MULTIPHASE MODELING OF LIQUID STEEL ENTRY BEHAVIOR IN A CURVED BILLET MOLD WITH OPEN STREAM AND SUBMEGED ENTRY NOZZLE[1]

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Abstract

The objective of the present study is to simulate the liquid steel flow entry behavior into a curved billet mold when is delivered by an open stream and when is equipped with a submerged entry nozzle (SEN). For the SEN modeling, misalignments of the nozzle were considered in order to determine its effects on the dynamics of the mold. For the numerical model a Cartesian coordinate system in three dimensions was used, employing structured meshes. Three phases were considered, liquid steel, slag and air, this to study the interphase fluctuation and the slag entrapment into the steel; this can be eliminated by the use of SEN. However, a misaligned nozzle generates strong turbulence and non-symmetric flows; which can be controlled with an inclination towards the inner radius and the interphase is much more stable.
Keywords: Billet casting;Multiphase systems; Mathematical simulation.

MODELAGEM DE VÁRIAS FASES DE COMPORTAMENTO DE ENTRADA DE ACO LÍQUIDO EM UM MOLDE DE BILLET CURVADO COM FLUXO ABERTO E SUBMEGED ENTRADA BOCAL

Resumo

O objetivo do estudo presente é similar o aço fluxo entrada comportamento líquido em um molde de billet curvado quando é entregado por um fluxo aberto e quando é equipado com um bocal de entrada sumergido (SEN). Pelo SEN modelar, maus alinhamentos do bocal eram considerados para determinar seus efeitos nas dinâmicas do molde. Para o modelo numérico um sistema de coordenada Cartesiano em tres dimensões era usado, enquanto empregando malhas estructuradas. Três fases eran aço considerado, líquido, escória e ar, isto para estudar a flutuação de interfase e o enredo de escória no aço; isto pode ser eliminado pelo uso de SEN. Porém, um SEN desalinhado gera turbulencia forte e fluxos não-simétricos; isto pode ser controlado com uma inclinação para o rádio interno e a interfase é muito mais estável.
Palavras-chave: Billet; Sistema de varias fases; Simulação matemática.

1 *Technical contribution to the 41th Steelmaking Seminar – International, May, 23h-26th 2010, Resende, RJ, Brazil.*
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1 INTRODUCTION

It is widely known that steel quality depends on a suitable control of turbulent phenomena into the continuous casting mold. Problems like non-metallic inclusions, powder entrapment, steel re-oxidation and non-uniform solidified shell can come up. The most of the studies found in this field are focused on conventional[1-8] and thin slab casting[9-11], leaving a clear lag in relation to billet and bloom casting. Recently it was shown[12,13] that steel flow dynamics for billet casting is equally complex than that of conventional slabs and then it requires the same attention. Taking into account the late, it is worthwhile to mention that billet mold feeding is carried out by either open stream or Submerged Entry Nozzle (SEN). Fluid flow behavior is far different in both cases and non-studied yet, highlighting a nozzle misalignment due to the manual operation in the actual process. The most of steelmakers that produce very commercial steel rarely use SEN, allowing contact with atmospheric air and subsequent re-oxidation problems. The SEN employment is not the panacea for all casting problems, since a small deviation in its placement could come up free surface instabilities. Also, given the inherent curvature of the continuous casting machines; it is possible to wear the solidified shell in the jet impact zone and a break-out of the line can occur. Thanks to the scarce information about fluid flow behavior into the billet casting mold, the topic represents a great opportunity area to study actual process variables. Major concern in this research are; in one hand, to establish the main differences by using open stream versus SEN and in the other to test ±1 and ±2 degrees of SEN misalignment respect to the exit of the tundish outlet. Variables like turbulence, velocity, wall shear stress, phases behavior (i.e. air-slag-steel) and bath surface oscillations usually the most important to analyze in this process and its relation with the final quality of semi-finished steel products. This is important to point out that fluid flow phenomena in the actual process is extremely difficult to study; owing to that, this study was carried out through mathematical modeling, using actual steelmaking data for the simulation process.

