Mechanism Analysis of Free-Surface Vortex Formation during Steel Teeming

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To develop an effective technology to prevent vortex forming in ladles, the mechanism underlying vortex formation during steel teeming must be studied. For simulations using the numerical simulation software Fluent, a geometric model of the ladle was generated, and initially water teeming in the ladle was simulated for different initial tangential velocities. The results obtained help to verify the validity of the numerical computations. Similar simulation conducted for steel showed that the tangential velocity increases from the liquid level to the bottom of the ladle, and the flow at the bottom is related to vortex formation. The inference is that vortex formation begins from the ladle bottom. Causes for vortex formation during teeming are discussed to help lay a theoretical basis for ladle design in preventing vortex formation during steel teeming.

KEY WORDS: free-surface vortex; slag entrapment in the ladle; clean steel; critical height; volume-of-fluid model (VOF).

1. Introduction

For the steel industry, reducing inclusion content in melt is important in producing clean steel. During continuous casting, vortex always forms above the nozzle when molten steel flows from the ladle to the tundish. The vortex quickly leads to slag entrapment. In particular, when the steel liquid level is below a critical height at the end of teeming, slag and even air are strongly entrapped. It results in inhibiting inclusion floating, causing nozzle corrosion and clogging, increasing molten steel reoxidation, and seriously affecting the quality of steel. Therefore, if the principle underlying the formation of the free-surface vortex can be more clearly understood, controlling the vortex might be possible and helpful in designing against vortex formation.

Over recent years, many researchers in related fields have done much in studying factors leading to formation and critical submergence depth of the free-surface vortex; also called critical height for short, the critical submergence depth is the vortex depth when the vortex extends to nozzle. In regard to theories and experiments, Lewellen et al.1) studied the formation of the inspiration vortex when a small orifice is opened at the bottom in viscous and incompressible flows. Piva et al.2) found that vortex formation depends mainly on the initial maximum tangential velocity and the nozzle location relative to the cylinder axis. In addition, they also analyzed why the height of vortex formation is lower in the ladle of an off-centered nozzle than that of a centered nozzle. Lin et al.3) analyzed several factors in detail (including initial liquid level, nozzle diameter, nozzle eccentricity, and slag layer) which influenced the critical height of vortex. Odgaard,4) Gordon,5) and Reddy and Piekford6) also proposed a formula to estimate critical height. Sankaranarayanan et al.7) pointed out that vortex were formed from two distinct features, namely, vortexing funnels and non-vortexing funnels, which are determined by two entirely different sets of variables. Their research is important for continuous casting production. Kojola et al.8) exactly predicted the critical height of non-vortexing funnels using spherical control volume and cylindrical control volume models. In regard to numerical simulation, Zhao et al.9) solved the free-surface problem using the multiphase volume of fluid (VOF) model. They obtained through simulations the structure and movement of free-surface vortex, and considered that this vortex was caused by locally concentrated rotational energy and was similar to the Rankine vortex. Kuwana et al.10) used particle image velocimeter to measure velocities for water-teeming in a ladle, and simulated this model using computational fluid dynamics (CFD) software. They also found that vortex formation is related to the initial tangential velocity, and obtained a relation among critical height, Froude number, and Reynolds number. However, they did not specifically analyze the vortex forming process. Davila et al.11) used a VOF model to simulate steel teeming under thermal insulated and thermal non-insulated conditions. They pointed out that the vortex formation height increased due to buoyancy caused by temperature gradients. Although researchers have done much work on free-surface vortex and have made some advance, there are still no explicit...
explanations for the formation of the free-surface vortex. Shapiro\textsuperscript{12} and Binnie\textsuperscript{13} confirmed experimentally that vortex in the northern hemisphere tended to rotate counterclockwise due to the Coriolis force caused by the Earth’s rotation.\textsuperscript{14} Trefethen et al.\textsuperscript{15} also confirmed experimentally that vortex in the southern hemisphere tended to rotate clockwise. However, Haugen et al.\textsuperscript{14} considered this effect was not significant for small-scale vortex. Moreover, Pedlosky et al.\textsuperscript{16} reported that counterclockwise and clockwise directions were both possible when vortex occurred. Suh et al.\textsuperscript{17} pointed out that when compared with initial tangential velocity, the Coriolis effect can be neglected under normal flow conditions except when fluids had completely settled for a long period of time.

