A DPIV Study of Liquid Steel Flow in a Wide Thin Slab Caster Using Four Ports Submerged Entry Nozzles

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Influence of SEN design and its depth below the meniscus on liquid steel flow inside a large width thin slab mold was studied using a 1 : 1 scale water model. Fluid flow characterization was performed through Digital Particle Image Velocimetry techniques, measurements of bath oscillations and tracer dispersion experiments. Two designs of SEN with four ports (two lateral ports with two bottom ports) were investigated. SEN-1 has a wider bottom base and SEN-2 has a narrow one. Both SEN's provide fluid flows in the mold with upper and lower recirculating flows. Jets emerging from the lateral and bottom ports do not overlap although the surface area of the lateral jet of SEN-1 works inefficiently as compared with that of SEN-2. SEN-1 promotes higher bath oscillations than SEN-2 because the lateral jets travel almost horizontally toward the narrow face. This enhances fluid velocities along the narrow wall until the bath surface. A recirculating flow is formed close to the SEN-1 in the upper bath surface that provokes also high bath oscillations. Design of SEN-2 avoids these flow defects yielding more stable fluid flows. Rising the SEN depths alters negatively the flow characteristics, although SEN-2 is better than SEN-1. Generally speaking both designs yield complex turbulent and unsteady flows and a better SEN design is suggested.

KEY WORDS: thin slab; mold; DPIV; path lines; design; tracer; bath level oscillations; turbulence.

1. Introduction

To avoid entrainment of argon bubbles, flux entrapment, inclusions distribution and to control thickness of the solidified shell is important to understand fluid flow dynamics in conventional thick slab casters. Many studies of fluid flow about these type of molds can be found in the literature including the effects of argon gas flow, application of magnetic brakes, two-phase flow through the slide-gate tundish nozzles, swirling jets, etc. More recently one-phase and two-phase flows have been characterized using Digital Particle Image Velocimetry (DPIV) techniques and mathematical simulations of instantaneous velocity fields using computational approaches like Large Eddy Simulation. A complete review on this theme was reported by Thomas and Zhang. Most of all those works relate the importance of the gas load, casting speed, mold design, operating policy of mold and SEN design on two-phase flows patterns, generation of biased flows, turbulence intensity, metal-flux interface stability, argon bubbles entrainment, etc. However, fluid flow phenomena in thin slab molds have been scarcely studied. In these molds, due to their funneled shape and large aspect ratio, all problems mentioned before, become more influential on steel quality because turbulent flow, from higher casting speeds, is intensified inside the cavity. In this case design of a metal delivery system is particularly challenging. Uncontrolled turbulence may lead to uneven shell growth or shell thinning, mold powder entrapment, lack of inclusion flotation and meniscus freezing. These problems make worthy to carry out a thorough study of fluid flow in these molds as affected by the SEN design.

Complexity of fluid flow and its influence on heat transfer problems in a thin slab mold was studied by Wunnenberg and Schwerdtfeger who showed that the longitudinal profile of temperature in the wide wall is permanently unsteady. Nam et al. reported a numerical analysis of fluid flow and heat transfer in a funnel mold. Although these authors do not give details of their SEN design it is assumed to be a conventional one. According with those results fluid flow does not show the typical double roll above and below the entering jet that it does in thick slab molds. Instead, the basic flow pattern is characterized by four large recirculations above the jet and two small eddies near the narrow face. There are not recirculating flows in the lower part of the mold and there the fluid flows steadily down the strand. In another work Park et al. reported mathematical simulations of fluid flow, solidification and heat transfer testing a straight SEN with a single parallel-walls exit and two bifurcated SEN’s. They found smaller velocities close to the bath surface using bifurcated SEN’s than using the straight SEN. Thickness of the solidified shell is also affect-
ed by the SEN design as would be expected because it dominates fluid flow in the mold. Odenthal et al.\textsuperscript{18)} performed simulations and modeling of fluid flow with two different SEN designs and casting speeds using computational and DPIV methods, one is bell type and the second one is a bifurcated nozzle. The bell type SEN yields a large upper recirculating flow with high bath surface velocities that makes of this design a not recommendable approach. On the other side, the bifurcated design yields a strong lateral jet that impacts the narrow wall outside the mold leaving a stagnant zone in the upper part of this mold. This design is also not suitable for the purposes of flow control. Moreover, they found that the amplitude of the standing wave close to the narrow wall increases linearly with raises of casting speed. Their findings showed once more that SEN design is determinant to control fluid flow.

