EFFECTS OF THE SUBMERGED ENTRY NOZZLE DESIGN ON THE SLAB MOLD FLOW PATTERN AND STEEL QUALITY

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ABSTRACT

The fluid flow pattern in the continuous casting mold has a major impact on the final product quality. It transports non-metallic inclusions and argon bubbles to either the top slag layer, where they will be entrapped, or the solidification front, where they will become defects. Moreover, excessive surface level fluctuations and high meniscus velocities may cause mold slag entrapment, deeper oscillation marks and other defects. The flow pattern could also affect the liquid slag penetration in the gap and have impact on the longitudinal crack index. One of the best ways to control the mold flow pattern and obtain high quality steel is through an optimal Submerged Entry Nozzle (SEN) design. In this work, the flow patterns for different SEN designs were evaluated through numerical simulations. The obtained flow fields were analyzed with focus on the prevention of defects in the final product. Through these studies, it was possible to understand how changes in the SEN design affect the mold flow pattern, and consequently, the steel quality.

INTRODUCTION

The study of the flow pattern in continuous casting molds is of great importance to the steel mill industry, and to the refractory industry as well, since many problems on steel quality have their origins in this step and are directly assigned to a low control of the mold's flow conditions.
The flow patterns in the slab casting mold can be divided into three types: Double Roll (DR), Single Roll (SR) and unstable (U). The DR is characterized by the steel jet colliding with the narrow face and splitting into two large recirculation zones, one towards the meniscus and the other towards the lower part of the mold. The SR, on the other side, consists on the steel jet traveling directly to the meniscus and then flowing down the mold along the narrow faces (NF). Finally, the U flow pattern happens when the flow is neither SR or DR but keeps permanently unstable even under constant flow conditions.

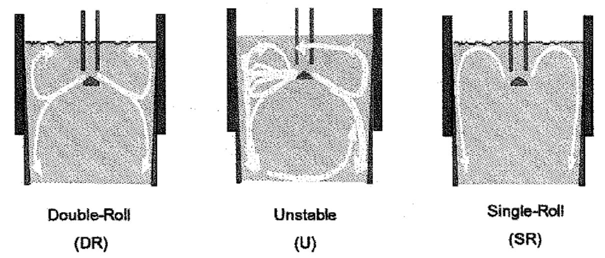

Fig. 1: Types of Flow Patterns in the Mold.[1]

Dauby[1] described the inherent flaws of each flow pattern type, stating that the preferred, defect-free flow, would be a DR which would be not too strong (DR+) and not too weak (DR-). A DR+ flow pattern could cause high meniscus velocities and level fluctuations, giving rise to mold powder entrainment and sliver defects. On the other side, a DR- flow would cause a cold meniscus with slow velocities and insufficient washing on the solidification front, risking defects such as long solidification hooks, slag patches on the slab surface and inclusion-based slivers. A SR flow would have the disadvantages of thinning of molten slag layer close to the SEN and propelling inclusions and argon bubbles deep into the slab, with the strong descending loop counteracting the flotation of the impurities. Such a flow could cause defects such as mid-broad face longitudinal cracks, pencil pipe defects and dirty subsurface. Finally, an U flow could provoke vortexing, uneven molten slag layer thickness and high mold level fluctuations, causing problems such as mold powder based slivers, uneven solidification shell and longitudinal cracks.
As the different flow pattern types are associated with a wide range of possible defects, controlling the flow to achieve a DR flow pattern which is stable enough to not cause problems due to meniscus velocities that are too high or too low is crucial to achieve a high steel quality. Therefore, the SEN design should encourage good flow patterns in the continuous casting mold. As stated by Thomas [2] "the shape of the nozzle is one of the few casting design variables that has an important impact on quality and yet can be easily changed at low cost over a wide spectrum of design shapes".
However, before changing the SEN design in the casting machine, mathematical modeling tools should be employed to predict whether the chosen concept will enhance the mold's flow pattern. The most widely used modeling techniques in fluid dynamics are physical and numerical. The former consists of creating a reduced scale model of the equipment using a common fluid, usually water, to study the flow behavior. The latter consists of modeling the equipment in a computational environment and using numerical methods to solve the fluid motion equations for the system. These mathematical results give insight on the flow behavior under different conditions and are a valuable tool to increase the chosen concept's probability of performing well on industrial practice.
In this work, the effect of different SEN design parameters in the mold flow pattern were analyzed through numerical simulations. The results were compared considering the defects associated with each flow pattern. The objective of this study is to provide further insight on how changes in the SEN design can enhance or degrade the final product quality.