2 NUMERICAL MODEL

2.1 Fundamental Equations

Three dimensional continuity and the Navier-Stokes equations, shown in equations (1) and (2) in Cartesian co-ordinates were solved, together with the k-ε standard turbulence model and for the particle tracking the Lagrangian discrete phase model, through the volume finite method embedded in FLUENT® code.

$$(\nabla \cdot u) = 0 \tag{1}$$

$$\rho[\nabla \cdot uu] = -\nabla P + \mu_{eff} \nabla^2 u + \rho g \tag{2}$$

Where, $\mu_{eff} = \mu + \mu_t$ and $\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}$

2.2 The k-ε Standard Turbulence Model

The turbulence model is defined as follows,

$$\rho \frac{\partial k u_i}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k - \rho\varepsilon \tag{3}$$

$$\rho \frac{\partial \varepsilon u_i}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}G_k - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{4}$$

Model constants are: $C_1 = 1.44$, $C_2 = 1.92$, $\sigma_\varepsilon = 1.3$, $\sigma_k = 1.0$, $C_\mu = 0.09$.

2.3 Multiphase Model

The Volume of Fluid (VOF) model was employed to solve the multiphase system air-steel-slag. This scheme performs the calculation of the interface between the phases (*p* and *q*) present at each cell, based on their fraction as shown[15,16].

$$\rho_{mix} = \alpha_p \rho_p + (1-\alpha_q)\rho_p \tag{5}$$

$$\mu_{mix} = \alpha_p \mu_p + (1-\alpha_q)\mu_p \tag{6}$$

A unique continuity equation for the transient system is derived depending on the number of phases; therefore, the Equation 7 is divided by the amount of phase q in the cell. Mass exchange between phases can be modelled by introducing an additional source term (S_{α_q}).

$$\frac{\partial}{\partial t}(\alpha_q \rho_q) + \nabla\cdot(\alpha_q \rho_q \vec{v}) = S_{\alpha_q} + \sum_{p=1}^{n}(\dot{m}_{pq} - \dot{m}_{qp}) \tag{7}$$

The VOF model solves a single set of momentum transfer equations when two or more phases coexist in the cell.

$$\frac{\partial}{\partial t}(\rho_{mix}\vec{v}) + \nabla\cdot(\rho_{mix}\vec{v}\vec{v}) = -\nabla p + \nabla\left[\mu_{mix}(\nabla\vec{v} + \nabla\vec{u})\right] + \rho_{mix}\beta\Delta T g - S_s + S_\sigma \tag{8}$$

The tracking of the interface is accomplished by an implicit method, which solves the face fluxes ($\dot{m}$) in each grid cell through Equation 9.

$$\frac{\alpha_q^{n+1}\rho_q^{n+1} - \alpha_q^n \rho_q^n}{\partial t}V + \sum_f\left(\rho_q^{n+1}U_f^{n+1}\alpha_{q.f}^{n+1}\right) = \left[S_{\alpha q} + \sum_{p=1}^{n}\left(\dot{m}_{pq} - \dot{m}_{qp}\right)\right]V \tag{9}$$

As the previous equation requires the volume fraction values of the actual time step, an additional scalar transport equation for the steel and slag is solved iteratively at each time step for the transient state.

2.4 Modeling Conditions

The fluid flowing into the billet was supposed to have Newtonian behavior with no changes in density. Simulations were developed under unsteady state and isothermal conditions. Inlet and outlets were defined as a velocity-inlet condition. The inlet velocity is calculated to maintain the desired casting speed at the outlet. A pressure inlet condition is applied at the mould top (P=101325 Pa, T=273 K) to model the effects of a system open to the atmosphere. The physical properties of fluid and the parameters of simulation are shown in Table 1.
Momentum transfer equations were solved using appropriate boundary conditions such as no-slip condition for all surfaces, a velocity distribution inside the nozzle that

