Effects of Immersion Depth on Flow Turbulence of Liquid Steel in a Slab Mold Using a Nozzle with Upward Angle Rectangular Ports

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Fluid flow of liquid steel in a slab mold influenced by a submerged entry nozzle (SEN) with ports of high aspect ratio and upward angle of 10° was studied using a water modeling approach and experimental techniques including tracer injection, particle image velocimetry and ultrasound velocimetry. Fluid dynamics near the ports indicate that the discharging jet is subdivided into upper and lower jets when the SEN is at its deep position (185 mm) forming a double roll flow (DRF). At the shallow position (115 mm) the tendency to form two jets decrease with a general trend to form a single jet and a single roll flow (SRF) pattern. These flows are attributed to the difference of the hydrostatic pressures between both submergences. Both, the upper flow in the DRF and the upper flow in the SRF induce free shear flows near the free bath surface that give origin to vortexes and unstable meniscus dynamics. Therefore, nozzle ports with upward angles create small pressure gradients which, in spite of their small magnitudes, have profound effects on fluid flow patterns of the fluid in the whole working mold volume. The results indicate that this nozzle works with less turbulence in the shallow position.

KEY WORDS: slab mould; continuous casting; fluid flow; vortex; SEN; immersion depths.

1. Introduction

As pointed out by Dauby,1) during the last thirty years the casting community believed that liquid steel exiting form bifurcated submerged entry nozzles (SEN) would travel along the mold width at high velocity, impacting the narrow mold faces and splitting there into upper and lower roll flows. This ideal flow pattern is called as Double Roll Flow (DRF). In principle DRF permits a gentle flow along the meniscus transporting steel in contact with the molten flux and transporting steel down the mold to provide even solidification conditions. However, actual facts indicate the existence of severe energy dissipation that gives origin to raveling jets impacting the narrow mold faces with irregular patterns and weakened forces. Thereby, the DRF is under a fragile equilibrium because it can be easily transformed into different and undesirable flow patterns almost by any change of mold operation. Indeed, it was not until the melt speed was measured in a 2,700×220 mm² mold using the AMEPA-MFC sensors that it was realized the existence of other flow patterns such as the single roll flow (SRF).2)

Even worst is quite possible, depending on bore size of the SEN, immersion depth, cast speed, etc., that the flow pattern becomes completely instable not being DRF neither SRF and then is called as permanent unstable flow (PUF). This flow has been detected in medium thickness slab molds where instability of the flow is permanent due to uncontrolled turbulence. Figure 1 illustrates, schematically, the nature of these types of flows. Basically mold widths above 1,800 mm and casting speeds above 1.2 m/min lead to PUF while low casting speeds, smaller than 1.3 m/min, and mold width smaller than 1,400 mm lead to SRF. DRF’s are observed at intermediate mold widths such as 1,200–2,200 mm and casting speeds from 0.8 to 2.5 m/min.1,3) For fixed casting conditions such as casting speed and SEN design there is a certainty that shallow immersion depths lead to SRF.4) Large port areas lessen the effects of the port angle on the angle of the discharging jet and, generally, the later is steeper than the former. Small port areas enhance the effects of the port angle bringing this angle closer to that of the jet.5) Down-
wards port angles are preferred over upwards port angles because the later promote larger turbulence on the melt meniscus.\(^6\)\(^7\) Large port dimensions lead to recirculating flows just in the upper edge of the port leading to backflow conditions aggravating clogging problems.\(^8\)\(^9\) Therefore, smoothing the angle of the upper port edge decreases the clogging and the backflow issues.\(^7\) Circular ports generate more swirls and have a larger spread angle than rectangular ones having the same cross section area. M. J. Lu et al. claimed that port shape is less important than port size and angle in controlling the flow\(^10\) but this statement has not been corroborated using modern research tools. Immersion depth of the SEN has been a very important operation variable because too shallow or too deep immersion leads to increases of frequency for longitudinal cracks of slabs\(^11\) having always an optimum immersion depth. This is the first of a series of papers intended to be published related with the effects of the geometry of the SEN ports on fluid flow and turbulence generation in the mold using a combination of mathematical simulations. The first case, which is the one that the present work is dealing with, is focused on a very specific design of a SEN with a high height/width ratio-upward ports angle presented in Fig. 2. This type of nozzle is employed in a caster in the USA looking for a general approach of physical and mathematical modeling. The following lines explain all the findings and discussions related with this research.