At the end, certainly SEN design is the most cost effective measure at hand to change fluid flow pattern on benefit of product quality. Consequently, in the present work the influence of two SEN designs on the fluid flow of liquid steel in a large width ratio thin slab mold is performed. Specific goals in the present work are to study the effects of SEN geometry and SEN depth on fluid flow turbulence, bath level oscillations and fluid flow patterns of liquid steel using a water model. In the following lines experimental results, their discussion and the final conclusions are to be presented and discussed.

2. Experimental Procedure

2.1. Water Model

The dimensions of a water model, 1 : 1 scale, of a thin slab mold are shown in Fig. 1, its width is 1.85 m, and its thickness is 0.05 m with a height of 1.0 m and a funneled shape. To perform this study a 0.02 m thick plastic water-model was built using a 1 : 1 scale model. Basic criteria, Reynolds and Froude numbers are fulfilled; allowing a closer modeling of what is actually the fluid flow in the real mold. In order to contain the high volumes of required water, maintaining a fixed casting speed of 5 m/min (0.5 m\textsuperscript{3}/min); this mold model was fitted into an aluminum vessel with the same width and thickness of the mold to continue the down-strand geometry of the caster. The joint between the mold and the aluminum vessel was sealed with a thick layer of silicon polymer to avoid water leakages. The mold and the aluminum vessel were reinforced with steel belts adjusted with steel screws and bolts just to support the water weight. At the end of this vessel water is drained to another storing vessel which has in its inside a high-power submerged pump to recycle again water into the mold. In the pipe from the pump to the SEN there is a flow-meter in it fitted with a capacity to measure a flow rate of up to 1.5 m\textsuperscript{3}/min of water. Just below the flow meter there is an orifice in the pipe to allow the injection of a red dye tracer using a syringe.

The mold and the aluminum vessel are mounted in a vibration proof steel structure which is fixed from the ceiling and the floor of the laboratory so that water flow vibrations in the pipe, that may affect the water level readings in the mold, can be completely eliminated. The system has three valves, the first one connects the aluminum vessel with the water storing vessel, the second one is just inside the water storing vessel to purge all piping system and the last one is located just before the flow meter and the red dye injection orifice. Using this system of valves is possible to handle water flows with a high accuracy. Figures 3(a) and 3(b) show front and back views of the experimental setup.

2.2. Measurements of Fluid Velocity

Measurements of fluid flow velocity and streamlines inside the mold were carried out through a DANTEC’s Digital Particle Image Velocimetry (DPIV) apparatus, Fig. 3(a). The basic principle of this technique has been already explained by the authors.\textsuperscript{10)} Fluid velocities are calculated through software. This software analyzes all signals and processes them using Fast Fourier Transforms (FFT). Path lines of the fluid flow were calculated from its velocity fields using a finite difference approach.\textsuperscript{10)} Due to optical capabilities of this equipment the flow field, had to be divided in one half of the mold, which was subdivided into quadrants. The first quadrant is located just.
in the upper side of the SEN and includes the bath surface. The second quadrant is located just in the lower part of the SEN. The third quadrant is located in the lower part close to the narrow face of the mold. Finally, the last and fourth quadrant is located in the upper part of the mold and includes the narrow face of the mold and the bath surface.

The analyzed plane is that one which is located in the half thickness of the mold, that is, the symmetrical plane parallel to the wide face of the mold. Maps of velocity fields close to the SEN were also determined in the same plane and in another parallel plane 5 mm separated from the central plane. Averaged velocity fields include the processing of 50 images recorded in the computer’s memory. These images were processed in order to obtain time averaged images that are those to be presented in this work.

2.3. Measurements of Bath Level Oscillations

Bath level oscillations in three critical points along of the mold width were recorded by a Sony video camera; the upper corner, starting point of the funnel and close to the SEN. These critical points correspond to places where the oscillations showed large variations, see Fig. 2. Comparing the video images with a millimeter printed background paper the bath level measurements were performed. Those images were sent directly from the video camera to a PC through a video cable. Static bath level was arbitrarily assigned a zero reference level. Using an image analyzer program, the level variations were quantified as functions of the time for a total of 60 s elapsed during the observations.

