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Numerical Investigation of interfacial fluctuation with turbulence effects in casting mold due to submerged entry nozzle

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KEYWORDS

Submerged Entry Nozzle,
Interfacial Fluctuation,
Shell Thickness,
Numerical Simulation,
Fluid Flow

ABSTRACT

Submerged Entry Nozzle (SEN) plays an important role in determining the flow behavior inside the casting mold. As molten steel flow inside the casting mold is turbulent in nature. Level of turbulence as well as breaking of surface wave with entrainment of slag into the mold controls the quality of final product. So minimizing the turbulence effect inside the mold is important in order to avoid mold flux entrainment which is converted to silvers in the final product, to avoid meniscus instability and heat transfer distribution evenly aiming for uniform shell growth. So present water model is based on numerical analysis of interfacial fluctuation as well as turbulence effect inside the casting mold. By taking certain similarity criteria the behavior of water and air is similar with steel and argon. The present numerical work shows the effect of shell thickness,different Port to Bore ratio (P/B) , Submergence height to port diameter ratio (H/P) on interfacial fluctuation, surface velocity ,turbulent kinetic energy and its intensity. Stabilazation of fluctuation level inside the mold is necessary for improving the final product.

Introduction

As there is a sharp demand of casting steel product. So both quality and quantity of the final product must be maintained. In a continuous slab caster, a higher casting speed is necessary but subjected to consideration of interfacial fluctuation. Higher fluctuation at the interface develops vortex and entrap slag into the casting mold which spoil the quality of the final product.

Both experimental and numerical analysis has been done by different researchers to investigate fluid flow behavior inside the casting mold. Dash et al 2004 studied the fluid flow behavior inside the casting mold and made a conclusion that the interfacial fluctuation is unsteady in nature. After some time, unsteadiness dies out to a great extent it means free surface fluctuates within a certain limit.Gupta and Lahiri [1994] analysed the behavior of interface by taking different port diameter, port angle and immersion depth and concluded that interface is wavy in nature & there is a formation of vortex depending upon the design of the nozzle. X. Jin et al [2011] studied the fluid flow behavior in solidified shell and made a conclusion that mold having solidified shell has more interfacial fluctuation, surface velocity and poor slag distribution as compared to mold without solidified shell. Das et al 2014 numerically analyzed the behavior of interfacial fluctuation as well as turbulence level within the mold by taking water model. ZHANG Qiao-ying, WANG Xin-hua [2010] analysed the fluid flow pattern inside mold and concluded that higher casting speed should be avoided and lower casting speed should be used. Das and Dash [2013] numerically investigated the fluid flow pattern inside the mold as well as designed a nozzle by taking different water velocity, Port to Bore ratio. Das and Dash [2012] studied transience behavior of free surface by taking different water velocity, air velocity and size of upper recirculation roll. Baokuan LI and Fumitaka Tsukihashi, [2006] made a conclusion that surface velocity depends on nozzle outflow angle and casting speed which influence on vortex intensity.

Hai-qi et al. [2010] numerically analysed the flow behavior inside the mold as well as the variation of interface between molten steel and liquid slag layer by using different parameters like submergence depth, port angle, casting speed and argon gas flow rate. Singh et al [2006] have done both experimental and numerical work and made a conclusion that bubble penetration depth depends upon water flow rate rather than air flow rate.Wu and Cheng [2008] concluded that interfacial fluctuation depends upon different factors like port angles, port diameter and height and by using these factors nozzle was designed. Chen et al [2012] developed a new type of self braking submerged entry nozzle which gives lesser interfacial fluctuation as compared to traditional SEN. Zheng and Zhu[2010] developed a new approach for estimating fluctuation amplitude inside the mold with argon blowing. They have done experimental work and concluded that interfacial fluctuation is mainly around the nozzle wall.

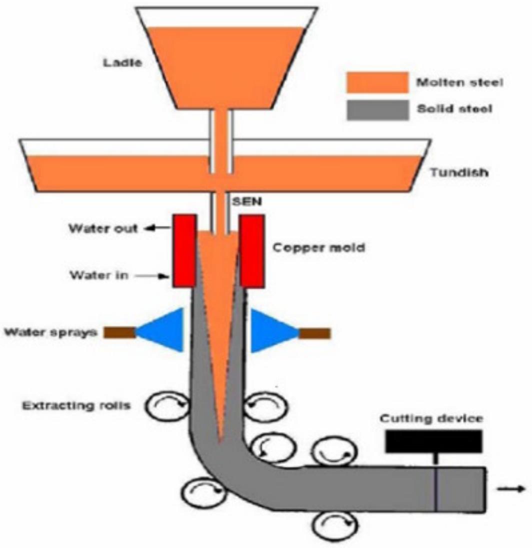


Figure.1 The Continuous Casting Process

Governing Equations

As the fluid flow is incompressible, viscous flow with unsteady in nature, the following governing equations are used.