3. Mathematical Model

The mathematical simulations consists of a combination of a Unsteady Reynolds Averaged Model (URANS) based on the Unsteady Reynolds Stress Model (RSM)\(^6\) combined with the Volume of Fluid Model (VOF)\(^17\) to track the interface between water and air. Using the VOF model avoids the need to assume an unrealistic boundary condition of zero momentum transfer at the liquid-gas interface. Therefore, the physical properties of both phases in the mixture (at the liquid-gas interface) are given by,

\[ \rho_{\text{mix}} = \alpha_i \rho_i + (1 - \alpha_i) \rho_g \] ........................... (1)

\[ \mu_{\text{mix}} = \mu_i \rho_i + (1 - \alpha_i) \mu_g \] ........................... (2)

Where \(\alpha_i\) is the volume fraction of phase “i”, \(\mu\) is viscosity and \(\rho\) is density. Using the Reynolds decomposition given by, \(U_i = \langle U_i \rangle + u_i\), where \(\langle U_i \rangle\) is the instantaneous velocity in direction “i”, \(\langle U_i \rangle\) is the average velocity and \(u_i\) is the fluctuating velocity the continuity and momentum equations can be written as,

\[ \rho \frac{\partial \mathbf{v}}{\partial t} + \rho (\mathbf{v} \cdot \nabla) \mathbf{v} = -\nabla p + \mu \nabla^2 \mathbf{v} + \mathbf{f} \] ........................... (3)

\[ \frac{\partial}{\partial t} (\rho \mathbf{v}) + \frac{\partial}{\partial x_j} (\rho \mathbf{v} \mathbf{v}_j) = -\frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_j} \left( \mu \frac{\partial \mathbf{v}}{\partial x_j} \right) + \rho \mathbf{f}_j \] ........................... (4)

Where \(p\) is the pressure, \(v\) is the velocity, \(\nabla\) is the gradient operator, and \(\mathbf{f}\) is the external force.

Fig. 2. SEN with high height-width ratio upward ports.

Fig. 3. Transducer location within the slab mold.
The third term in the right hand side of Eq. (4) corresponds to the momentum contribution of Reynolds stresses. Different to other turbulent models the RSM, (which make an approximation of these stresses using a turbulent viscosity) solves directly a complete set of transport equations for these stresses given by,

\[ \partial \left( \alpha_i \right)_t + \left( U_i \right) \cdot \partial \left( \alpha_i \right)_x = 0 \] ............................. (3)

\[ \rho_{max} \left( \partial (U_j) \right)_t + \frac{\partial}{\partial x_i} \left( \rho_{min} \left( U_j U_i \right) \right) \]

\[ = \frac{\partial (P)}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \mu_{eff} \left( \partial (U_i) \right) + \partial (U_j) \right) \frac{\partial < \rho_{max} U_i U_j >}{\partial x_i} \] ............................. (4)

The third term in the right hand side of Eq. (4) corresponds to the momentum contribution of Reynolds stresses. Different to other turbulent models the RSM, (which make an approximation of these stresses using a turbulent viscosity) solves directly a complete set of transport equations for these stresses given by,

\[ \frac{\partial (\sigma_{ij})}{\partial x_j} + \left( U_i \right) \cdot \frac{\partial (\sigma_{ij})}{\partial x_i} \]

\[ = \frac{\partial (\sigma_{ij})}{\partial x_j} + \frac{\partial}{\partial x_i} \left( \mu_{eff} \left( \partial (U_i) \right) + \partial (U_j) \right) \frac{\partial < \rho_{max} U_i U_j >}{\partial x_i} + \rho_{max} \sigma_{ij} \]