obeys the 1/7 law[16], a kinetic energy in nozzle tip defined by the velocity distribution. In the viscous sublayer the high velocity gradients were connected with the main flow through the logarithmic law[17].
The governing equations are discretized in FLUENT using an implicit, first-order upwinding scheme and the SIMPLEC algorithm for pressure-velocity coupling[14]. Convergence criterion was obtained when the residuals of the output variables reached values equal or smaller than $1X10^{-4}$. The dimensions of the billet mold are shown in Figure 1. The computational grid was conformed of 900 000 structured cells and is shown in Figure 2; the meshes were constructed in GAMBIT. All CFD simulations were performed in five Pentium-IV Personal Computers at 3.1 GHz with 2 GB RAM memory.

Table 1. Physical properties of fluids and parameters of simulation

Property	Value	Parameter	Value
Density of Steel	7010 Kg/m^3	Nozzle immersion	90 mm
Density of Slag	2600 Kg/m^3	Steel level in billet mold	850 mm
Density of Air	1.225 Kg/m^3	Casting speed	2 m/min
Viscosity of Steel	0.006 Kg/m-s		
Viscosity of Slag	0.4 Kg/m-s		
Interfacial tension Steel-Slag	0.12 N/m		
Interfacial tension Steel-Air	1.6 N/m		

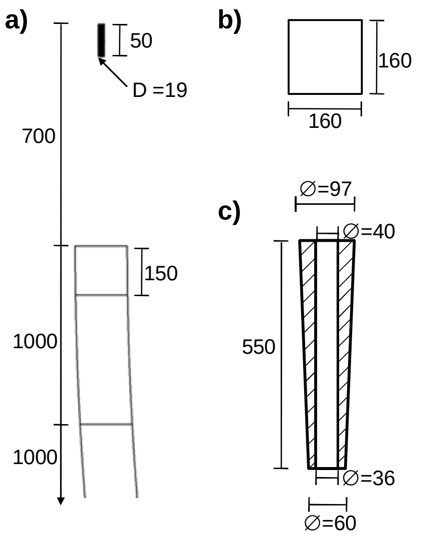

Figure 1. Dimensions of the billet mold (mm), a) Lateral view of the mold, b) Top view of the mold, and c) SEN

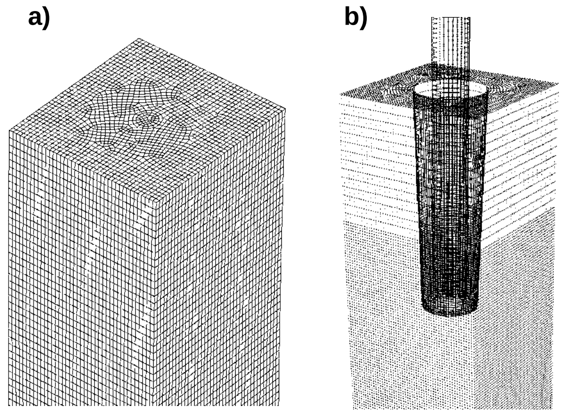

Figure 2. Isometric view of the mold mesh, a) Mold for Open Stream, and b) Mold with SEN.

3 DISCUSSION OF RESULTS

The open stream case was firstly simulated, considering the air/steel system. This case was employed to study the high intensity fluctuations of the molten steel free

surface. This first stage was considered as a start point to understand the importance of using the Submerged Entry Nozzle (SEN)
Figure 3 shows velocity fields at the longitudinal-symmetric plane of the mold. It was observed re-circulating air flows in the upper part of the figure due to the momentum rate between the falling steel stream and the environmental air. Also, it is easy to note, that the highest velocities are located in the impacted stream zone and the flow patterns inside the mold are very chaotic. These variations are linked to the fall of the steel jet, the turbulence generated, and the dragged air into the mold that rises as bubbles, as shown in Figure 4. These variables induce great and constant unstable changes to fluidynamics of the molten steel. Additionally, Figure 3 shows a characteristic of open streams which is the buffer zone; this zone corresponds to the maximum depth of steel jet penetration.

