the computational grid and that the gross grid represents a suitable compromise between accuracy and computational effort. The mathematical model used for the calculation was the k-epsilon standard wall function [12].

3. EVALUATION OF SIMULATIONS

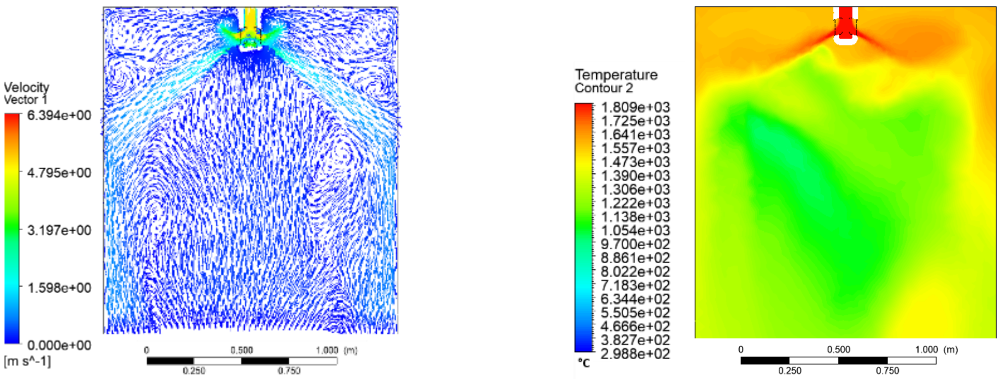
The results were evaluated by observing the flow pattern of the liquid steel at the selected levels using contours, vectors, streamlines and the temperature distribution of the flowing molten steel in the region of the tundish shroud and the mold walls. For a more detailed view and comparison of the velocity profiles and temperature gradient, line segments were created and placed at the side wall of the mold and below the level of the molten steel in the mold. The simulations were run at two casting speeds, 0.8 m/min and 1.4 m/min.

Figure 2 (a) shows the vector field of the liquid steel flow in the mold during the continuous casting process. The nature of the flow corresponds to two main streams which are considered to be optimal in terms of solidification quality and efficient inclusion removal [13].

The molten steel is passed through the SEN tundish shroud, which divides it into two main streams. The upper stream, directed diagonally upward toward the melt surface, helps move inclusions to the surface where they are subsequently captured by the flux powder. The lower stream, directed diagonally downward, provides intensive mixing in the lower parts of the mold and promotes stable growth of the solidified casting shell.

The significant symmetry of the vector field around the vertical axis of the SEN indicates a well-stabilized flow, without the occurrence of a single main stream that could negatively affect solidification uniformity and cause casting shell breakage. Also, no excessively intense stagnation zones are observed, confirming efficient bypassing and heat distribution. Temperatures in the surface region of **Figure 2**(b) range from approximately 1600-1800 K (orange-red regions). This indicates that there is still a warm melt on the surface, which is important for trapping inclusions. Temperatures on the walls decrease downwards. In the coolest zones they reach values below 900 K (green-blue color). The most pronounced temperature gradient is seen from the SEN (top center) downward and toward the sidewall, where the steel cools significantly and the casting shell begins to form.

Overall, the visualized flow represents the desirable flow dynamics of molten steel, which is suitable for uniform heat transfer, efficient removal of inclusions and thus an increase in the quality of the final casting [14].



(a) (b)

Figure 2 Illustration of vector (a) and temperature field (b) for liquid steel flow in a mold.

Three main influences on the flow pattern of the molten steel, such as the immersion depth of the SEN tundish, the casting speed and the steel grade, were investigated. **Table 2** shows the tested configurations.

Table 2 Overview of simulated configurations

Configuration	Steel grade	SEN immersion depth (mm)	Casting speed (m/min)	Distance from the surface where the liquid temperature was reached (m)	Evaluation
1A	409L	245	1.4	0.25	Higher flow rates result in good mixing but higher turbulence. Ferritic steel better tolerates faster heat removal
1AC	S275N	245	1.4	0.75	Same immersion depth but less turbulence, stable solidification. S275N is more sensitive to temperature changes, so quieter dynamics are preferred.
2A	409L	195	1.4	0.6	Lower immersion depth, which promotes intensive mixing. Can lead to surface instability, but ferritic steel handles this better
2AC	S275N	195	1.4	0.8	Likewise, low depth causes a reduction in velocity, higher viscosity and the need for higher stability. Less suitable for intensive mixing
3A	409L	295	1.4	0.4	The flow is more stable and even. Advantageous for uniform solidification, ferritic steel handles higher flow without defects
3AC	S275N	295	1.4	0.55	Higher velocity across the width, resulting in intense mixing but also increased turbulence, but still the lowest and most stable velocity profile across the height, which is favourable for solidification stability.
2AA	409L	195	0.8	0.75	Stable speed and temperature profile, suitable for uniform solidification. Ideal compromise between mixing and flow stability.
2AAC	S275N	195	0.8	0.25	Lowest flow velocity, weaker mixing, higher temperature gradients. Suitable only if level and temperature regime is controlled
3AA	409L	295	0.8	0.25	The large immersion depth ensures a stable temperature profile, uniform solidification. Suitable for thicker formats and quiet casting
3AAC	S275N	295	0.8	0.3	Very stable temperature field, low turbulent energy. Suitable for S275N - helps prevent defects

4. DISCUSSION

In this work, different configurations of simulations of molten steel flow in the mold during continuous casting were evaluated, specifically the variants labelled as 1A, 1AC, 2A, 2AC, 3A, 3AC, 2AA, 2AAC, 3AA, and 3AAC.

