International Journal of Advanced Computer Research (ISSN (print): 2249-7277 ISSN (online): 2277-7970)
Volume-3 Number-1 Issue-8 March-2013

Numerical Analysis of Free Surface in Water Model for Design of Submerged Entry Nozzle

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Abstract

Two-dimensional numerical simulations using finite volume method and an interface capturing scheme are used to predict the shape of free surface wave that is created in a mold due to the flow from submerged entry nozzle. In the present work, instead of steel and argon, water and air enter into the mold. It has been observed that the free surface is wavy in nature. Three different submerged entry nozzle(SEN)models were taken for numerical analysis. Contribution of water velocity, different port to Bore ratio (P/B), size of upper recirculation roll on free surface were investigated for designing a submerged entry nozzle. It was observed that Pent-Roof type nozzle is a better one as it shows lesser fluctuation.

Keywords

Fluid flow, Submerged Entry Nozzle (SEN), Interfacial fluctuation, computer simulation

1. Introduction

Recently steel makers aim is to improve the quality of steel with high productivity. So the casting speed of the liquid steel has to be high which creates several other problems in the mold leading to loss of quality. Higher casting speed leads to more fluctuation in the free surface as well as frequent vortex formation. Formation of vortex entraps the slag and the surrounding air, thereby spoiling the quality of steel. So designing a better submerged entry nozzle (SEN) is the demand of the time to understand how it affects flow in the mold. A short summary of relevant work reported in literature is given here. In 2004, Dash et al. [1] have studied and concluded that free surface is transient in nature and the free surface does not change very much after initial transience. In 1994, Gupta and Lahiri [2] proposed that free surface is wavy in nature. Beyond a certain flow rate there is a formation of vortex and bubble entrapment by the free surface depending upon the nozzle configuration. In 1998, Panaras et al. [3] suggested a criterion to adopt maximum velocity which helps to avoid instability on the free surface. In1992, Andrzejewski et al. [4] have studied a full scale water model to find out the flow pattern inside the mould. They suggested an optimum operating condition in terms of casting rate, immersion depth. In 2008 Wu and Cheng, [5] studied in detail the role of various nozzle port angles, port width and heights on free surface fluctuation. Based on these, submerged entry nozzle was designed. By taking similarity criterion between the water model and real steel caster, one can assure similar dynamic behaviour between both fluids. Then it is hoped that casting speed influence in the same way on the free surface of molten steel in the casting mould. In 2009, Chaudhary et al. [6] stated clearly the similarity criteria between the water model and the real steel caster. In 2012, Mishra et al. [7] , Real-Ramirez et al. [8], in 1993 Qinglin He [9], in 2005 Li and Tsukihashi [10] have studied the hydrodynamic behaviour inside the mould. In 2010, Quao-ying and Xin-hua [11] stated the influence of casting variation on surface fluctuation. In 2010,Zheng and Zhu [12] proposed new approach to study interfacial fluctuation. Figure1 shows the continuous casting process.

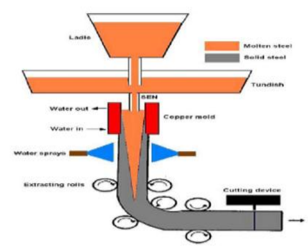
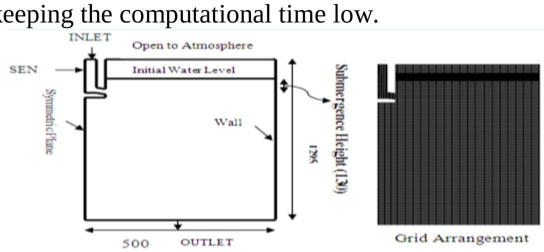


Figure 1: The Continuous Casting Process

2. Problem Description

The objective is to analyze free surface for different submerged entry nozzles for finding a better nozzle which shows lesser fluctuation. Fig.2 (a) shows the model of a continuous casting mold which will be used for analysis of free surface fluctuation. Due to symmetrical structure of the mold only half of the casting mold is considered for analysis. The diameter of the SEN is 60 mm and the port opening is 50 mm with submergence depth of 130 mm from the free surface. The width and height of the mold is 1000 mm 1295 mm respectively. Figure 2(b) shows the grid arrangement. The grid is finer near the free surface region in order to track sharply. Free surface is open to atmosphere. Variation of air velocity is not significant in this region. So cells are made coarser there. The present work is two dimensional for keeping the computational time low.