Momentum Equation

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

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

Momentum Equation

As fluid flow inside the casting mold is turbulent in nature, hence κ-ϵ model is used for capturing the fluid dynamics which are given by the following equations

Turbulent kinetic energy, κ :

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

Rate of dissipation of κ :

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

Where $\upsilon_t = \frac{C_\mu\kappa^2}{\varepsilon}$

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

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

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

Constants used in the κ-ϵ model are C_1 = 1.44, C_2 = 1.92, σ_C = 1.0, σ_κ=1.0, σ_ϵ = 1.3, and C_μ = 0.09

The present numerical analysis is based on two-dimensional work. Volume of fluid (VOF) method is used for tracking the volume fraction of each of the fluids throughout the computational domain. HRIC (High Resolution Interface capturing) scheme is used for simulating interface. The density of water is constant and the volume fraction for the second phase (air) has the following equation.

$$\frac{\partial c}{\partial t} + U.\nabla c = 0$$

(5)

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

$$\mu = \mu_1 c + \mu_2(1-c) \quad \rho = \rho_1 c + \rho_2(1-c),$$

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

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

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

Result and Analysis

Validation with Experimental Results

The experimental work was done by (Gupta and Lahiri,1994) about breaking of surface wave. Fig. 2(a) shows experimental snap shot of interfacial fluctuation under high velocity condition. Fig. 2(b) shows numerical results of interfacial fluctuation. Both experimental and numerical results closely match with each other. Experimental snapshot was taken just at the time of entrapment of air bubbles (but the exact time of entrapment was not mentioned).The free surface time gap was taken 0.04 sec with starting time of t=3.2 sec. It was observed from both experimental and numerical work that free surface wave breaks to form a trough and entrapment of air bubbles occur at this point. Fig.2(c) shows the free surface wave breaking and entrapment of air bubble in the computational work. Fig.2c (e) shows the phenomena of breaking of surface waves and entrapment of air bubbles into the mold. In real caster, because of breaking of surface wave, slag enters into the mold and mix with molten steel resulting the final product defective. Figure 2(d) is the computational two dimensional model with grid arrangements for simulation of the experiment.The interfacial region should be finer in order to get a better result. The interface is located 1072 mm from the bottom of the mold. The submergence height is taken as 150 mm.

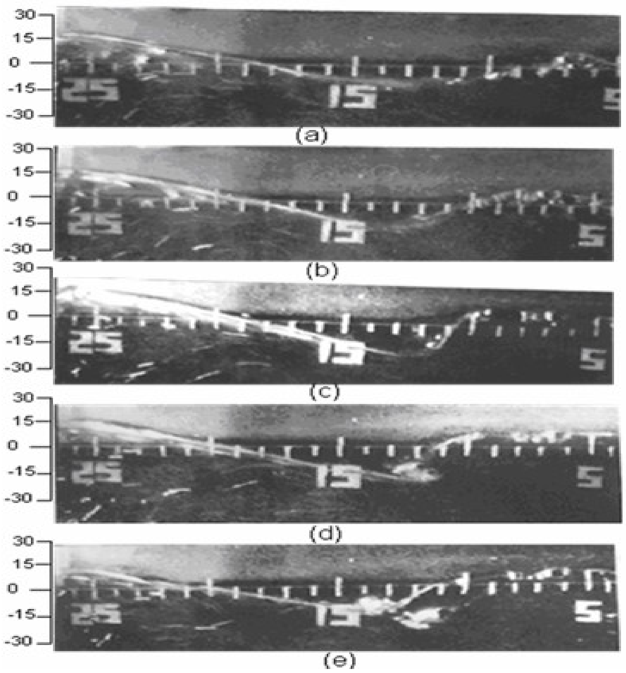


Figure 2(a) Experimental Snapshots of the free Surface fluctuation developed with Parallel Port SEN at an time interval of 0.04 sec, Port exit velocity 1.94 m/s Source: (Gupta and Lahiri, 1994).All dimensions are in mm