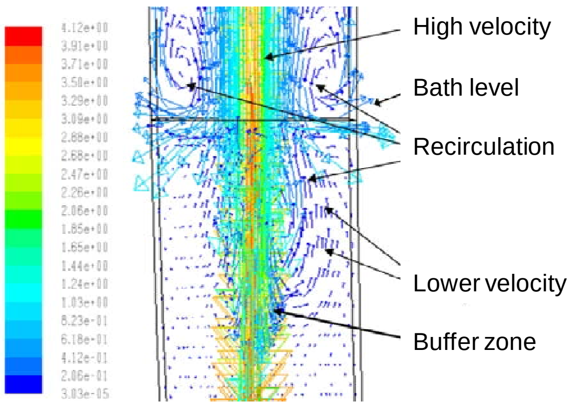

Figure 3. Velocity profiles at the symmetric plane in the mold.

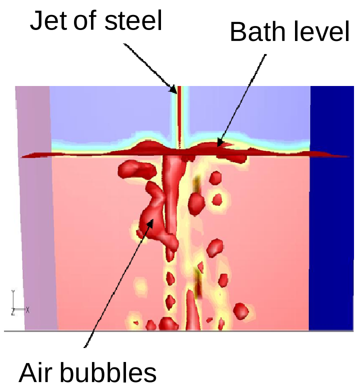

Figure 4. Isometric view of the air bubbles and bath level oscillation.

Solidifying shell growth process in the meniscus is strongly dependent of bath level flowdynamics. Consequently, these strong fluctuations of the bath surface are undesirable phenomena because affect directly the solidification mechanisms in that area.
Figures 5a-5d show the bath surface behavior at different convergence times. It can be shown that the largest level fluctuations are located at the impacted steel jet and these gradually decrease as the steel goes to the mold walls. It must be notice that level fluctuations are very different for each time, which is due to the random nature of bubbles formation into the molten steel. This figure illustrates that the late described fluctuations are present throughout the continuous casting process as the involved phenomena. Hence, casting operation using open stream is not recommended for higher-quality steels.
A second stage of this modeling study was done with the SEN position along the vertical axis of the system. Velocity fields and path lines at the longitudinal-symmetric plane of the mold were obtained in order to analyze the flow patterns, shown in Figures 6a and 6b, respectively. By these figures, it can be seen that the steel jet leaving the nozzle is not completely centered, in relation to the both radii of the mold (inner and outer), resulting in asymmetric flow patterns.

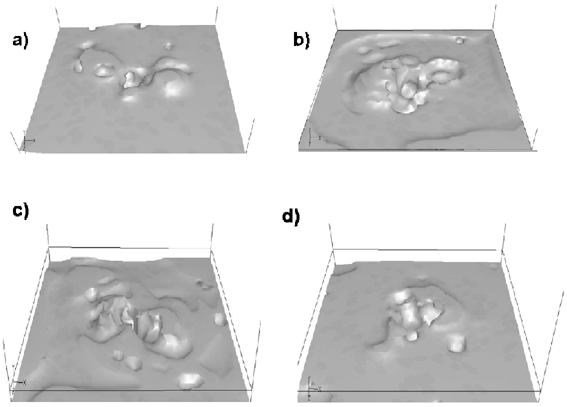

Figure 5. Isometric view of the bath level oscillation taken at different simulation times; a) 10s, b) 30s, c) 60s, and d) 120s.

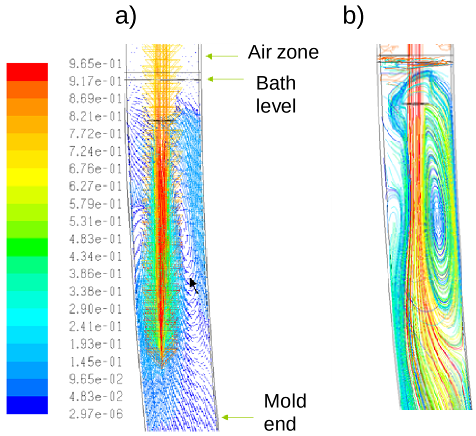

Figure 6. Flow patterns at the symmetric plane of the mold, a) Velocity vectors and b) Path lines.