(a) **(b)**

Figure 2: Schematic view of SEN in a continuous casting mold (All dimensions are in mm)

3. Numerical models

In the present work three nozzles has been taken for analyzing the free surface.

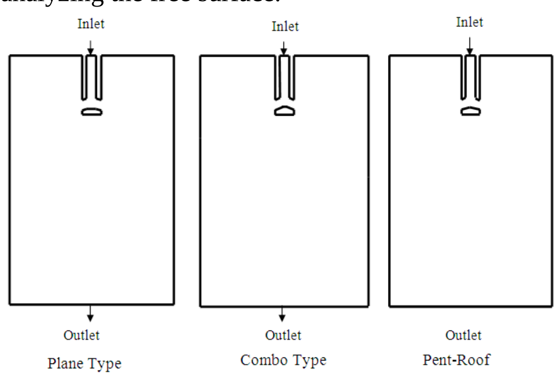


Figure 3:Nozzles used in continuous casting mould

For incompressible viscous flows with free surface, the following governing equations are used which are as follows

Continuity: $\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho U_i) = 0$ (1)

Momentum:

$$\frac{D(\rho U_i)}{Dt} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left\{\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right\} - \overline{\rho u_i u_j}\right] + \rho g + F_\sigma \quad (2)$$

Flow of water in the mold is turbulent in nature, hence κ-є model is used for capturing the flow dynamics in the mold which are given by the following equations

Turbulent kinetic energy, κ :

$$\frac{D(\rho\kappa)}{Dt} = D_\kappa + \rho p - \rho\varepsilon \quad (3)$$

Rate of dissipation of κ :

$$\frac{D(\rho\varepsilon)}{Dt} = D_\varepsilon + C_1 \rho P \frac{\varepsilon}{\kappa} - C_2 \frac{\rho\varepsilon^2}{\kappa} \quad (4)$$

Where

$$\overline{u_i u_j} = \frac{2}{3}\kappa\delta_{ij} - \upsilon_t\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right), \ \upsilon_t = \frac{C_\mu \kappa^2}{\varepsilon}$$

$$D_\phi = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\phi}\right)\frac{\partial \phi}{\partial x_j}\right],$$

$$p = -\overline{u_i u_j}\frac{\partial U_i}{\partial x_j}, \quad \phi = k \, or \, \varepsilon$$

Constants used in the κ-є model are
$C_1 = 1.44$, $C_2 = 1.92$, $\sigma_C = 1.0$, $\sigma_\kappa = 1.0$, $\sigma_\epsilon = 1.3$, and $C_\mu = 0.09$

The present work is two-dimensional unsteady with multi-phase flow. Volume of fluid (VOF) method is used for tracking the volume fraction of each of the fluids throughout the computational domain. The density of water is constant and the volume of fraction of water has the following equation.

$$\frac{\partial c}{\partial t} + U.\nabla c = 0 \quad (5)$$

Where c and U are the volume fraction of liquid and the mean-velocity of water respectively. The grid extends to both liquid and gas phases. If $c = 1$, then entire control volume is filled by liquid; otherwise, if $c = 0$, the control volume is filled by gas. Both liquid and gas are treated as single effective fluid whose properties change in space according to the volume fraction of each phase i.e.

$$\left.\begin{aligned} \mu &= \mu_1 c + \mu_2(1-c) \\ \rho &= \rho_1 c + \rho_2(1-c) \end{aligned}\right\} \quad (6)$$

where, subscripts 1 and 2 denote the two fluids such as liquid and gas respectively. The effect of surface tension force per unit volume at the free surface is given by the equation

$$\kappa = -\nabla.(\frac{\nabla c}{|\nabla c|}) \qquad F_{\sigma} = \sigma \frac{\rho \kappa \nabla c}{0.5(\rho_1 + \rho_2)} \qquad (7)$$

Where σ, K, ρ are the surface tension co-efficient, the curvature of free-surface and average volume density respectively.