Flow variables like \(<U_i>, <P>, <U_i U_j>\) and \(\varepsilon_{ij}\) (dissipation of Reynolds stresses) are directly simulated; however, the Reynolds stress transport tensor \(T_{ij}\), the pressure rate of stress tensor \((R_i)\) and the stress dissipation rate tensor \(\varepsilon_{ij}\) should be modeled at each computing time step. The mean flow convection term \(\frac{\partial}{\partial t} \left( U_i U_j \right)\) and the production rate of Reynolds stresses \(\varphi_{ij}\) are fortunately in closed form. To model \(T_{ij}\) the model equations of Daly and Harlow was employed\(^{18}\) and the pressure rate-of-strain tensor, \((R_i)\) was calculated using the isotropization of production (LRR-IP) model.\(^{19}\) The dissipation rate of Reynolds stresses \(\varepsilon_{ij}\) was calculated using the balances of dissipation rate of kinetic energy and the turbulent kinetic energy equations. Both equations are similar to those employed in turbulent models like \(k-\varepsilon\) and \(k-\omega\).\(^{20,22}\) Once knowing the dissipation rate of turbulent kinetic energy \(\varepsilon\), a scalar quantity, and the tensor \(\varepsilon_{ij}\) was calculated through the equation,

\[ \varepsilon_{ij} = \frac{2}{3} \delta_{ij} \left( \rho_{max} \varepsilon \right) \]

Substituting all these terms, calculated at each times step, in Eq. (5) makes possible the simulation of the Reynolds stresses without resourcing to a turbulent viscosity approach. Further substitution of the Reynolds stresses in Eq. (4) makes possible the solution of the momentum equations. More details of this model can be found in Refs. 22), 23). Boundary conditions include no-slip velocity at all solid surfaces and log-law approaches to link the mesh in the boundary layer with bulk flow.\(^{24}\) At the meniscus, continuity of the momentum shear stress between the liquid and gas was assumed. All simulations were performed with water, with a viscosity of 0.001 Pa s, a density of 1 000 kg/m\(^3\) and gas-liquid surface tension of 0.073 N/m all at room temperature. The physical domain was subdivided by a hybrid mesh consisting of 1 373 172 cells as is shown in Fig. 6. The computing approach is finite volume with an upwind differencing scheme\(^{25}\) for momentum and continuity equations. The computing algorithm was that known as SIMPLEC\(^{26}\) - pressured force weighted approach. The model was run in a four cores, six Gb Intel processor machine. First, the mathematical model was run during 300 seconds assuming that a steady state has been reached. Flows at longer times than 300 seconds are considered as reliable fluid flow dynamics
to be analyzed. A video that lasts about 40 seconds was recorded from the numerical simulations at times longer than 300 seconds for further analysis.

4. Results

4.1. Immersion Depth of Nozzle at 185 mm

Flow pattern in the general investigation area was determined through a previous Computer Fluid Dynamics (CFD) simulation with an immersion nozzle depth of 185 mm, whose results are presented in Fig. 7(a); as seen, the jet leaves the port and impacts directly the mold narrow face forming a DRF. Figure 7(b) shows the corresponding flow measured through the PIV; essentially, the measured flow conserves its DRF behavior. However, the actual jet yields oscillating boundaries and the impact with the mold narrow face is not as defined as the CFD simulation indicates, which actually reports time averaged magnitudes. Furthermore, both Figs. 7(a) and 7(b), show the existence of a compact jets exiting from the nozzle port but a zoom view of the fluid outgoing through the port shows a quite different characteristic. Actually, the flow exiting through the port determined by PIV measurements; is divided in two, lower and higher jets, which change with time at a high frequency, see Fig. 7(c). Figures 8(a)–8(c) and 8(d) show the general flow fields, taken at different times, demonstrating the dynamic and changing nature of those jets. At some given instant, Fig. 8(a), the jet is divided or raveled in various streams one, marked by number “1”, forms a recirculating flow close to the corner, other, marked with number “2” is a detached flow from the main jet affecting the meniscus and the last one, marked with “3”, is deviated toward the lower part of the mold. Figure 8(b) shows the detached flow, is now closer to the nozzle and marked with number “4”. Other detached flow can embrace great volumes of fluid affecting the meniscus stability as is indicated by the number “5” in Fig. 8(c). To link this global flow with the flow dynamics through the ports the velocity profiles along the port height were examined using as a reference vertical line that is 10 mm separated from the nozzle wall and the results are shown in Figs. 9(d), 9(e) and 9(f) corresponding to the velocity fields shown in Figs. 9(a), 9(b) and 9(c), respectively. In the first figure there are two well defined velocity peaks, in the second figure there is a main peak followed by two smaller velocity peaks. The third and last figure yields again two velocity peaks with a smaller one in between them. Single peaks accompanied by smaller peaks, double peaks and double peaks with smaller peaks in between them were observed during the full experimental time. Experiments using tracer injections indicated that the flow was highly asymmetric due to the highly instable jets generated at the ports, as was described above. Those conditions lead to the formation of vortexes, at different times, with different lengths on the bath surface as can be seen in Figs. 10(a)–10(d). Their appearances are intermittent and their positions include practically a distance which is close to the nozzle. Formation of those vortexes are, apparently, direct related with the streams detached from the main jet as is indicated by numbers 2, 4 and 5 in Figs. 8(a), 8(b) and 8(c), respectively.