2.4. Tracer Experiments

To complement this study tracer experiments were also carried out. For that purpose red dye was injected, at some given instant after reaching steady state conditions of the fluid flow, through the orifice in the pipe that transports water to the SEN. Tracer dispersion for all cases studied were recorded by videos and photos to see the way that water mixes in the mold.

2.5. Submerged Entry Nozzles

Two designs of SEN were tested in the present study; the first one has a wider bottom than the second one. Both have a pair of bottom ports and a pair of lateral ports. Figure 4(a) shows the SEN with the wider bottom, which will be called here as SEN-1 and Fig. 4(b) shows the SEN with the narrower bottom, which will be called here as SEN-2. Then the two main variables considered in this study were the SEN design and its depth in the bath. Here a depth of a SEN in the liquid of 0.40 m is called deep and a depth of 0.20 m is called as shallow.

3. Results and Discussion

3.1. Velocity and Path Lines

Figures 5(a), 5(b), 5(c) and 5(d) show the velocity fields produced by SEN-1, at its deep position, corresponding to quadrants 1, 2, 3 and 4, respectively. A recirculating flow is formed in front of the lateral port as is seen in Fig. 5(a), the fluid flows back toward the SEN at high velocities close to the bath surface suggesting the existence of strong bath level oscillations in that zone. As is seen this field indicates that approximately only the lower half part of the lateral port works to deliver the fluid into the mold cavity. However, in spite that it can not be recorded it is inferred that the bottom jets are promoting large recirculating flows below the field view of the PIV measurements. In quadrant 3, is seen how the fluid ascends vertically along the narrow wall with relatively high velocities and this flow pattern prevails until the bath surface. In quadrant 4 is seen how the fluid reaches the bath surface with relatively low velocities. At the bath surface there is a back flow with high fluid velocities directed toward the SEN. Again this vertical ascending flow suggests the existence of strong bath oscilla-

Table 1. Summary of the experimental program.

| Experiment No. | SEN Depth | Description                  |
|----------------|-----------|------------------------------|
| 1              | MAX (0.40 m) | SEN-1 with wider bottom, axial plane |
| 2              | MIN (0.20 m) | SEN-1 with wider bottom axial plane |
| 3              | MAX (0.40 m) | SEN-2 with narrower bottom axial plane |
| 4              | MIN (0.20 m) | SEN-2 with narrower bottom axial plane |

Casting speed is 5.4 m/min
tions in the upper corner of the mold. Figures 6(a), 6(b), 6(c) and 6(d) show the velocity fields produced by SEN-1, at its shallow position, for quadrants 1, 2, 3 and 4, respectively. In this case a similar recirculating flow similar to that described by Fig. 5(a) is observed in Fig. 6(a). In the lower part of this SEN-1, Fig. 6(b), the emerging jets from the lower and lateral ports conserve their identities, and again the later deliver jets that originate a large recirculating flow outside the view field of PIV measurements. In quadrant 3, Fig. 6(c), the stream from the lateral port goes deep into the liquid as it does when SEN-1 is at the deep position. This is because the recirculating flow close to the narrow wall has been displaced now toward the upper part, indeed, the velocity vectors are now more vertically oriented toward the bath surface as can be seen in quadrant 4, Fig. 6(d). This flow promotes very high oscillations of the bath level in the upper corner of this mold and in the starting point of the funnel.
Fluid flow patterns produced by SEN-2 at its deep position for quadrants 1, 2, 3 and 4 are presented in Figs. 7(a), 7(b), 7(c) and 7(d), respectively. As seen, by comparing Figs. 7(a) and 7(b) with Figs. 5(a) and 5(b) respectively the change of shape of the SEN has effects on the fluid flow in front of the lateral port. In this case the emerging jet has a slightly steeper angle than that produced by SEN-1. Figure 7(c) indicates also that the distance into the mold where the jet bends is slightly shorter than that observed in Fig. 5(c). Again both jets emerging from the lateral and lower ports conserve their identities forming, in between, a zone with a shearing-recirculating flow. Now comparing Figs. 7(c) and 7(d) with Figs. 5(c) and 5(d), respectively, is seen that in the present case the lateral jet does no reach the narrow wall forming a slow ascending flow along the narrow wall until reaching the bath surface. Naturally this flow is a consequence of the fluid flow pattern in front of the lateral port already described. Actually a near stagnant zone is observed in the upper corner of the mold where small bath oscillations are observed. This situation although is of benefit to keep a quite bath surface in that critical point, it may bring about problems of inefficient convective heat transfer promoting excessive solid growth at the meniscus level in the actual caster. Figures 8(a), 8(b), 8(c) and 8(d) show the fluid flow patterns produced by SEN-2, at its shallow position, for quadrants, 1, 2, 3 and 4, respectively. As can be seen, by comparing Figs. 8(a) and 7(a), raising the SEN-2 produces a recirculating eye above the entering jet close to the bath surface. Again small bath oscillations are observed due to the very small fluid velocities in that zone. This fluid flow pattern is obviously related to the direct effects observed by the corresponding flow in quadrant 3, Fig. 8(c), where is seen that the lateral jet is unable to have influence on the fluid which is close to the narrow wall.