4. Results and Analysis

4.1 Validation with Experimental Results:

The wave breaking process has been experimentally done by Gupta and Lahiri [2]. Fig. 4(a) and 4(b) show the results under high velocity conditions. Experimental snapshot was taken just at the time of entrapment of air bubble (but the exact time of entrapment was not mentioned).The numerical results of the free surface has taken at an interval of 0.04 s starting from the time of t=3.2 s. It was observed that the experimental (d) and (e) snapshot match closely with numerical results of the frames (d) and (e). From both experimental and numerical work, it was concluded that surface wave breaks near the trough and entrapment of air bubbles. The fig.4(c) is the snapshot of the computational work. The last snapshot (e) shows the breaking of waves and entrapment of air bubbles into the mold. In the real caster due to surface wave break, slag enters into the mold and mixes with molten steel, which leads to loss of its quality.

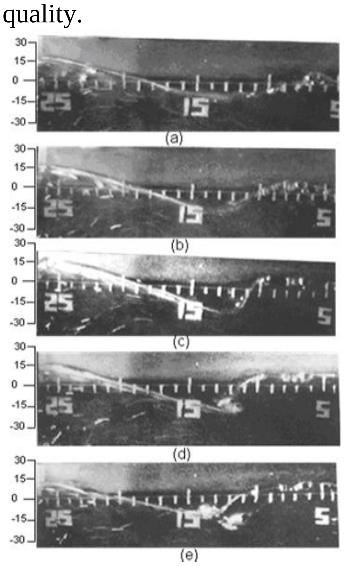


Fig. 4(a): Experimental photographs of the free surface developed with a parallel port SEN at an interval of 0.04 s port exit velocity 1.94 m/s. Source: Gupta and Lahiri [2].All dimensions are in millimetre.

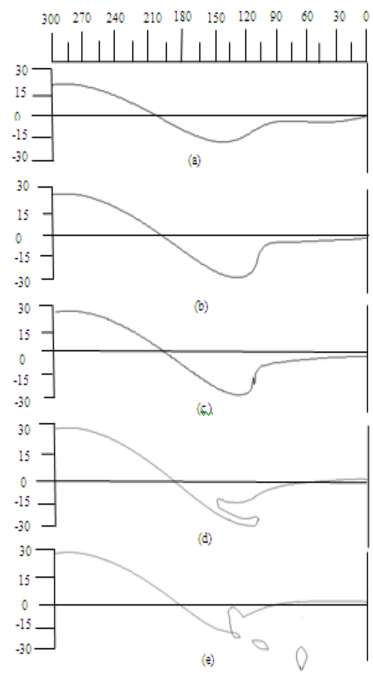


Fig 4(b): Numerical results of the free surface, a comparison with the experimental results

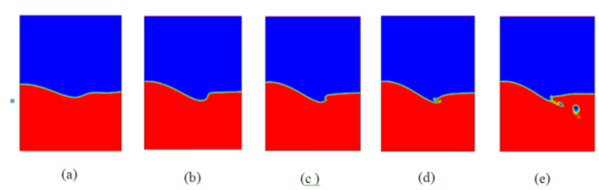


Fig. 4 (c): Snapshot of the computational work

4.2 Fluctuation of water/air interface for different SEN:

Figure 5(a) shows the interfacial fluctuations of different submerged entry nozzles by taking water velocity 1.2 m/s without air injection. In the fig. left side of the x-axis indicates the nozzle side and right side indicates the wall side. In the figure minimum and maximum location is nothing but a band. The free surface is unsteady in nature. It has been found that after initial transience the free surface fluctuates within this band. From the figure it was concluded that the Pent-roof type nozzle fluctuates lesser as compared to other nozzles.The fluid comes out of the nozzle and proceeds as a jet and hits the wall, then the fluid divides into two branches. One branch moves up and second moves down creating two recirculation zones. The upper recirculation roll has impact on free surface. If angular velocity of recirculation roll is more, free surface fluctuates with a greater amplitude. The Table 1 shows the angular velocity of different nozzles. It has been found that Pent-roof nozzle is having lesser angular velocity, so free surface fluctuates with a lesser amplitude.