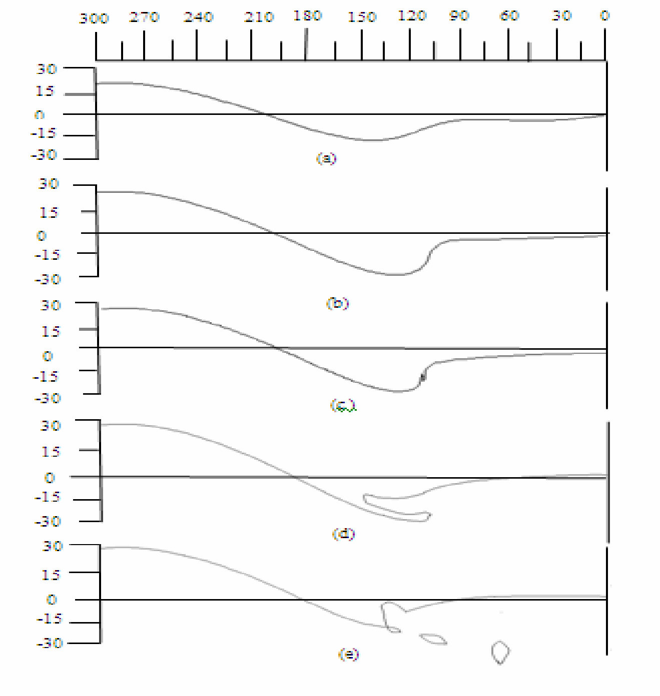


Figure 2(b) Numerical results validated with Experimental results

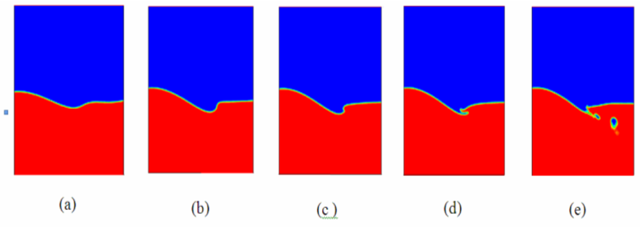


Figure 2(c) Breaking of Free Surface with entrapment of air bubbles

Effect of shell thickness on Surface fluctuation, Surface velocity, turbulent intensity and turbulent kinetic energy

Figure.4 shows that as shell thickness goes on increasing continuously inside the mold, fluid through SEN strikes the wall with a higher impact resulting more recirculation roll. So fluid reaches free surface with a higher momentum resulting more interfacial fluctuation.

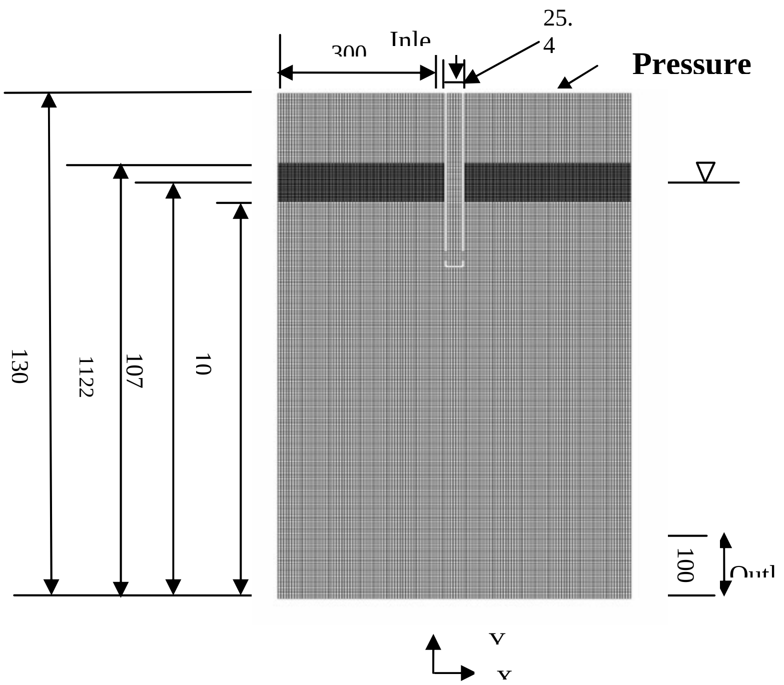
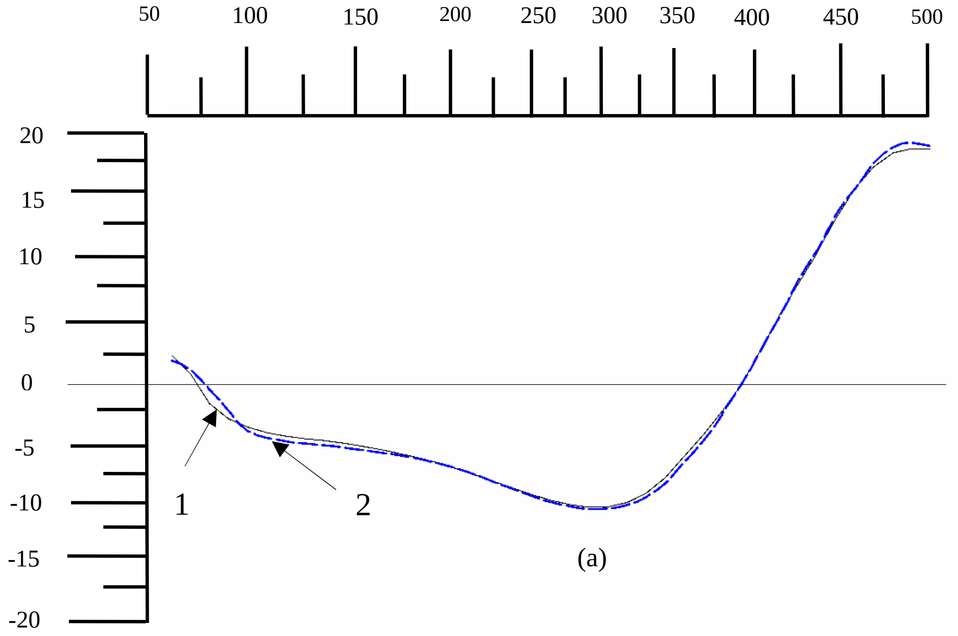