The mold curvature and the gravitational force induce that the steel jet trajectory goes closer to the outer radius. This behavior produces a major gap between the inner radius and the incoming steel jet generating a pronounced re-circulating flow, which allows major volume of steel rising towards the bath surface. However, path lines indicate that this ascending flow does not reach completely the top surface, because most of this ascending flow changes its trajectory and impacts the SEN tip flowing around it to continue its ascend close to the outer mold radius. In consequence, non-symmetric flow patterns resulted in the bath surface as shown in Figure 7. The liquid ascending close to the SEN in the outer mold radius (point 1) surrounds the nozzle for both directions and meets in point 3. The flow supply the bath level close to the inner mold radius flows in a contrary trajectory to the mentioned before, because of that there is the formation of 2 recirculations indicated by point 2. In spite of all these flow pattern variations, bath surface is more stable than in the case of open stream, as a result the meniscus remain almost steady conditions close to the mold walls. At this point, it is possible to conclude that SEN application allows a better control of the turbulence and consequently more stable fluid flow patterns in the mold and in the bath level.

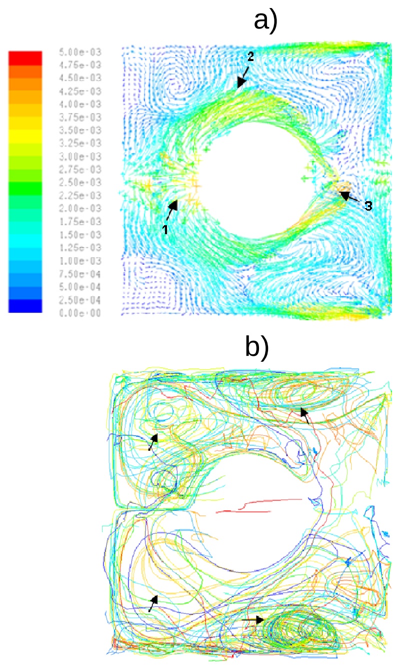

Figure 7. Flow patterns at bath level of the mold, a) Velocity vectors and b) Path lines.

It is known that the nozzle positioning, in the actual caster machine, is not always the correct due to risky that represents a fast change of a new SEN. Then, the nozzle can be deviated respect to the vertical axis of the system. Considering these possible conditions, it was decided to simulate a hypothetical deviation of the SEN axis respect the system axis of 1 and 2 degrees towards the inner and the outer radius of the mold.

Figure 8 shows the velocity profiles at the longitudinal-symmetric plane of the mold to the four cases mentioned above. In Figures 8b and 8d it can observe that a SEN deviation towards the outer mold radius induces that the jet gets considerably closer to the mold wall, which promotes an increment of the steel volume that ascends and re-circulate in that zone. As a result, the fluid flow patterns are very asymmetric and turbulent for the two conditions and an asymmetric profile in the bath surface could be expected. When the SEN has a deviation of 2 degrees to the inner mold radius (Figure 8c) the velocity profiles show a mirror image of those shown in Figure 6. However, when the SEN has a deviation of 1 degree to the inner mold radius (Figure 8a) the flow patterns inside the mold are considerably symmetric due to the closer alignment between SEN and the mold walls; these patterns give as a result the developing of recirculation flows but with lesser intensity than any of the previous cases.