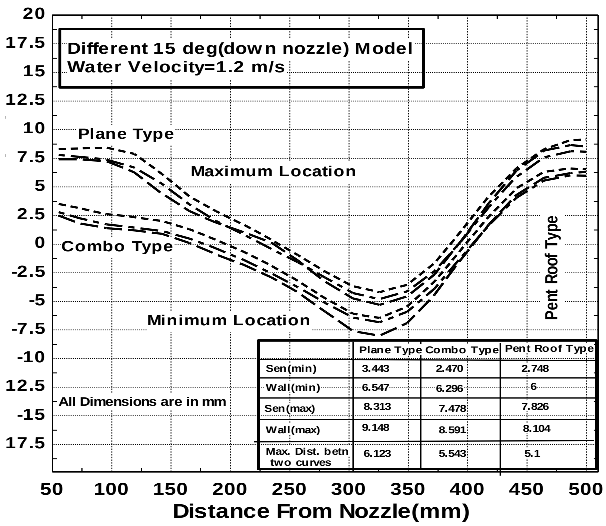


Fig. 5(a): Comparison of free surface fluctuation for different nozzles

Table 1: Angular velocity of different nozzles

Different Types of SEN	Angular Velocity ω (rad/s)
Plane Type	$11x10^{-3}$
Combo Type	$4.86x10^{-3}$
Pent-roof Type	$4.63x10^{-3}$

Figure 5(b) shows the interfacial fluctuations of different Port to Bore ratio (P/B). It has been found that as (P/B) ratio increases, free surface fluctuates with a lesser amplitude. Table 2 shows that angular velocity decreases with increasing (P/B) ratio.

Table 2: Angular velocity of different port to Bore ratio

Port to Bore ratio (P/B)	Angular Velocity (rad/s) ω
1.4	$14.9x10^{-3}$ rad/s
2	$7.5x10^{-3}$ rad/s
2.6	$5.21x10^{-3}$ rad/s

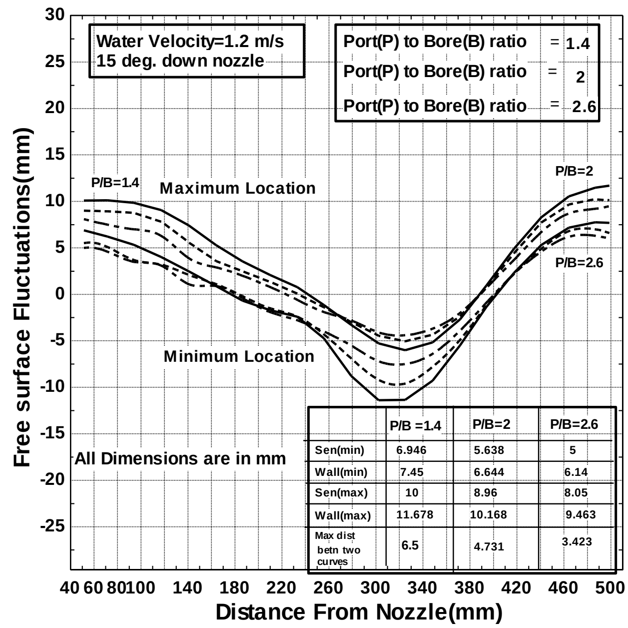


Fig. 5(b): Comparison of free surface fluctuation for different Port to bore ratio

4.3 Impact of jet velocity on side wall and size of upper recirculation for different Port-to-Bore ratio

The figure 6 (a) shows the results for different Port-to-Bore ratio. After flowing through the nozzle,the fluid strikes the side wall having certain velocity. Impact jet velocity has influence on free surface.It has been found that as Port-to-Bore ratio increases, impact jet velocity on side wall decreases resulting less interfacial fluctuation. Figure 6(b) shows the effect of different Port to Bore ratio on the size of upper recirculation roll. The distance between the free surface level and the top most point of the jet touching the side wall can be taken as the size of the recirculation roll. Increase in size of upper recirculation roll is because of rise in Port to Bore ratio. It means the fluid reaches the free surface with a lesser momentum resulting less interfacial fluctuation. Figure 6 (c) shows a dimensionless plot between Port to Bore ratio and free surface Velocity- to- Exit Velocity. Free-surface fluctuates less as increase of Port-to Bore ratio resulting decrease in free surface velocity. From the figure it was found that rise in port-to-Bore ratio decreases the surface velocity-to-Exit velocity ratio.