Figure 2(d) Computational domain with grid arrangements for the simulation of Experiment. All dimensions are in mm

Grid independent free surface



(a)

Figure 3 Grid Independent Test) **(All dimensions are in mm)**

Figure 3 shows grid independent test where, x-axis shows the distance from nozzle to side wall and y-axis shows free surface fluctuation. It was found that after making the cell size half in both x and y directions. (1) cell size=5x5 mm (2) cell size=2.5x2.5 mm, the free surface does not change very much because of changing of cell size.

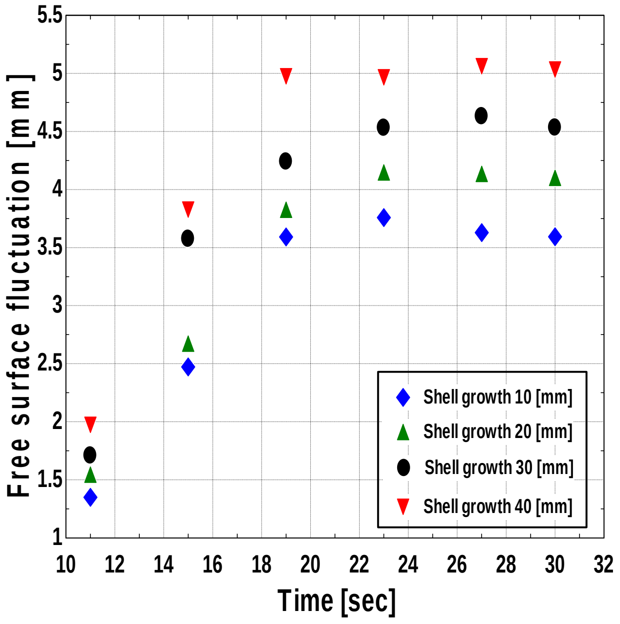


Figure.4 Effect of shell thickness on interfacial fluctuation

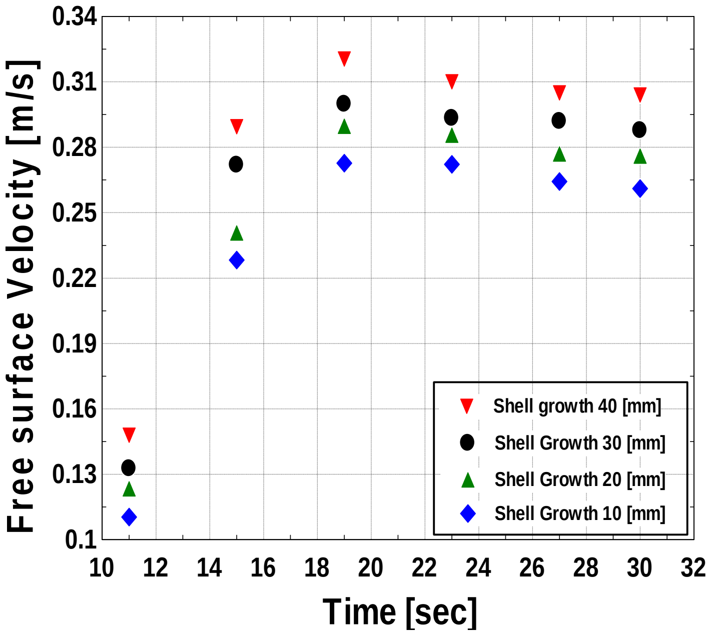


Figure.5 Effect of shell thickness on Surface Velocity

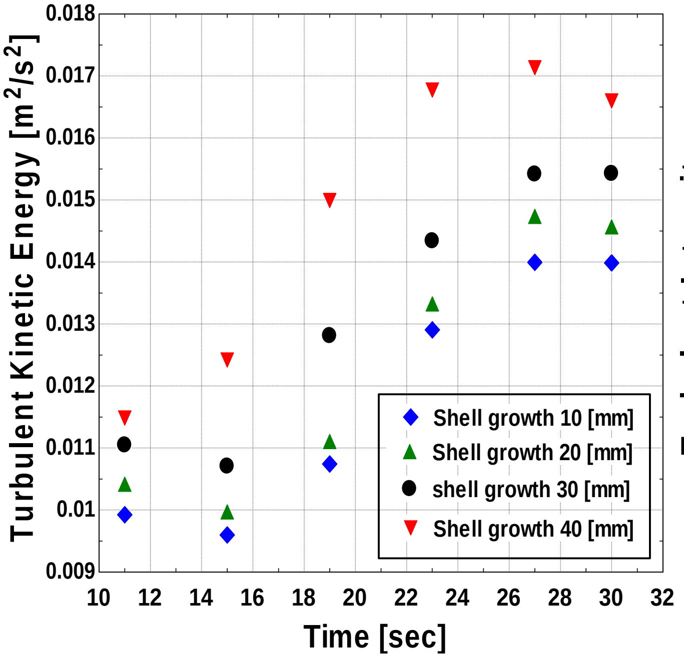


Figure.6 Effect of shell thickness on turbulent intensity

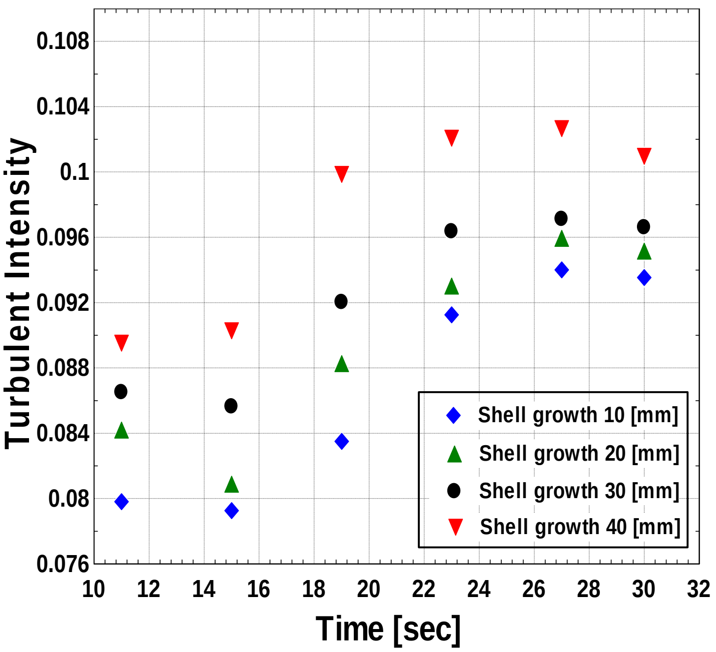


Figure.7 Effect of shell thickness on turbulent intensity

As time goes on free surface fluctuates within a certain limit but still the phenomena is time varying. Similarly figure 5 shows that with increase of shell growth inside the mold amplitude of free surface fluctuation increases resulting more surface velocity. Figure 6 and 7 shows that as shell thickness increases continously level of turbulence inside the mold increases resulting the final product defective.

Effect of Port to Bore ratio on Interfacial fluctuation, Surface Velocity,Turbulent kinetic energy and Turbulent Intensity

Figure 8 and 9 shows that as Port to Bore ratio (P/B) increases continously the free surface fluctuates with a lesser amplitude resulting less surface velocity. Figure 10 and 11 shows that by increasing Port to Bore ratio (P/B), kinetic energy of turbulence and its intensity decreases inside the mold.