The main evaluation criteria were the grade of casting steel (ferritic stainless 409L and structural S275N), the immersion depth of the tundish shroud, and the casting speed (1.4 m/min and 0.8 m/min, respectively).

Ferritic steel 409L, which has higher thermal conductivity and better heat removal capability, showed good tolerance to both faster flow and shallower immersion depth. Configurations such as 2A and 3A (both with a higher casting speed of 1.4 m/min) exhibited high dynamic flow with intense mixing, which was advantageous for uniform temperature distribution but at the risk of faster flow. The 2AA and 3AA configurations, with a lower casting speed (0.8 m/min), provided more stable thermal and velocity fields and represented an optimal compromise between dynamics and stability, especially at greater immersion depths (295 mm).

By contrast, S275N structural steel is more sensitive to changes in thermal gradient and requires more stable flow. Configurations such as 1AC, 2AC and 3AC at higher casting speeds offered acceptable conditions, but the best results were obtained at lower casting speed (0.8 m/min) in 2AAC and 3AAC configurations. These exhibited very low turbulent energy, uniform temperature profiles and surface stability, which is desirable for this steel to prevent defects during solidification.

In terms of immersion depth, it was found that the greater the immersion depth of the SEN (295 mm), the more stable the flow in the crystallizer and the more uniform the thermal field. Although the lowest immersion depth (195 mm) increased the flow dynamics, it also increased the risk of surface instability, which was more problematic especially for the S275N casting. Based on the results of the simulations, the distance from the steel surface when the liquidus temperature was reached was also evaluated. The evaluation was based on the influence of the steel grade, the casting speed and the immersion depth of the tundish shroud (SEN).

Effect of steel grade (409LSS vs. S275N) - 409LSS steel (stainless, with higher liquidus temperature ≈ 1505-1515 °C) reaches this temperature significantly higher in the stream, i.e. closer to the surface, than S275N steel (lower liquidus temperature ≈ 1490-1500 °C). This means that under the same casting conditions, S275N steel cools more slowly, and solidifies lower in the stream. This difference is due to the lower liquidus temperature of S275N, which allows the melt to remain in the liquid state longer.

Effect of casting speed (1.4 m/min vs. 0.8 m/min) - Reducing the casting speed to 0.8 m/min caused the temperature shift of the liquid to move higher from the surface (e.g., at 3AA 0.8 m/min → 0.25 m vs. 3A 1.4 m/min → 0.4 m). This effect is expected because the lower casting speed provides more time for cooling, leading to a faster arrival at the liquidus temperature.

Effect of SEN immersion depth (195 mm, 245 mm, 295 mm) - Increasing the SEN immersion depth leads to a decrease in the height where the liquidus temperature is reached, hence the liquidus moves deeper into the mold. For example, for 409LSS steel, at configuration 1A with 195 mm immersion → liquidus temperature reached as early as 0.25 m, at configuration 2A with 245 mm immersion → liquidus at 0.6 m, and configuration 3A with 295 mm immersion → liquidus as low as 0.4 m. Therefore, too little immersion causes too rapid cooling, more immersion can improve flow distribution and delay solidification - which can be beneficial for more uniform flow but increases the risk of segregation if cooling is not stabilised.

5. CONCLUSION

The numerical simulation results confirm that the height at which the steel reaches the liquidus temperature depends on the steel grade, the casting speed and the depth of immersion of the shroud (SEN). For ferritic 409L stainless steel (with a higher liquidus temperature), this height was typically closer to the surface, which is related to its higher thermal conductivity and ability to dissipate heat more quickly. Conversely, structural steel S275N, with a lower liquidus temperature, exhibited a deeper solidification zone, reflecting its slower heat dissipation.

Reducing the casting speed from 1.4 m/min to 0.8 m/min resulted in a significant upward shift of the liquidation point, as the lower speed provides a longer heat transfer time and an earlier achievement of the solidification temperature. This effect was particularly pronounced for 409LSS steel, which formed a more stable flow with a uniform temperature field at the lower speed.

With regard to the SEN immersion depth, it has been confirmed that a greater depth (e.g. 295 mm) results in a lower liquid point, thus keeping the melt in the liquid state for longer. This property is advantageous for solidification control in thicker casting shapes (slabs), but requires a stable flow, especially for the more sensitive S275N steel.

For 409L steel, configurations with higher speeds (1.4 m/min) and medium to deeper immersion depths (245-295 mm) proved optimal, providing both intensive mixing and uniform solidification. For S275N steel, deeper immersion and lower speed configurations (0.8 m/min), such as 2AAC and 3AAC, were most suitable, producing a very stable temperature field, ideal for preventing surface defects.

CFD simulations have thus proved to be an effective tool for optimising continuous casting process parameters with respect to the specifics of individual steels. The results provide specific recommendations for the adjustment of immersion depth and casting speed, which can serve as a basis for industrial application and quality improvement of the final products.

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