MATHEMATICAL MODEL DESCRIPTION

This study adopted the numerical technique of the finite volume method to analyze the flow in the continuous casting mold. It consists in modeling the problem of interest in a computational platform and discretizing its domain into cells in which the partial differential equations that rule the fluid mechanics are linearized and solved in a simultaneous and interconnected way. The solutions obtained allow one to know theoretical values of quantities of interest, like pressure and velocity, in all simulated domains. Hence, is possible to acquire a general comprehension of the flow pattern of simulated conditions.
The simulations were made through the platform ANSYS CFX. The transport equations were solved to ensemble-averaged values throughout the time, with turbulent oscillations being filtered. This approach is known as Unsteady Reynolds Averaged Navier-Stokes (URANS), for transient flow

simulations, and it allows the obtainment of results with bigger practicality and lower computational cost when compared to Three different SEN geometries were compared in this study. All of them have upward port angles of approximately 10 degrees. The SEN port and bottom design varied between the different configuration. Design #1 has a well-bottom and a port geometry of 65 x 30 mm. Design#2 has an inverse mountain-bottom with ports sized 40 x 60 mm. Finally, Design #3 has the same port geometry of #2 but with a well-bottom. Fig. 2 shows the three SEN designs:

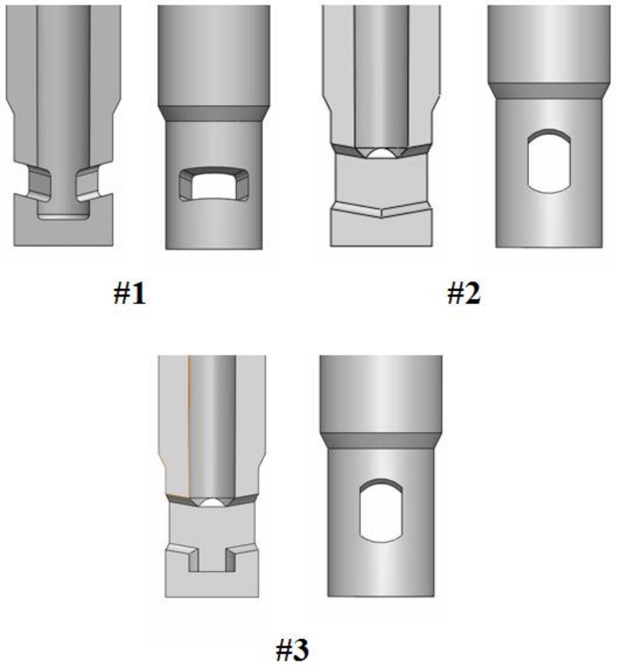

Fig. 2: SEN Geometries Compared.

The mold casting conditions and the considered material properties are listed in Table 1.

Table 1: Problem Description

Mold Width (mm)	1200 and 1500
Mold Thickness (mm)	200
Immersion Depths (mm)	120 and 170
Casting Speed (m/min)	0.7 m/min
Steel Viscosity	0.005 Pa.s
Steel Density	7000 kg/m^3

Symmetry was adopted at half the mold's width. No-slip boundary conditions with mass and momentum sinks to account for the solidification were applied to the mold walls. Details of this boundary condition can be found at the references[3,4]. No-slip conditions were also applied to the meniscus boundary, due to its viscosity being considerably higher than steel's.
The evaluated simulation results were the overall flow pattern in the mold and meniscus velocities. In the next section, these results will be compared for the three SEN geometries and prevention of defects in the final product will be discussed.

RESULTS DISCUSSION

Flow pattern

The flow pattern in the mold obtained under each different SEN configuration is evaluated through the averaged-velocities results in the mid-plane between the wide faces. Fig. 3 shows other models which aim to calculate the turbulent fluctuations in a direct way.
the scale adopted for all velocity results in this subsection and also in the next (Meniscus Velocities).

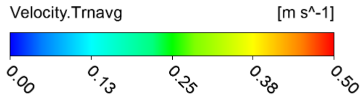

Fig. 3: Averaged Velocities Scale.

Fig. 4 shows the flow pattern results for the 1200 mm wide mold.