4.2. Immersion Depth of Nozzle at 115 mm

The flow using the SEN at a depth of 115 mm is shown in Figs. 11(a)–11(d) where it is seen that the shallow position induces, essentially, a SRF pattern. The main jet impacts the narrow mold face and the fluid flows downwards the mold. The jet is also raveled giving origin to detached flows, from the main jet, that reach the meniscus.
level causing instability of the surface at positions located around the midway between the mold narrow face and the nozzle wall as is indicated by numbers “1”–“4” in the mentioned figures. Those detached streams from the main jet body (particularly those indicated by numbers “2”, “3” and “4” in Figs. 11(b), 11(c) and 11(d), respectively) give origin also to asymmetric flows. Flow conditions are reflected in the meniscus stability as is shown in Figs. 12(a)–12(d) where the generation of meniscus waves and vortexes are visible. Differently from the previous depth, in the present one the vortex lengths are shorter (compare with Figs. 10(a)–10(d)) and their appearances are also confined to regions located close to the SEN. The velocity fields just in the discharging port at different times are shown in Figs. 13(a)–13(c) and the corresponding velocity profiles along a vertical line located in the front of the port are shown in Figs. 13(d)–13(f). Different to the profiles shown in Figs. 9(d)–9(f), in the present case instead of multiple velocity peaks single or, as the most, two velocity peaks are developed. The difference of velocity profiles developed by the two immersion depths are clearly shown by the time-averaged velocity profiles.
There, it is seen that the deeper immersion induces a two-peak pattern while the shallow immersion yields a single peak profile. The most important to notice here is that the single velocity peak has a magnitude of about 2.4 m/s and concentrates most of the momentum transferred from the jet through the lower part of the port. The deep immersion yields two velocity peaks with a maximum magnitude of about 1.35 m/s; however, the lengths of the vortexes generated in the meniscus are larger than those generated with the SEN at the shallow position. This can be seen in Fig. 15(a), the average vortex length developed at the surface bath when the SEN is at the deepest position is close to three times the averaged vortex length when the SEN is at the shallow position. The frequencies of the vortex formation remain similar for both immersion depths as seen in Fig. 15(b).

4.3. Fluid Flow Dynamics

To complement the information supplied by the PIV measurements, mathematical simulations were carried out by using a RSM-VOF model which, was described above. The results at a horizontal plane located 20 mm below the bath surface for a SEN depth of 185 mm are presented in Figs. 16(a)–16(b), while for depth of 115 mm, Figs. 16(c)–16(d) show the same type of information at two different times. About 120 images of this plane, obtained from the CFD files, were stored and displayed each second and were examined in order to detect the jet's horizontal oscillations. These complex flows indicate that the fluid emerges reaching that plane alternatively through the mold corners with a frequency of 0.4 s⁻¹ and 0.53 s⁻¹ for immersion depths of 185 and 115 mm, respectively. The discharging jets oscillate from the back wall to the frontal wall forming shearing flows on the bath surface. Accordingly, the fluid coming from the narrow wall to the SEN meets another flow coming in the opposite direction like the one shown by number “2” in Fig. 8(a) or by those flows marked with numbers “2” and “4” in Figs. 11(b) and 11(d). Those physical interactions induce shearing flows of opposite sign in regions where both streams meet giving origin to the formation of vortexes like those indicated by the small squares in Figs. 16(a)–16(d) and observed in the video images, (Figs. 10 and 12). The cyclic nature of those flows is clearly evidenced by the measurements of the fluid speed along the central distance which goes from the narrow wall to the nozzle (see Fig. 3) performed by the Ultrasound Velocimetry in Figs. 17(a) and 17(b) for immersion depths of 185 and 115 mm, respectively. The horizontal axis in these figures indicates the distance from the narrow wall to the SEN and the vertical axis is the time and the color scale gives the sign and magnitude of the fluid speed. Negative magnitudes indicate that the fluid approaches the narrow wall and positive ones indicate that the fluid is going toward the position of the nozzle. All the green regions mean that the horizontal component of the fluid velocity is negative (towards the SEN) and the yellow and red regions mean that the fluid is going toward the narrow wall.