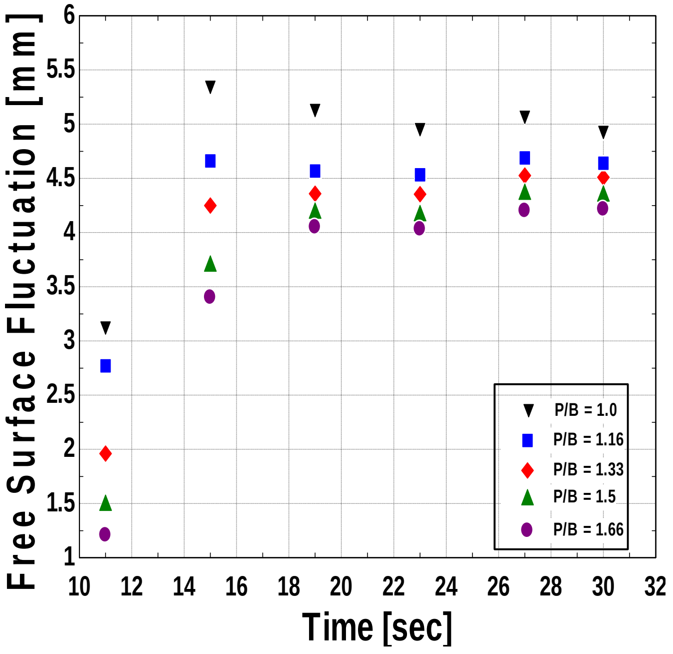


Figure.8 Effect of port to Bore ratio on interfacial fluctuation

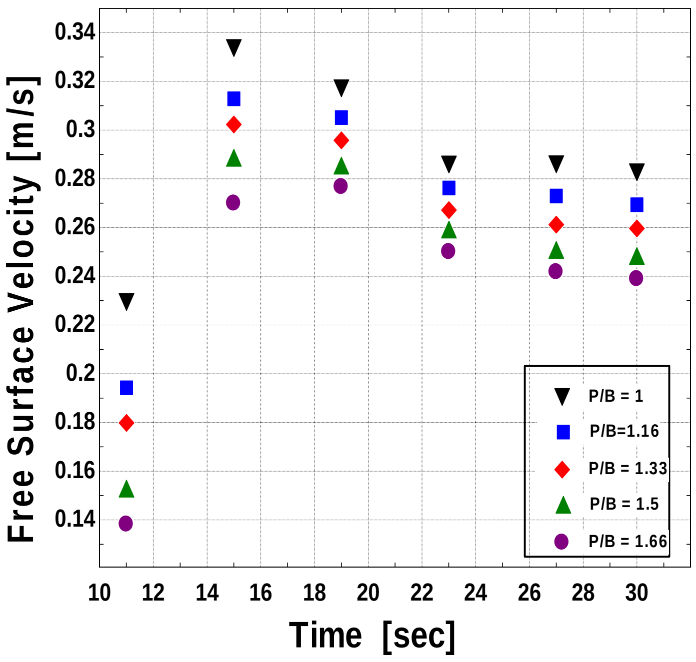


Figure.9 Effect of port to Bore ratio on surface velocity

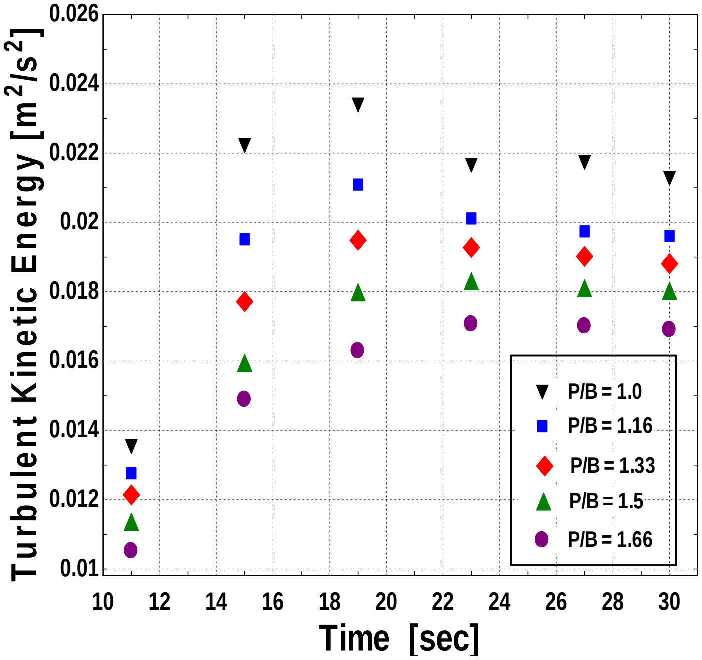


Figure.10 Effect of Port to Bore ratio on Turbulent Kinetic Energy

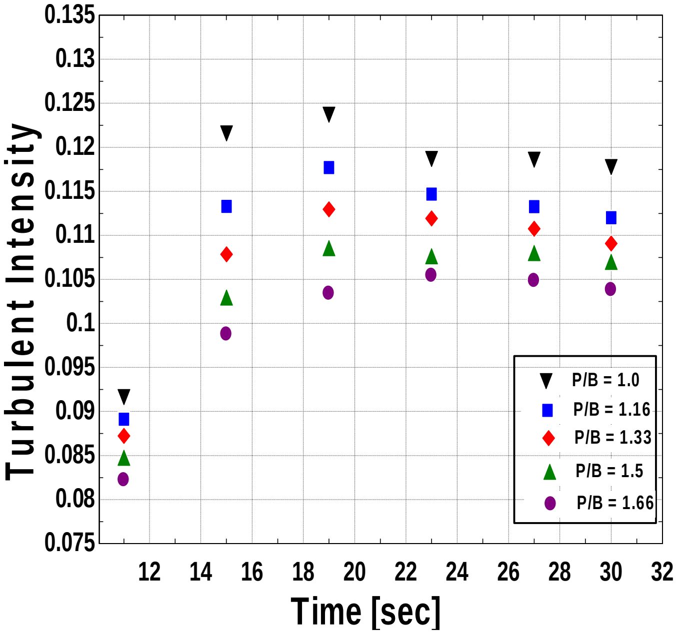


Figure.11 Effect of Port to Bore ratio on Turbulent Intensity

Effect of Submergence Height to Port ratio (H/P) on Interfacial fluctuation, Surface Velocity, Turbulent kinetic energy and Turbulent Intensity