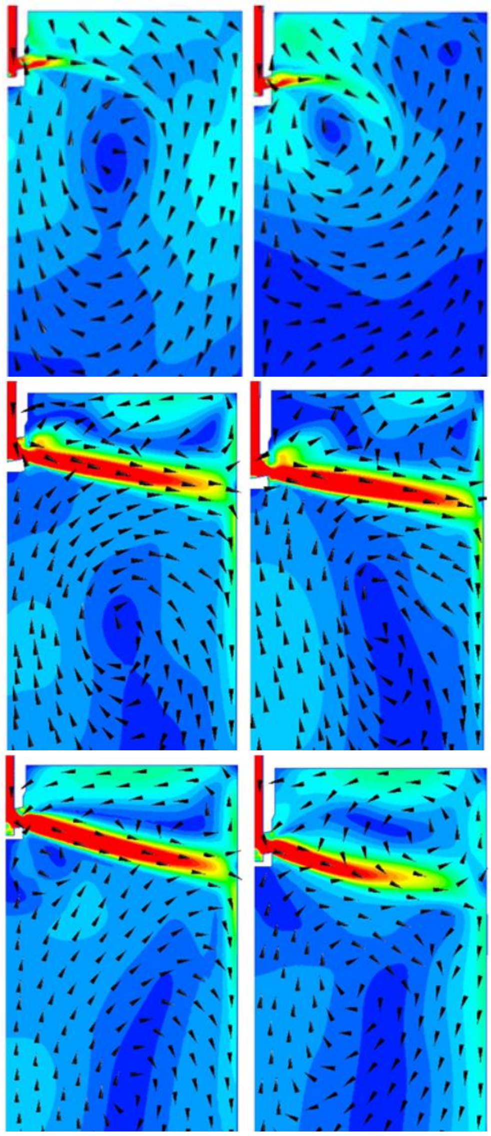

Fig. 4: Flow Pattern for the 1200 mm wide mold. Upper row(#1), mid row (#2) and lower row (#3). Immersion Depths of 120 mm on the left and 170 mm on the right.

. It can be seem that a SR flow pattern is obtained for both immersion depths under design #1. Configuration #2 showed a DR- flow pattern, especially for the deeper immersion, with the upper roll not developing completely due to secondary upward jets flowing against the primary downward jet which forms the recirculating upper roll. Finally, #3 shows a DR which seems to be well developed. It is interesting to note that the steel jet flows downward for designs #2 and #3 even though the ports have an upward angle. According to Thomas[2], "a consequence of large exit ports is that the nominal angle of the edges of the outlet port has less effect on the jet direction". Therefore, the port design of #2 and #3 is probably oversized in the vertical direction, causing the momentum of the downward flow in the SEN to be more influential on the jet direction than the port angle.

Fig. 5 shows the flow patterns obtained for the 1500 mm wide mold:

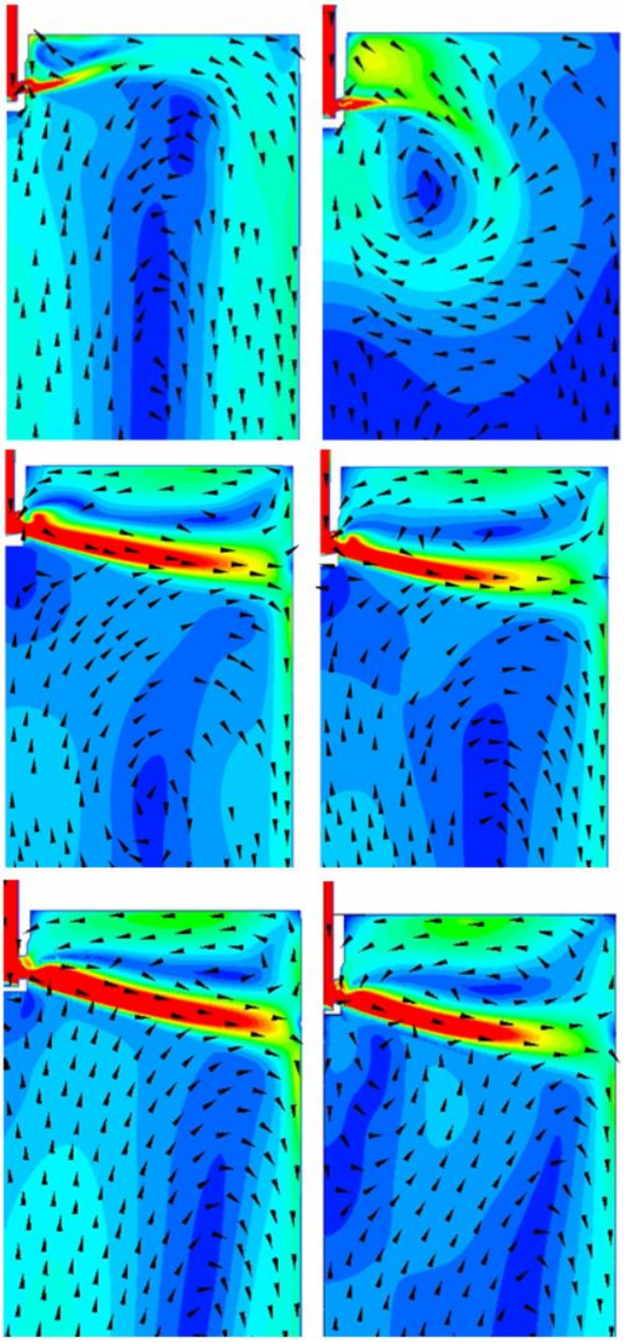

Fig. 5: Flow Pattern for the 1500 mm wide mold. Upper row(#1), mid row (#2) and lower row (#3). Immersion Depths of 120 mm on the left and 170 mm on the right.

Design #1 still shows SR flow patterns for both immersions. However, for the 1500 mm wide mold, #2 presents a better developed DR flow pattern. The reason for the different behavior compared to the 1200 mm wide mold is that with an increase of the mass flow rate, necessary to keep the same casting speed for the wider mold, the momentum-driven upper recirculation roll became stronger than the secondary upward jets, causing the upper roll to develop completely. Design #3 still shows a DR flow pattern, not changing its behavior between the different mold widths.

Meniscus Velocities

Meniscus velocities have a strict optimum range for assuring steel quality. According to Thomas[2], values below 0.1 – 0.2 m/s risk meniscus stagnation, which consequences are inadequate melting of the powder and also freezing of the steel meniscus, which aggravates the formation of hooks and associate defects such as entrapment of surface inclusions. On the other side, values above 0.3 – 0.4 m/s can cause excessive level fluctuations, giving rise to serious surface defects such as mold slag entrapment and surface depressions.

Fig. 6 shows the meniscus velocities for the 1200 mm wide molds.

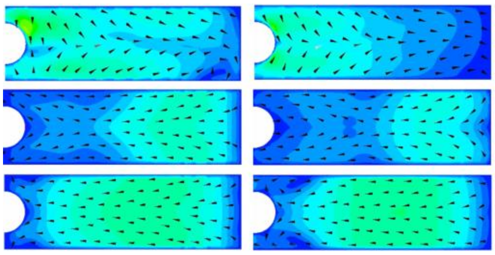

Fig. 6: Meniscus Velocities for the 1200 mm wide mold. Upper row(#1), mid row (#2) and lower row (#3). Immersion Depths of 120 mm on the left and 170 mm on the right.

From the results, excessive meniscus velocities were not detected for any of the simulated designs. However, Design #1 showed velocities below the recommended minimum for the 170 mm immersion in the narrow face region. Design #2 also showed low meniscus velocities close to the SEN for both immersion depths. Only Design #3 showed a steady profile of meniscus velocities across the entire width of the mold.

Fig. 7 shows the meniscus velocities for the 1500 mm wide mold.

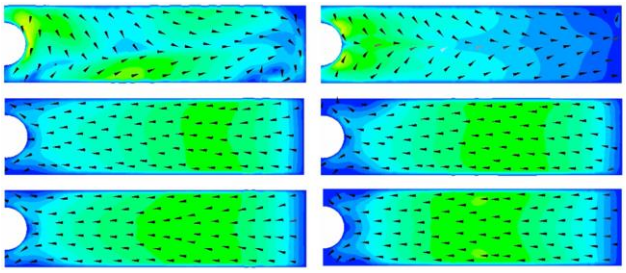

Fig. 7: Meniscus Velocities for the 1500 mm wide mold. Upper row(#1), mid row (#2) and lower row (#3). Immersion Depths of 120 mm on the left and 170 mm on the right.

The wider mold results show that for both Designs #2 and #3, the meniscus velocities are consistently close to 0.25 m/s for its entire width, which is inside the optimum range. As for Design #1, the 170 mm immersion case shows a decrease in the meniscus velocity from the SEN to the narrow face, having a region of lower velocities close to the NF.