(calculated from 300 images shown in Figs. 14(a) and 14(b) for 185 and 115 mm, respectively).
velocity vector is small and the green region corresponding to the immersion of 115 mm is smaller than that for an immersion of 185 mm. Also the flow structure, in the later case, indicates a blurred speed distribution at the deeper nozzle position with a longer period of oscillation. The more defined speed structure of the shallow position indicates that the oscillation period of the flow is shorter in this case. The positions of the vortexes formed at both nozzle immersions give additional information and complement the explanation about the flow dynamics. Figure 18 shows the positions of vortext flows from the nozzle estimated from the video of the numerical simulations and compared with the corresponding positions observed through the videos of the physical model. As seen, a remarkable agreement is found between physical observations and mathematical predictions. The vortex events take place in the first 300 mm from the nozzle wall which agrees with the changes of flow direction reported in Figs. 17(a) and 17(b) (those regions different from the green areas closer to the narrow wall).

5. Discussion

5.1. Hydrostatic Pressure and Control of Water (Steel) Throughput

According to the present experimental and theoretical results, the flow fields in the discharging ports of the SEN are very sensitive to the hydrostatic pressure (or metallic head) and the SEN’s port shape. With only an increase of the immersion depth of 70 mm the jet changes from a single to a double jet in the discharging ports. An explanation for this phenomenon is directly related with the internal and external pressure fields inside and outside the stopper rod-nozzle set. To have a quantitative explanation, the hydrostatic pressure profiles were calculated considering the scheme of Fig. 19 that shows the tundish-stopper rod-SEN configuration where some critical or key points are indicated. To carry out these calculations the relationship between the lift of the stopper rod and the gap area for flow formed between the seat wall and the stopper rod tip (see Fig. 5) was previously determined. Later on, using the equation of Bernoulli, shown in Table 1, those pressures were calculated and plotted in Figs. 20(a) and 20(b), for small and large stopper lifts. Due to the Venturi effect, large negative pressures, (with very high fluid velocities through the annular gap between the stopper and the seat walls), are developed as well as in the port and in the bore when the lift is very small like 4–5 mm (Fig. 20(a)). Physically this means that there will not be flow and even suction effects may be observed. With a small increase of the lift to 6 mm and further increases to 7 and 8 mm all pressures become positive (Fig. 20(b)). Therefore, lift changes from 6 to 8 mm mean radical changes of the pressure profile in the stopper rod which emphasizes the importance of a strict control of the stopper lift. Besides, according with the required casting speed, the necessary lift
is 7.56 mm to give a water flow rate of 6.055 l/s (equivalent to a steel throughput of 2.77 tons/min). The pressure profile was recalculated for this specific lift at the two immersion depths, 115 and 185 mm, and the results are presented in Fig. 21. Since the difference is only 70 mm not appreciable pressure difference can be expected and then there is, essentially, only a single curve for both nozzle immersions particularly when the stopper lift is above 6 mm. However, making a zoom of the pressure in the nozzle ports a difference of about 680 Pa is identified as seen in the inset of the same Fig. 21. Therefore, this pressure difference, even being small, is large enough to alter the velocity profiles in the nozzle ports and, consequently in the entire flow field inside the mold. Turbulent flow fundamentals are helpful to complement further explanations about the effects of the hydrostatic pressure on fluid flow through the ports. Therefore, the fluctuating velocity in turbulent flows is defined according to the Reynolds decomposition as,

\[ u_i = U_i - \langle U_i \rangle \] .............................. (7)