Figure 12 and 13 show that as (H/P) ratio increases continously,fluid strikes the side wall with a less impact resulting less recirculation roll. So free surface fluctuates with a lesser amplitude along with less surface velocity. Figure 14 and 15 show that as H/P ratio goes on increasing, turbulence level inside the mold decreases. So kinetic energy of turbulence as well as its turbulent intensity decreases.

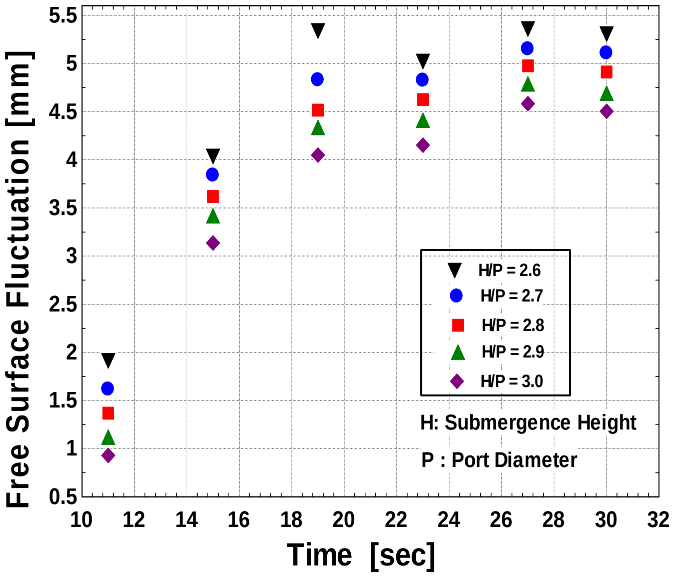


Figure 12 Effect of submergence height and port (H/P) ratio on interfacial fluctuation