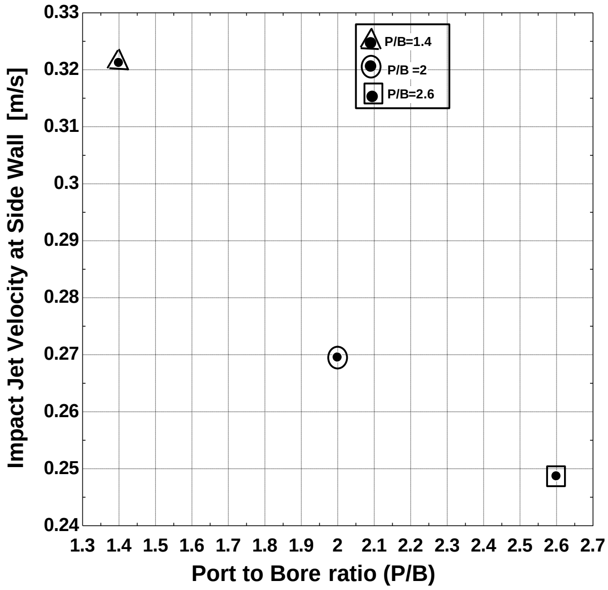


Fig. 6(a): Effect of Port to Bore ratio on impact jet velocity

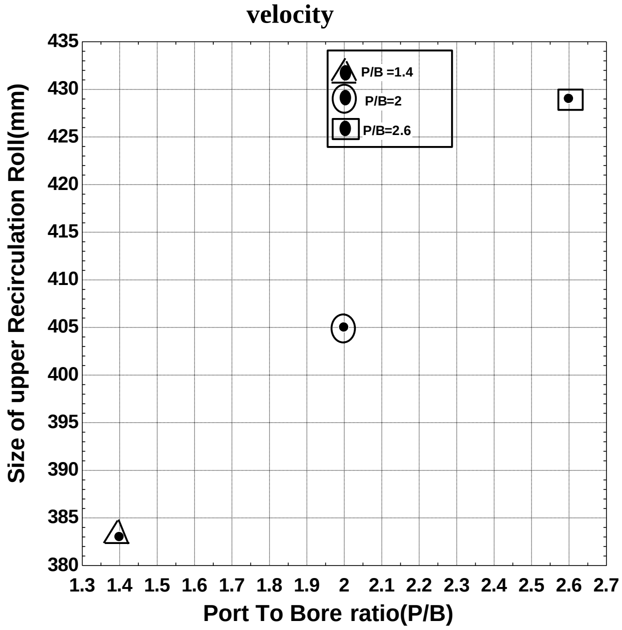


Fig.6 (b): Effect of Port to Bore ratio on upper recirculation roll

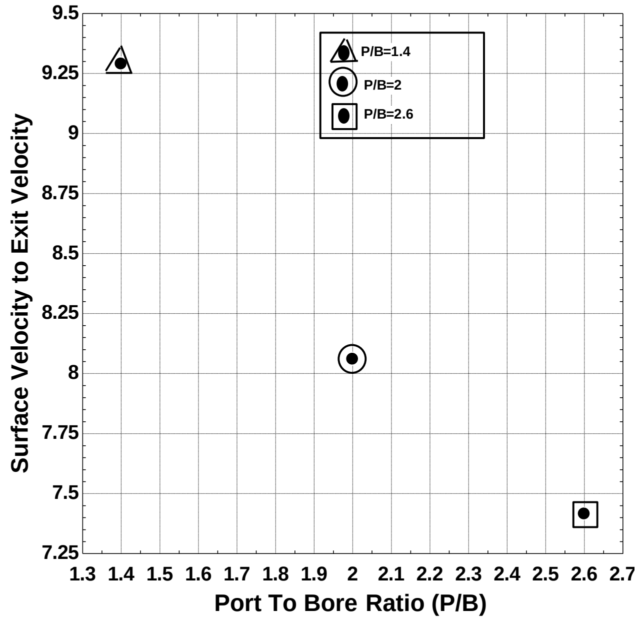


Fig.6(c): Dimensionless Plot

5. Conclusion

Water model study has been carried out in order to understand the various designs and operating parameters of SEN in a interfacial fluctuation. From the present numerical investigation the following conclusion were drawn, Water flowing through the SEN, impinges on the side wall and split into two recirculating zones i.e. upper and lower recirculating zones. After initial transience, interfacial fluctuation is limited within certain band but still it is time varying. The numerical results were found closely match with the experimental results reported in the literature [2]. It was also found the variation of interfacial fluctuation for different submerged entry nozzles and Port to bore ratio. From the numerical investigation it was concluded that the size of upper recirculation roll increases, impact jet velocity on side wall decreases and Surface Velocity to Exit Velocity ratio decreases with increase of Port to Bore ratio. By taking different water velocity and submergence height, hydrodynamic behaviour and interfacial fluctuations inside the mould can be predicted.

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