The averaged (in time) fluctuating velocity provides us the standard deviation in the x and y directions of horizontal \( U_i \) and vertical \( V_j \) velocities respectively which are plotted in Fig. 22(a). As seen there, standard deviations of horizontal and vertical velocities are larger for the deep immersion indicating the presence of higher turbulence intensities than in the case when the nozzle is immersed at the shallow position. Furthermore the cross correlation coefficient of velocities defined as,

\[ \rho_{UV} = \frac{\langle UV \rangle}{\sqrt{ \langle U^2 \rangle \langle V^2 \rangle} } \] .............................. (8)

is plotted in Fig. 22(b). This coefficient follows the Cauchy-Schwarz inequality given as,

\[ -1 \leq \rho_{UV} \leq 1 \] .............................. (9)

Near the bottom of the port those correlations are low for both SEN immersions until reaching a peak at about 14 mm from which both correlations follow similar trends. Both correlations become zero at about 41 mm which is the position where there is a transition between the two emerging sub-jets as is seen in Figs. 9(a)-9(c). In the upper side of the
port there are high negative correlations and that region corresponds to where the flow shows velocities of opposite signs at which the flow become instable and shows a slight trend of back flow. Although cross correlation coefficients follow a similar trend for both immersions, it is not the case of the standard deviation which indicates higher turbulence for the SEN at the deeper positions. This aspect can be reinforced through the estimation of the turbulence intensity given by,

\[
U_{\text{rms}} = \sqrt{\frac{\sum_{i=1}^{N} (U_i)^2}{N}}
\]

(10)

where \(N\) is the number of measurements (300 in the present case) which when divided by the speed of the main stream gives the relative turbulence intensity;

\[
I_t = \frac{U_{\text{rms}}}{U_c}
\]

(11)

Or, in terms of the turbulent kinetic energy \(k\),

\[
I_t = 100 \sqrt{\frac{2 k}{3 \left(U_{c}^{2}\right)}}
\]

(12)

The turbulent intensity fields, calculated through the mathematical model, in the central-vertical plane of the nozzle, viewed from the mold narrow wall are shown in Figs. 23(a) and 23(b) for the SEN immersions of 115 and 185 mm, respectively. There, it is seen that the latter case yields higher turbulence intensities along the nozzle and especially in the bottom. These calculations agree qualitatively with the results reported in Fig. 22(a) corresponding to the standard deviations of liquid speed. Therefore, a larger immersion depth causes a larger hydrostatic pressure at the port level that represents an additional resistance to the flow. To overcome such a resistance and to maintain the continuity of mass, further turbulent kinetic energy is required and this is manifested as larger velocity fluctuations in the horizontal and vertical directions as seen in Fig. 22(a). In other words, that resistance receives the effects of larger Reynolds stresses transporting vorticity from the very opening of the port. Actually the normal-vertical Reynolds stresses \(<V_jV_j>\) are the most affected by the increase of immersion depth due to the impact of the stream with the nozzle bottom as is seen in the simulation results given in Fig. 24(a). Other normal Reynolds stresses affected by the immersion depth are those which are perpendicular to the wide mold walls, \(<W_iW_i>\), due to the close proximity of the internal wall of the nozzle as is reported in Fig. 24(b). Normal Reynolds stresses to the port area are not very different for the shallow and deep immersions because of the free flow of liquid through the port and therefore they are not presented here. Therefore, these figures make well evident that a larger immersion yields larger normal Reynolds stresses; vertical and horizontal (the later perpendicular to the mold wide wall) which are inside the nozzle. These are the stresses that contribute the most to the turbulent kinetic energy budget and the corresponding turbulent intensity.

5.2. Practical Implications

A first comment regarding practical aspects is related with the actual usefulness of the upward angle applied in the upper and lower sides of the ports. As is seen in Figs. 13 and 14 this angle does not affect the jet trajectory at all. Flow turbulence, particularly in the meniscus is directly linked to the jet raveling effects using either nozzle as can be seen in Figs. 8 and 11. This SEN design delivers well fresh liquid to the mold corners but at the expenses of meniscus turbulence and the flow patterns found in this study are driven factors to entrain mold slag.13)

However, to make a decision, the most suitable operative condition to use this nozzle could be at the shallow immersion depth because the level of turbulence promoted is considerably smaller. Besides, this condition also ensures supply of hot steel to the mold corners without the risk of
long vortices that might entrain mold slag into the melt. This particular design is considerably affected by the pressure gradient developed by the nozzle immersion depth. As a summary, changes of SEN design are actually recommendable to improve steel flow in a slab mold to make the flow pattern less dependent on nozzle immersion depth and on gradient of the hydrostatic pressure.