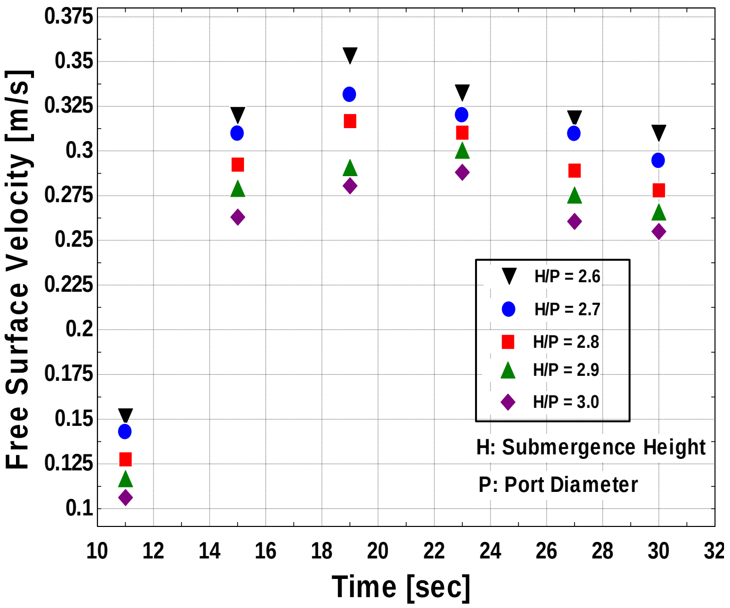


Figure 13 Effect of submergence height and port (H/P) ratio on surface velocity

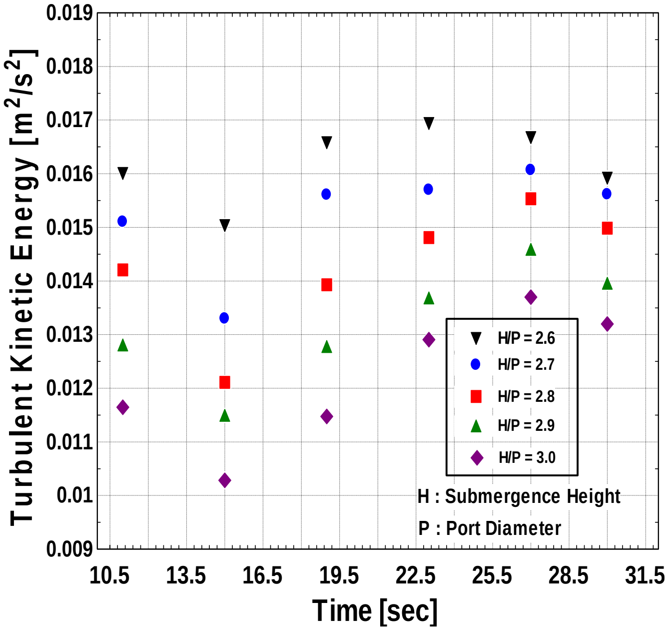


Figure 14 Effect of submergence height and port (H/P) ratio on turbulent kinetic energy

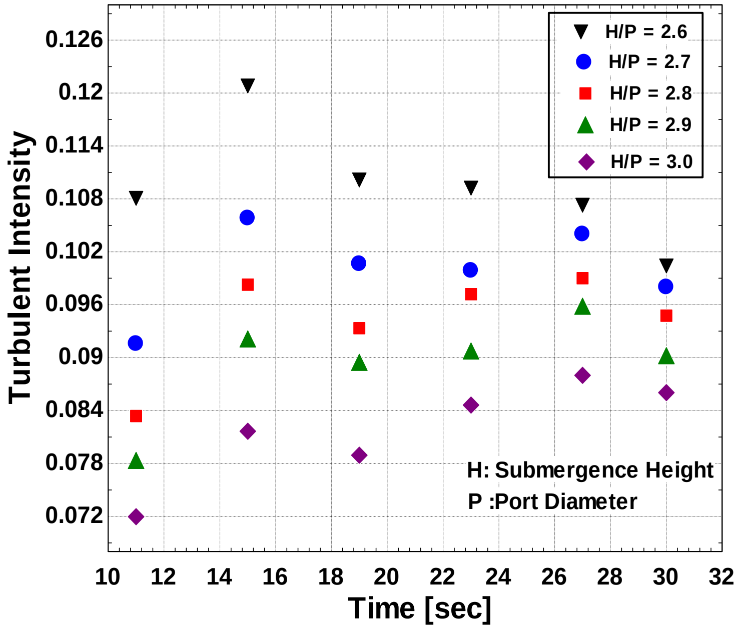


Figure 15 Effect of submergence height and port (H/P) ratio on turbulent intensity

Conclusion

Water model technique along with mathematical modeling were used to analyze the interfacial behavior inside the mold. The interfacial behavior along with level of turbulence inside the mold is analyzed by taking different operating parameters like shell thickness, Port to Bore ratio(P/B), Submergence height to Port ratio(H/P). Numerical and experimental results closely match with each other. From experimental and numerical results, conclusion was made that beyond a certain water velocity, wave breaking phenomena takes place and air bubbles enter into the mold. From the present paper it was concluded that with increase of Port to Bore ratio (P/B), Submergence height to Port ratio (H/P) the interface fluctuates with a lesser amplitude and hence turbulence level is less. Similarly as shell thickness inside the mold goes on increasing continously the amplitude of free surface increases with level of turbulence increases which controls the quality of the final product. The present numerical method gives the right direction in predicting the flow behavior inside the mold.

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