Fluid flows close to the lateral port of SEN-1, at its deep position for planes located (a) at half the mold thickness and (b) at 5 mm from that plane, and (c) and (d) for the same planes at its shallow position.
recirculating flow with very small velocities is observed. Thus the lateral port works partially through its inferior part and above this port a near stagnant zone is formed; this is the cause of the heavy bath oscillations. Now comparing the flows determined for both planes it can be said that there are some differences in spite of their closeness, for instance the fluid volume, located at the bottom of the lateral port moving with high velocities is slightly larger in the symmetric plane than that which is 5 mm separated. This leads to conclude that 2-D mathematical models are not reliable to simulate fluid flows even in vessels with high aspect ratios. Figures 9(c) and 9(d) show the fluid flows produced by SEN-1, at its shallow position for the same planes mentioned above. Rising SEN-1 makes more inefficient work since now the recirculation flow provokes a counter-flow against the upper part of the lateral port and the recirculating flow is intensified. The upper counter-flow in the upper bath surface induces the existence of the highest bath oscillations.

Corresponding fluid flows produced by SEN-2, at its deep position, for the two vertical planes, symmetric or half thickness and the other one located 5 mm from the first plane, are shown in Figs. 10(a) and 10(b), respectively. Comparing these Figures with their equivalents Figs. 9(a) and 9(b), belonging to SEN-1, is well evident that SEN-2 works with considerably higher efficiency since practically the full cross section of the lateral port is working to deliver the liquid into the mold volume. At the shallow position, Figs. 10(c) and 10(d) for the same planes, the efficiency of the lateral port is considerably decreased to approximately 1/2 of the total cross section of the lateral port. In the upper part there is also a counter-flow against the top of the port with high velocities and consequently also high bath oscillations are also a consequence in this case, although, their magnitude are smaller than those corresponding to SEN-1. In this case the fluid flow patterns of both planes observe a higher similarity than that found for SEN-1.

Basically the incomplete usage of the full cross section of the SEN gives origin to unbalanced-biased flows accompanied by strong variations of the dynamic pressure following an intermittent cycle. As a consequence oscillations of high amplitude of the free bath surface are observed when either of the SEN’s is at a shallow position and due to this same reason SEN-1, which reports partial working ports leads to higher amplitude oscillations than SEN-1. Then an important factor to decrease the amplitude of the bath oscillations is the complete use by the fluid of the cross section of port in a SEN.

Figures 11(a) and 11(b) show the path lines maps, in quadrant 1, of SEN-1 at its deep and shallow positions, respectively. As would be expected the recirculating eye is displaced upwards-right when SEN-1 is located the shallow position. At this position a more defined recirculating flow is generated in the bottom of SEN-1. Figures 11(c) and 11(d) show the corresponding path lines maps, of the same quadrant, for SEN-2 at its deep and shallow positions, respectively. Using SEN-2, similarly to SEN-1, the recirculating eye is displaced upwards the nozzle when the SEN changes from deep to a shallow position. Thus rising both SEN’s leads to displacements of the recirculating eyes toward the bath surface and closer to the SEN axis worsening fluid flow conditions.

### 3.2 Bath Level Oscillations

Magnitudes of bath level oscillations produced by SEN-1 at its deep and shallow positions for the three critical points along the mold width, corner, funnel starting point and close to the SEN are presented in Figs. 12(a), 12(b), 12(c), 12(d), 12(e) and 12(f). At the deep position bath level oscillations are under 0.02 m and the highest are located in the corner and close to SEN. At the shallow positions the oscill-
lations grow to values close to 0.04–0.045 m particularly in the mold corner, and close to the SEN. Oscillations in the funnel are mostly negative i.e. under the static bath level. Magnitudes of bath level oscillations produced by SEN-2 at its deep and shallow positions for the three critical points along the mold width; corner, funnel and close to the SEN are presented in Figs. 13(a), 13(b), 13(c), 13(d), 13(e) and 13(f). Comparing with results of SEN-1 is clear that this design originates considerable smaller bath level oscillations particularly in the mold corners at the deep position. Oscillations grow with SEN-2 at the shallow position but remain below 0.015 m. Both SEN’s yield standing waves with positive oscillations in the mold corner and close to the SEN and negative oscillations at the starting point of the funnel.