6. Conclusions

The effects of immersion depth (shallow 115 and deep 185 mm), rectangular ports of a SEN on the fluid flow of liquid steel in a wide slab mold were studied using a 1:1 scale slab mold model. The techniques used to study flow dynamics of steel included tracer injection, Particle Image Velocimetry (PIV) and Ultrasound Velocimetry (UV) and CFD simulations and the conclusions reached through the experimental results are as follows:

1. General flow patterns are directly dependent on the fluid flow dynamics in the discharging ports and on the immersion depth of the nozzle. Velocity fields in the discharging port region indicate that single or multiple velocity peaks determine the flow conditions of turbulence in the mold.

2. At deep SEN immersion position the jet is clearly subdivided in two sub-jets and at the shallow position the jet oscillates between two and single jets. This effect is related with a larger pressure field when the immersion depth of the nozzle is larger. At higher pressures (immersion depth of nozzle) the fluid exits through the ports with larger turbulence intensities.

3. The discharging jets suffer raveling effects, either at the deep or shallow positions (115 and 185 mm respectively) due to the entrainment of the surrounding fluid and the loss of momentum from the jets. The streams originated by this effect observe regular periodic oscillations, forth and back the wide mold walls, affecting the meniscus stability.

4. The upward angle of the ports does not influence fluid dynamics of the discharging jet. The benefit of the upward angle is the melt stirring and transport of hot melt (4) The upward angle of the ports does not influence fluid dynamics in the discharging ports and on the immersion depth of the nozzle. Velocity fields in the discharging port region indicate that single or multiple velocity peaks determine the flow conditions of turbulence in the mold.

5. A shallow immersion depth position of the nozzle is more recommendable than the deep immersion depth to avoid long vortices capable of giving place to mold flux entrainment.

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Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
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<tbody>
<tr>
<td>( u_i )</td>
<td>Average velocity in direction “i”</td>
<td>m/s</td>
</tr>
<tr>
<td>( u_t )</td>
<td>Fluctuating velocity in direction “i”</td>
<td>m/s</td>
</tr>
<tr>
<td>( g )</td>
<td>Gravity acceleration</td>
<td>m/s²</td>
</tr>
<tr>
<td>( \mu )</td>
<td>Viscosity</td>
<td>Pa.s</td>
</tr>
<tr>
<td>( \rho )</td>
<td>Density</td>
<td>Kg/m³</td>
</tr>
<tr>
<td>( A_G )</td>
<td>Gap area</td>
<td>m²</td>
</tr>
<tr>
<td>( A_M )</td>
<td>Cross section of mold</td>
<td>m²</td>
</tr>
<tr>
<td>( A_P )</td>
<td>Port area</td>
<td>m²</td>
</tr>
<tr>
<td>( A_B )</td>
<td>Bore area</td>
<td>m²</td>
</tr>
<tr>
<td>( h_M )</td>
<td>Distance from tundish bottom to meniscus level</td>
<td>m</td>
</tr>
<tr>
<td>( h_P )</td>
<td>Distance from tundish bottom to upper edge of port</td>
<td>m</td>
</tr>
<tr>
<td>( h_T )</td>
<td>Steel level in the tundish</td>
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<tr>
<td>( h_B )</td>
<td>Distance from the steel level to the midway point in the SEN bore</td>
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<tr>
<td>( Q_m )</td>
<td>Mass flow rate</td>
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<tr>
<td>( P_T )</td>
<td>Pressure at tundish bottom</td>
<td>Pa</td>
</tr>
<tr>
<td>( P_G )</td>
<td>Pressure at Stopper-SEN gap</td>
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<td>( P_B )</td>
<td>Pressure at SEN bore</td>
<td>Pa</td>
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<td>( P_P )</td>
<td>Pressure at SEN port</td>
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<td>( P_M )</td>
<td>Pressure at Meniscus level</td>
<td>Pa</td>
</tr>
</tbody>
</table>

REFERENCES