In summary, some researchers studied the factors of vortex formation and proposed different formulas about the critical height of vortex through experimental, dimensional, and mathematical analysis. These experimental studies were however unable to give a detailed analysis of changes in the entire flow field in the vessel at different times, especially when the measurement of parameters of the molten steel is difficult in practice. Therefore, it is difficult to use experimental methods to analyze the mechanism of vortex formation in the ladle during steel teeming. Moreover, in respect to numerical simulations, researchers have already studied temperature effects on vortex formation, and arbitrary initial tangential velocities in simulations. Nonetheless, the simulation results were not compared with experimental results, thus the validity of the simulation was not confirmed. For this study, a geometric model of a ladle similar in manner as described in the research literature\textsuperscript{18} was generated for computer simulations. Teeming of water in the ladle was simulated using the Fluent simulation software, and the numerical simulation method verified by comparing simulation results with experimental data. Steel teeming in the same ladle configuration was simulated using the same methods. The vortex formation at the end of steel teeming was analyzed. In this paper, a description of results is given along with a discussion of the mechanism and rule of vortex formation, to provide a reference and basis for preventing vortex formation in ladles during steel teeming.

2. Numerical Solution

2.1. Mathematical Model

The mathematical model for fluid flow in a ladle is based on the following assumptions: the fluid is viscous and incompressible; the effect of temperature is negligible; to simplify modeling, the ladle is assumed cylindrical; wall thickness of the ladle is neglected; the nozzle is centered in the ladle; the no-slip condition (zero velocity) for fluid flow near the ladle wall is assumed; and the slag layer on top of the molten steel is also neglected. The effect of Coriolis force on vortex intensity can be represented by Equation 1

$$\frac{\partial}{\partial t} (\rho u_i) + \frac{\partial}{\partial x_j} (\rho u_i u_j) = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} (\mu \frac{\partial u_i}{\partial x_j}) + \rho g_i$$

Turbulent kinetic energy equation ($k$):

$$\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_j} (\rho k u_j) = \frac{\partial}{\partial x_j} \left( \alpha_2 \mu_{\text{eff}} \frac{\partial k}{\partial x_j} \right) + G_k + G_h - \rho \varepsilon - Y_H + S_k$$

Turbulent dissipation rate equation ($\varepsilon$):

$$\frac{\partial}{\partial t} (\rho \varepsilon) + \frac{\partial}{\partial x_j} (\rho \varepsilon u_j) = \frac{\partial}{\partial x_j} \left( \alpha_1 \mu_{\text{eff}} \frac{\partial \varepsilon}{\partial x_j} \right) + C_{\text{t}} \frac{\varepsilon}{k} (G_k + C_{\text{th}} G_h) - C_{\text{t}} \rho \frac{\varepsilon^2}{k} - R_s + S_{\varepsilon}$$

where $P$ is the pressure; $\mu_{\text{eff}}$ is the effective viscosity; $G_k$ is the generation of turbulence kinetic energy due to the mean velocity gradients; $G_h$ is the generation of turbulence kinetic energy due to buoyancy; $Y_H$ is the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate, neglected because the fluid is incompressible; $S_{\varepsilon}$ user-defined source terms; $R_s$ the main difference between the RNG $k-\varepsilon$ model and standard $k-\varepsilon$ model lies in the additional term in the $\varepsilon$ equation; and $S_{\varepsilon}$ user-defined source terms. The model constants: $C_{\text{t}} = 1.42$;
2.2. Geometric Model

The ladle dimensions are as encountered in the research literature, see Table 1.

The ladle model is meshed using a combination of structured and non-structured grids.

2.3. Boundary Conditions, Initial Conditions and Solution Method

The inlet boundary is a pressure inlet and the exit boundary is a pressure outlet. The gauge pressures of inlet and outlet are 101325 Pa (1 atm). The flow direction of inlet is perpendicular to the boundary. The flow direction of outlet is obtained by iterative operation when the pressure conditions are set. The velocity values of inlet and outlet are also obtained by iterative operation. The velocities for the ladle wall and nozzle wall are 0 because of no-slip wall. The turbulent intensity of pressure outlet is 0.6, and the operation pressures of inlet and outlet are 0.

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The vortex, formed at the end of steel teeming, is a combination-type vortex like the Rankine vortex. The tangential velocity distribution of Rankine vortex is described as:

\[ u_0 = \frac{\omega r}{r} \quad 0 \leq r \leq a \]

\[ u_b = \frac{\omega a^2}{r} \quad r \geq a \]

Where \( \omega \) is the angular velocity and \( a \) the vortex core radius.