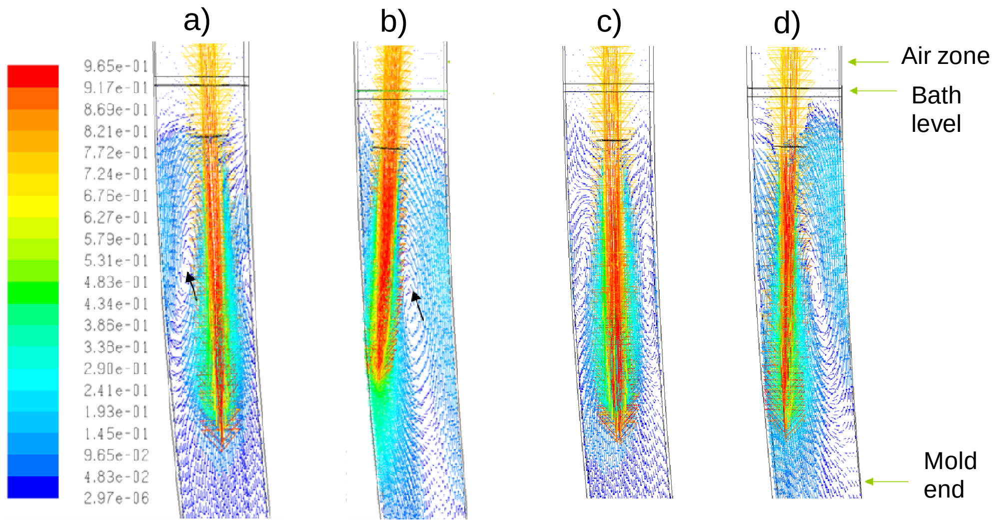

Figure 8. Velocity profiles at the symmetric plane of the mold, a) 2º to inner radius, b) 2º to outer radius, c) 1º to inner radius, and d) 1º to outer radius.

According to the paragraph above, it is necessary to analyze the fluid flow at the bath level. For this reason velocity profiles at this level were numerically obtained and are shown in Figure 9 for the same conditions that Figure 8. In Figure 9 it is obvious that the flow patterns at the bath surface are considerably irregular and asymmetric for all cases with the exception when the SEN has a 1 degree deviation toward the inner mold radius (Figure 9c). For this case, the velocity profiles show very symmetrical patterns and the steel is supplied by the corners of the mold and descends for the center of the wall faces inducing a very stable bath surface.