Port Velocities

Fig. 8 shows the port velocities in the horizontal direction (from the SEN towards the NF). Values below zero indicate regions of backflow. The velocity profiles at the ports did not vary significantly between the different immersion depths, therefore only the values for 170 mm immersion were considered.

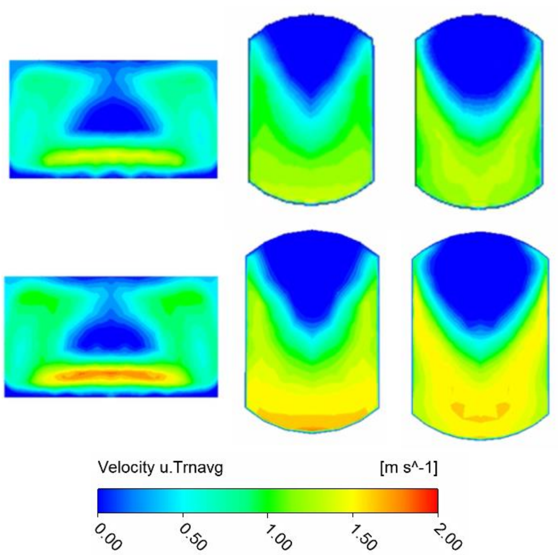

Fig. 8: Port Velocities. Upper row (1200 mm wide mold) and lower row (1500 mm wide mold). Left column (#1), middle column (#2) and right column (#3).

It can be seem that there is a large backflow zone in the upper region of the ports for Designs #2 and #3. On the other side, Design #1 shows a much smaller recirculation region. Large stagnation regions at the ports may aggravate clogging problems[2], so it is better to reduce them as much as possible.

Well-Bottom vs Mountain Bottom

As the port geometry effects on the flow pattern has been discussed, the last design variable left to be analyzed in this study is the differences caused by the choice of the well-bottom against the mountain-bottom.
The flow pattern analysis showed that, for the particular cases simulated in this study, the mountain-bottom produced a primary descending jet which would later form the upper roll and a secondary upward jet that would flow against the upper roll and disrupt its development for the molds of smaller width. The well-bottom, on the other side, would cause a single jet which would form a more stable DR.
To further investigate the reasons behind these changes, the eddy viscosity result was plotted in the inner channel of the SEN comparing Designs #2 and #3. Fig. 9 shows the scale adopted for the eddy viscosity results and Fig. 10 shows the plot results for the SEN:

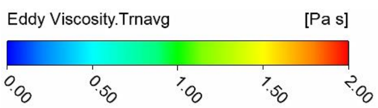

Fig. 9: Eddy Viscosity Scale.

It can be seem that the well-bottom encourages a higher exchange of momentum due to turbulent diffusion at the SEN bottom, leading to a more homogeneous steel jet exiting through the ports. This explains why the steel jet does not form the secondary upward jets for the well-bottom case, encouraging the full development of the DR flow pattern. Fig. 11 shows the eddy viscosity results at the ports for Designs #2 and #3.

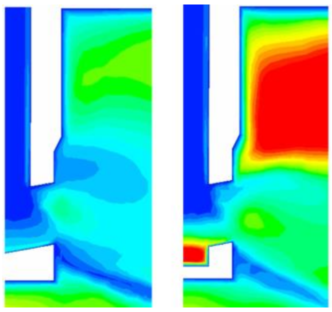

Fig. 10: Eddy Viscosity results at the SEN.

The eddy viscosity at the ports also show higher values of eddy viscosity for the well-bottom case, showing that turbulent diffusion plays an important role in stabilizing the steel jet leaving the SEN.

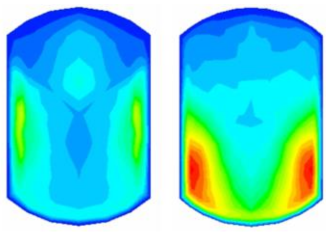

Fig. 11: Eddy Viscosity results at the ports.

CONCLUSIONS

This study showed a comparison between different SEN designs regarding port and bottom geometries and its influence on the mold flow pattern. From the results, the following general conclusions can be made:

- Under the same casting conditions, port geometry changes can change the flow pattern between SR and DR.
- The bottom design affects turbulent diffusion inside the SEN, which can improve the jet stability.
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For the particular continuous casting mold studied, the following specific conclusion can be made:

- #3 showed the best overall flow pattern, as it kept a stable DR under different conditions of mold width and immersion depths. This flow pattern type has been shown to be the most desirable regarding steel quality.

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