### 3.3. Tracer Dispersion

An overview of the fluid flow patterns produced by both SEN’s at their deep and shallow positions can be seen at the tracer dispersion patterns taken 7 s after the injection operation of the tracer in Figs. 14(a), 14(b), 14(c) and 14(d). The first two are for SEN-1 at its deep and shallow positions, respectively. Figures 14(c) and 14(d) correspond to SEN-2 at its deep and shallow positions, respectively. SEN-1 always provided higher bath level oscillations as already discussed, either in its deep or shallow positions than SEN-2. Uneven, unsymmetrical and oscillating flow patterns are characteristic of the fluid flow using SEN-1 with increasing effects at shallower positions as is seen by comparing Figs. 14(a) and 14(b). Biased flows are intensified at shallow positions since, as discussed; the lateral port works inefficiently to deliver liquid into the mold. As was mentioned before these effects have their root cause in the penetrating jets from the lateral ports and the small flows through the bottom ports are unable to compensate that effect. A change of the SEN geometry yields to a less penetrating lateral jet ushering a less oscillating and more symmetrical fluid flow, as is the case of SEN-2, but leaving an almost stagnant zone in the upper corners of the meniscus. As mentioned the slow liquid motion in the mold corner may derive, in the current caster, to the growth of a thick shell.

After the experience gained through the present study is clear that increasing the cross sections of the bottom ports and decreasing those of the lateral ports are recommendable measures to balance the momentum transfer is a further step to optimize fluid flow. This is a current activity in the author’s laboratory.

### 4. Conclusions

A DPIV study of the liquid steel flow in a thin slab mold using a 1:1 scale water model has been performed and from the obtained results the following conclusions can be...
(1) SEN-1, at its deep position, originates a large lateral recirculating flow from the stream that comes from the lateral port. This stream impacts the narrow wall of the mold and the fluid ascends along this wall. The ascending flow stirs the mold corner yielding, at this point, large bath level oscillations. Bottom ports promote large recirculating flows in the mold bottom and play a secondary role on the lateral large recirculating flow. Shallow positions of this SEN-1 enhance the effects already mentioned.

(2) Fluid counter-flows, after leaving the zone of the mold corner, toward the SEN-1 closing the upper recirculating flow loop. Fluid velocities close to the bath free surface and to the SEN-1 are high and increase when this SEN is at a shallow position.

(3) SEN-1 promotes biased and asymmetrical flows which behave unsteadily; this effect is stronger when this SEN is in a shallow position. The origins of these phenomena are related with the inefficient fluid delivery from the lateral port. Only about 1/3 of the cross section of this port is used to deliver liquid into the mold. This condition worsens when this SEN is at its shallow position giving place to counter-flows in the upper portion of the lateral port.

(4) SEN-2 generally gives a similar flow pattern to that of SEN-1 but with a shorter recirculating flow. Fluid from the lateral port is unable to impact directly the narrow wall leaving a near-stagnant zone in the mold corner. As a consequence bath level oscillations are smaller and fluid flow is more symmetrical. A shallow position enhances the bath level oscillations and fluid turbulence but not to the extent that SEN-1 does.

Fig. 13. Bath level oscillations by SEN-2 (a) corner, (b) funnel and (c) close to the SEN at its deep position and (d), (e) and (f) the same points respectively, at its shallow position.

Fig. 14. Mixing kinetics of tracer in SEN-1 at (a) deep and (b) shallow positions and SEN-2 at (c) deep and (d) shallow positions.

drawn:

(1) SEN-1, at its deep position, originates a large lateral recirculating flow from the stream that comes from the lateral port. This stream impacts the narrow wall of the
Different to the lateral port of SEN-1 the cross section of SEN-2 is fully used, and this promotes a less biased flow through both ports. As a direct consequence the amplitude of the bath level oscillations decrease.

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