In this study, the two initial tangential velocity distributions are introduced by way of a UDF program expressed in the form:

\[ \frac{u_0}{r} = \frac{\omega}{0.2069} \text{ rad/s} \]

\[ u_0 = 0.06 m/s \]

The conversion between the velocity \((\vec{u}_x, \vec{u}_y, \vec{u}_z)\) in the Cartesian coordinate system and the velocity \((\vec{u}_b, \vec{u}_a, \vec{u}_c)\) in the cylindrical coordinate system is:

\[
\begin{align*}
\vec{u}_x &= \vec{u}_b + \frac{|\vec{b}|}{\sqrt{x^2 + y^2}} + \vec{u}_a - \frac{|\vec{a}|}{\sqrt{x^2 + y^2}} \\
\vec{u}_y &= \vec{u}_b + \frac{|\vec{b}|}{\sqrt{x^2 + y^2}} + \vec{u}_a - \frac{|\vec{a}|}{\sqrt{x^2 + y^2}} \\
\vec{u}_z &= \vec{u}_c
\end{align*}
\]

When

\[ x = y = 0 \]

\[ \begin{align*}
\vec{u}_x &= \vec{u}_y = 0 \\
\vec{u}_z &= \vec{u}_c
\end{align*} \]

That means

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<td>Diameter of ladle, D (m)</td>
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<td>Height of ladle, Hladle (m)</td>
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<td>Initial liquid level, H0 (m)</td>
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<td>Diameter of nozzle, d (m)</td>
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<tr>
<td>Length of nozzle, l (m)</td>
<td>0.1235</td>
</tr>
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</table>

3. Verification of Simulation Method

3.1. Initial Tangential Velocity Distribution

In an ideal, incompressible, and inviscid liquid, the velocity distribution of a free-surface vortex and forced vortex are described as in Eqs. (5) and (6), respectively. With \( r \) denoting the distance from nozzle center, the tangential velocity, \( u_b \) is:

\[ u_b = \frac{\omega r}{r} \quad 0 \leq r \leq a \]

\[ u_b = \frac{\omega a^2}{r} \quad r \geq a \]

Where \( \omega \) is the angular velocity and \( a \) the vortex core radius.

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\vec{u}_z &= \vec{u}_c
\end{align*}
\]

When

\[ x = y = 0 \]

\[ \begin{align*}
\vec{u}_x &= \vec{u}_y = 0 \\
\vec{u}_z &= \vec{u}_c
\end{align*} \]

That means

<table>
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<th>Parameter</th>
<th>Value</th>
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<td>Water</td>
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<td>Surface tension, ( \sigma ) (N/m)</td>
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<tr>
<td>Steel</td>
<td>Dynamic viscosity, ( \mu ) (Pa s)</td>
<td>0.0053</td>
</tr>
<tr>
<td></td>
<td>Surface tension, ( \sigma ) (N/m)</td>
<td>1.6</td>
</tr>
</tbody>
</table>

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Where, \((x,y,z)\) is the coordinate value of any point in the flow field.

And the counterclockwise direction of velocity is positive, clockwise is negative. The direction of initial velocity is assumed counterclockwise by UDF. The two initial velocity distributions are the constant angular velocity of the forced vortex and the constant tangential linear velocity with value taken from the literature.\(^7\) Thus, whether the free-surface vortex like a Rankine vortex can be formed can finally be revealed. The result in the literature \(^7\) is initial tangential velocity value but not the initial tangential velocity distribution, so the initial velocity distribution is assumed as the two types. One distribution is constant angular velocity \(0.2069 \text{ rad/s}\), this is equivalent to the mean tangential linear velocity \(0.06 \text{ m/s}\). The other distribution is constant tangential linear velocity \(0.06 \text{ m/s}\). As long as the initial tangential velocity distribution is close to the actual interaction effect, the simulation results obtained through iterative computation will be consistent with the experiment result. Hence, the appropriate distribution of the initial tangential velocity which produces a dimple height for the vortex close to the experimental result\(^7\) can be determined.