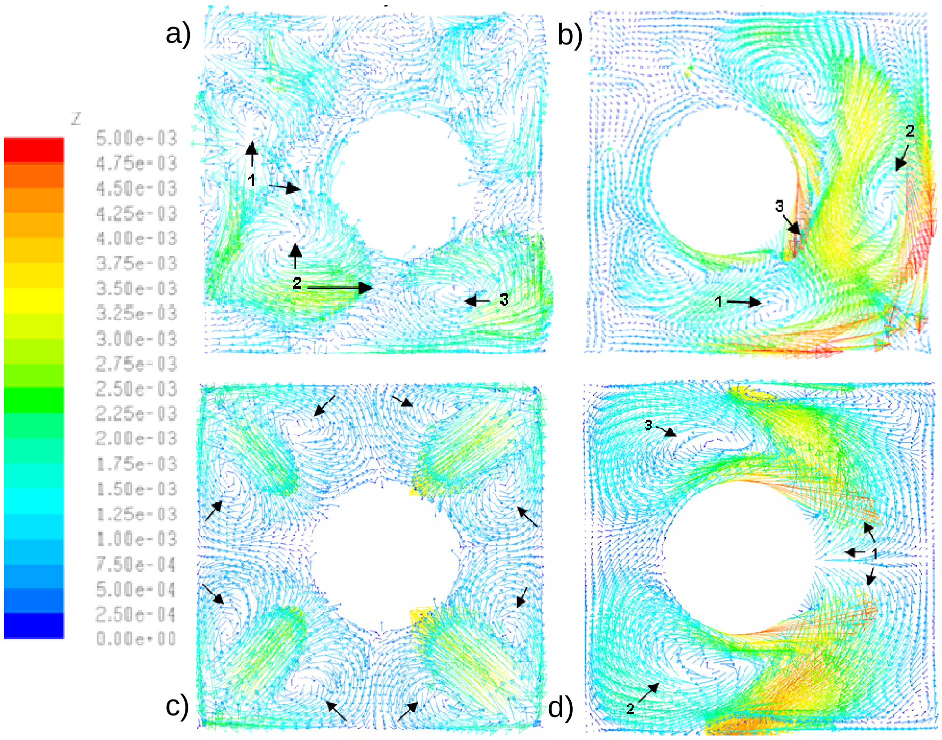

Figure 9. Velocity profiles at bath level of the mold, a) 2º to inner radius, b) 2º to outer radius, c) 1º to inner radius, and d) 1º to outer radius.

Knowing the negative effects of bath surface fluctuation on steel quality, it was decided to compute its maximum values for all cases where SEN is used and the results are shown in Figure 10, which clearly indicates that cases with centered SEN as well as those with the inclined SEN towards outer mold radius showed the highest deformation of free surface. On the other hand, the cases where the SEN deviation is toward the inner mold radius showed the lower deformation values. The better results were obtained for a SEN deviation of 1 degree towards the inner mold radius which showed the lowest fluctuations.

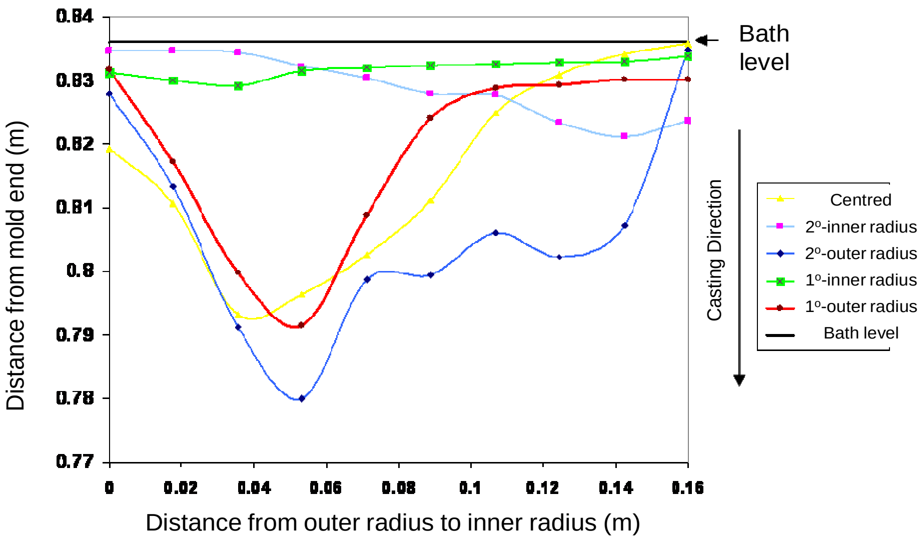

Figure 10. Bath level deformation for the cases that used SEN.

4 CONCLUSIONS

The numerical simulation results of the liquid steel entry behavior into a curved billet mold when is delivered by an open stream and when is equipped with a SEN allow concluding that:

- The numerical flow patterns for open stream and using SEN are considerable different and its application must be selected according to the desired steel quality, but the results suggest the SEN usage.
- The use of SEN decreases considerably the free surface fluctuations in comparison with the open stream case, but the flow patterns at baht surface are strongly affected by the SEN deviation.
- Operate with a centered SEN in a curved billet mold does not assure a symmetric flow into the mold. On the other hand, non-centered SEN promotes strong recirculation flows around the steel jet that affects negatively the flow pattern.
- SEN deviation necessary for optimum steel behavior into the mold may change with the particular caster configuration. For this study 1 degree deviation to the inner mold radius shows the most suitable condition to improve fluid flow patterns.

Future work

The further study of the SEN deviation towards the straight mold walls on fluid phenomena considering non-isothermal and the solidification process must be taken.

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