**Figure 1** shows the simulation results for two different initial tangential distributions. The initial liquid levels \(H_0\) are \(0.5 \text{ m}\) in two cases. Because the velocity field is symmetric with respect to the center axis, half of the curves for the two initial tangential velocity distributions can be compared. After the nozzle of the ladle is opened, the entire flow field is seen to tend gradually towards the distribution for a Rankine vortex. This behavior always occurs regardless of the initial tangential velocity distribution. And vortex core radius decreases with the distance to the ladle bottom decreasing in both left and right figures. The values of the vortex core radius are greater than the nozzle radius in left figure and the values are less than the nozzle in right figure. But these values of vortex core radius are approximately close to the nozzle radius. **Figure 2** shows the heights of the liquid surface started to dimple at \(0.34 \text{ m}\) and \(0.38 \text{ m}\) for the two different initial tangential velocity distributions. Comparing with the experimental value of \(0.39 \text{ m}\) reported in \(7\), the latter is much closer. Therefore, the results show that the initial tangential velocity should be set to a constant tangential linear velocity value. That is closer to actual interaction effect.

### 3.2. Verification of Model

With the same simulation method, the draining of water is simulated with initial tangential velocities of \(0.06 \text{ m/s}\), \(0.03 \text{ m/s}\), and \(0.01 \text{ m/s}\) all in a counterclockwise rotation. **Figure 3** shows a comparison of dimple height between our simulations and experimental results from literature \(7\); \(H_{\text{dimple}}\) is the height of the liquid when the fluid surface starts to form a dimple. In the same order as the initial tangential velocity,

\[
\begin{align*}
\mathbf{u} &= \mathbf{u}_c = 0 \\
\mathbf{u}_r &= \mathbf{u}_z = 0 \\
\mathbf{u}_z &= \mathbf{u}_c
\end{align*}
\]  

(12)
velocity, the dimple heights were 0.38 m, 0.31 m, and 0.16 m, respectively, which compare favorably with the experimental results from 7) of 0.39 m, 0.35 m, and 0.23 m. Their trends are consistent, and therefore the simulation method used in the study is correct. Moreover, the dimple height of the vortex increases as the initial tangential velocity increases; in other words, the larger the initial velocity, the sooner the vortex occurs.

4. Simulation Results and Discussion

Steel teeming is simulated with the same method. The values of the initial tangential velocities are set the same, 0.06 m/s, 0.03 m/s, and 0.01 m/s respectively, with a counterclockwise rotation. The simulation results are as follows.

4.1. Critical Height of Vortex

The critical height $H_{\text{critical}}$ is defined as the height of vortex when the vortex extends all the way to the nozzle. Critical height and its formation time are plotted against the initial tangential velocity in Fig. 4. When the initial tangential velocity was 0.06 m/s, the time it took for the air column to reach the nozzle was 19 s, and the critical height was about 0.29 m. When the initial tangential velocity was 0.03 m/s, the time extended to 29 s, and critical height lowered to 0.2 m. For an initial tangential velocity of 0.01 m/s, the time was 46 s, and critical height was about 0.07 m. Based on the above data, the critical height of the vortex increases as the initial disturbance increases.

4.2. Distribution of Tangential Velocity

The simulation results show that the radial distributions obtained for the tangential velocities are similar for each of the initial disturbances. The results for initial tangential velocities 0.01 m/s (left figure) and 0.06 m/s (right figure) are compared in Fig. 5(a) which shows the tangential velocity distribution at different heights at 4 s after nozzle open. These results are similar and in accord with the tangential velocity.
velocity distribution of a Rankine vortex. Although the vortex does not occur at 4 s, the tangential velocity increases with decreasing distance from the bottom of the ladle. Note that even before the surface begins to dimple, a vortex motion has already developed at the bottom of the ladle. Moreover, tangential velocities increase as the initial disturbance increases. And the values of the vortex core radius are also close to the nozzle radius. Figure 5(b) shows the radial distribution of the tangential velocity at a height of 0.05 m (for the initial tangential velocities 0.01 m/s (left figure) and 0.06 m/s (right figure)). Trends are similar in both simulation results. The simulation results show that the formation process progresses first with the vortex appearing, then forms an air column, and finally extends down to the nozzle, the tangential velocities gradually increasing at each same height to the bottom. And vortex core radius decreases as the time increasing in both left and right figures. According to the conservation of angular momentum, when the fluid flows towards the nozzle, the angular velocity of fluid increases quadratically as distance decreases from the center of nozzle. Therefore the vortex gradually forms and extends to the nozzle as time evolves.

From the analysis given above, we know that the tangential velocity increases as depth increases. More importantly, the vortex formation is closely related to the flow at the bottom. Therefore, we infer that vortex formation starts at the bottom of the ladle.

4.3. Analysis of the Mechanism of Vortex Formation at the End of the Steel Teeming Process

The energy in a free-surface vortex derives mainly from gravity acting on the fluid during the steel teeming, but viscous forces also play a role. The situation is similar to the formation of a tornado where the temperature difference leads to the rise of air and the shear force makes the air rotate. For the free-surface vortex, when the nozzle is opened at the bottom of the ladle, then with the effect of gravity, the static pressure in the molten steel near the nozzle is no longer balanced, thus forcing the molten steel to flow out rapidly. Meanwhile, the tangential disturbance to the molten steel leads to its rotation. The static pressure contours (Fig. 6(a)) and the velocity field (Fig. 6(b)) are given for the fluid in the ladle when the nozzle is open. The semicircle arc demarks the area near the nozzle. Region I is the vortex core region, with the vortex diameter being approximately equivalent to the nozzle diameter. Because of the static pressure difference, the molten steel near the nozzle in region I flows towards the nozzle. However, this volume of molten steel is also subjected to extrusion forces and viscous shearing stresses of the fluid in region II. Therefore axial velocity increases with decreasing distance to the nozzle and hence is a maximum in the center of nozzle. Owing to the molten steel outflow, a horizontal static pressure difference exists at the interface of regions I and II. Moreover, its direction points towards the nozzle; this causes radial flow and increases the tangential velocity. The horizontal static pressure difference gradually decreases in areas far away from the center of nozzle in region I. Thus the flow in the axial direction plays a dominant role near the nozzle in region I.

Similar to region I, when molten steel flows out of the nozzle, flows in the axial and radial directions are formed and the tangential velocity is increased by the horizontal and vertical static pressure differences in region II. Molten steel in region II is not directly above the nozzle, thus the vertical pressure difference is lower than that in region I. Because of the shear stress from the down-flow in region I, the axial velocity is larger at points closer to the interface between regions I and II. Molten steel in region II is not directly above the nozzle, thus the vertical pressure difference is lower than that in region I. Because of the shear stress from the down-flow in region I, the axial velocity is larger at points closer to the interface between regions I and II. Molten steel in region II flows towards region I because of the horizontal static pressure difference at the interface of these regions. In region II, the static pressure difference decreases as distance to the interface decreases. With the effect of viscous shear stress, the radial velocity increases as distance decreases to the interface. Tangential velocity, which is also affected by the horizontal pressure difference that acts as centripetal force, increases with decreasing distance to the interface. Thus radial and tangential velocities reach maximums near the interface. For molten steel in region II far away from the nozzle, all three velocity components decrease rapidly with increasing distance to the nozzle.
the static pressure balance has not been disturbed and therefore fluid rotates slowly in this region.

With the time increasing, the static pressure balance is destroyed gradually in the area far away from the nozzle in regions I and II; the law of the molten steel flow in this area is consistent with that near the nozzle in regions I and II. Flows in region III are relatively calm because of the distance from the nozzle. In this region, the static pressure remains almost in balance, so all three velocity components are very small; molten steel spirals slowly into region II. Figure 7(a) shows radial profiles of the velocity components at heights 0.05 m and 0.35 m away from the bottom. As these profiles are axial-symmetric, only half of the curves are shown in comparison. Velocity components at the higher height of 0.35 m are smaller than those at the lower height of 0.05 m. At the higher height, the tangential velocity is larger than either the axial or radial velocities. In contrast, at the lower height, in the area near the nozzle, the axial velocity is larger than the other two components. In the area distant from the nozzle, the tangential velocity is the largest of the three velocities. Figure 7(b) shows that the flow of molten steel is spiraling outward from the nozzle.

5. Vortex Prevention

5.1. Height for Dimple Formation

Comparing vortex and non-vortex funnels, the tangential velocities of vortex funnels accelerate the surface dimple. Kojola et al. derived a hydraulic model formula according to the Bernoulli equation for a cylindrical control volume in the absence of viscous forces:

\[
Q_{TH} = \frac{\pi d^2}{4} \sqrt{2g \left( H + l + \frac{D^2}{2 \rho_g} \right)} \\
Q_{TO} = \frac{2}{3} \pi d^2 \sqrt{2g \left( \frac{H}{\rho_g} \right)^{3/2}}
\]

Where \(Q_{TH}\) and \(Q_{TO}\) are the fluxes flowing into and out of the cylindrical control volume, \(d\) is the diameter of nozzle and \(l\) is the nozzle length (defined in Table 1), \(t\) is air layer thickness, \(H\) is surface height. Note that \(H\) and \(t\) are variables in Eqs. (13) and (14), whereas the other parameters are already known. Also, when \(Q_{TH}\) is greater than \(Q_{TO}\), the velocity of the outflow will continually increase driven by the static pressure. Moreover, with decreasing surface height, gravity cannot provide enough energy. Thus, \(Q_{TH}\) is
not sufficient, and finally a surface dimple appears. Compared with non-vortex funnels, in addition to a deficiency in vortex energy at the end of steel-teeming process, the tangential motion and viscous force also lead to a decrease in $Q_{th}$. Thus the amount of fluid in the control volume is not enough, and the surface rapidly forms a dimple. With an increase in the tangential disturbance, the vortex is formed earlier and air is also trapped in the vortex column. Therefore, the control and dispersion of the initial disturbance and the tangential velocity at the bottom of the ladle are very important. Figure 3 shows the comparison between the results and the value calculated by Kojola’s equation. The dot line in this figure indicates that the dimple height of non-vortex funnel is 0.069 m, which is calculated by Eqs. (13) and (14). The dimple heights for vortex in both the experiments and simulation are higher than this value. And the dimple height for vortex decreases with the initial tangential velocity decreasing. So, if the initial tangential velocity is controlled to be low enough, the dimple height for vortex can be closed to the dimple height of non-vortex funnel, and the slag entrapment will be reduced greatly.

5.2. Critical Height of Vortex

Figure 8 shows the relation between dimensionless critical height and Reynolds number $R_{ed}$, Weber number $W_{ed}$, Froude number $F_{rd}$. Conducting scaling analysis, see Eqs. (15) to (17).\(^\text{10}\)

\[
R_{ed} = \frac{\rho u_0^2 (d/2)}{\mu} \quad \text{(15)}
\]

\[
W_{ed} = \frac{\rho u_0^2 (d/2)}{\sigma} \quad \text{(16)}
\]

\[
F_{rd} = \frac{\rho u_0^2}{g(d/2)} \quad \text{(17)}
\]

Where $d$ is the diameter of nozzle (defined in Table 1).

In Fig. 8, it is found that the gravity is more important on vortex formation process than viscosity force and surface tension. When the Froude number $F_{rd}$ is same, the dimensionless critical heights of water and steel are equal in the same conditions. So without regard to temperature, water is a good fluid for simulating steel teeming in the ladle with the same structure. Because the critical height of vortex during steel teeming process is difficult to measure in practice, this simulation is a good method. The water model experiments and steel simulation are helpful to propose new vortex prevention approach.

In summary, as time evolves, the static pressure difference gradually increases. Furthermore, because of viscous force, the flow of fluid in all three directions near the nozzle spreads to the places away from the nozzle. Therefore, the control and dispersion of the initial disturbance and the tangential velocity at the bottom of the ladle are very important. The vortex core radius is primarily close to the nozzle radius and the vortex funnel formation starts from the bottom. Therefore, the electromagnetic force can be considered for vortex prevention near the nozzle in ladle. The effective steady electromagnetic field and rotational electromagnetic field will be studied to prevent vortex during steel teeming in future. By this method, the critical height of vortex funnel can be reduced to the critical height of non-vortex funnel or reduce lower than non-vortex funnel.
6. Conclusions

In this paper, the free-surface vortex during steel teeming was simulated using a numerical simulation method. The critical height of the vortex under different initial disturbance conditions and the radial profiles of the tangential velocity during the whole process were investigated. Moreover, formation and underlying mechanisms of free-surface vortex were discussed. The conclusions are as follows:

(1) The vortex formed during steel teeming is similar to a Rankine vortex; its tangential velocity distribution has the same characteristics as that for the Rankine vortex. And the vortex core radius is approximately the nozzle radius.

(2) The critical height of the vortex is an important parameter for the free-surface vortex. The more intense the initial disturbance is, the higher is the surface dimple height as well as the critical height. In other words, vortex is easily formed when the initial disturbance is greater.

(3) The simulation results show that formation begins with a vortex, then an air column develops, and finally the vortex extends down to the nozzle. The tangential velocity of the vortex always increases with decreasing distance to the bottom of the ladle.

(4) Gravity provides the energy for vortex formation. Aside from the static pressure imbalance, the initial tangential disturbance also leads to vortex formation. The formation is closely related to the pattern of fluid flow at the bottom of the ladle. Therefore, to prevent vortex forming, design considerations must be given to controlling the flow at the bottom. More importantly, flow mechanisms at the bottom of the ladle need to be further studied.

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