Experimental and Numerical Study of the Free Surface During the Side Teeming Ingot Casting Process

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The flow pattern affects the interaction between the mold flux and liquid steel, especially during the initial entry of liquid steel into the mold. Strong turbulence can cause mold flux entrapments during the ingot casting process. If this happens, nonmetallic inclusions are generated, which decreases the quality of the final product. Herein, the side teeming process is introduced as an alternative to the traditional uphill teeming process to decrease mold flux entrapments. Both physical experiments and mathematical modeling are conducted to study the free surface. Specifically, the Weber number is also evaluated to predict the possibility of mold flux entrapments at the free surface. The results show that a calmer free surface is formed in the side teeming process compared with the uphill teeming process. Also, the results show that the Reynolds stress model is more suitable to predict the free surface compared with the realizable k–ε model. The present findings strongly suggest that an implementation of a side teeming process would be an effective way of reducing the risk for mold flux entrapments.

1. Introduction

Many factors can influence the quality of the steel in the ingot casting process. For example, the filling rate affects macrosegregation,[5] a high mass flow rate during the teeming process flushes off small pieces of refractory,[6] high turbulence can cause mold flux entrapments,[3–5] and reoxidation during teeming can lead to the formation of inclusions.[6] In large ingots, gas bottom injection is used to improve the thermal and chemical homogenization.[7] Also, a concentric circular annulus for gas injection has been suggested to improve mixing.[8] The formation of nonmetallic inclusions represents a severe problem in the ingot casting process. The nonmetallic inclusion generation may require expensive ingot treatments and lead to rejections. For example, the ductility decreases with an increased amount of inclusions.[9] Furthermore, the fracture toughness decreases in the presence of nonmetallic inclusions, especially in higher strength lower ductility alloys.[6]

The nonmetallic inclusions can be divided into endogenous and exogenous inclusions.[10] The endogenous inclusions are deoxidation products, such as Al2O3 in aluminum killed steels and SiO2 in silicon killed steels.[11] Exogenous inclusions are generated due to the chemical and mechanical interactions of the steel with its surroundings. The main sources for exogenous inclusions are mold flux entrapments, erosion of refractory, reoxidation by air, and chemical reactions.[12] Exogenous inclusions are harmful due to their larger sizes compared with the endogenous inclusions. Zhang et al.[3] argue that exogenous inclusions cause the most significant problems during the ingot casting process. They reported the presence of several large inclusions in the size range from 150 to 600 μm and also one as large as 20 mm. Therefore, they point out the need for the development of detection methods to identify large inclusions.

Mold fluxes are essential during the ingot casting process. Those can protect the liquid steel from reoxidation and minimize heat losses. They were first used successfully in 1958.[13] Their properties include a good fluidability, a good thermal insulation, and a high melting rate. The methods of adding flux include hanging paper bags in the mold, continuous addition through a steel pipe, and so on. The method of addition also affects the initial interaction between mold fluxes and liquid steel. Here, mold flux entrapments are one of the largest sources for the formation of exogenous inclusions. After melting, the mold fluxes form a slag layer, which protects the liquid steel from atmospheric oxidation and absorbing some inclusions from the molten steel. However, mold fluxes may also be dragged down into the liquid steel if the movement of steel meniscus is large enough. To minimize this risk, Zhang and Thomas[3] suggested a lower teeming rate during the initial filling stage and an optimal dropping height of the powder bags. Also, Eriksson et al.[14] reported complex inclusions due to the interaction between liquid steel and mold fluxes. However, they showed that a severe reoxidation would occur without the addition of mold fluxes. Thus, many researchers have conducted investigations to find suitable methods to eliminate or reduce the amount of nonmetallic inclusions caused by mold flux entrapments.

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Eriksson et al.[15] conducted simulations using 2D mathematical modeling with different opening angles of the inlet nozzle in the uphill ingot casting process. They found that an increase in the opening angle, from $0^\circ$ to $30^\circ$, results in a gradual decrease in the horizontal velocity at the free surface. Furthermore, a higher opening angle leads to a lower value of the Weber number and reduces the tendency for mold flux entrapments. Therefore, they suggested an optimum value of $25^\circ$. Ragnarsson et al.[16] investigated three angles, $5^\circ$, $25^\circ$, and $45^\circ$. They concluded that a $5^\circ$ angle results in the smallest surface velocities. From these results, it seems clear that the optimal inlet angle is system dependent.

Hallgren et al.[17] conducted physical and mathematical modeling to investigate the resultant humps and axial velocities using a divergent nozzle and a swirl generator. The results showed that a divergent nozzle could reduce the hump height and axial velocity at the free surface. Bai et al.[18] investigated the swirling flow generated by a TurboSwirl device using both physical and numerical models. In their study, different flaring angles of divergent nozzle were implemented. They found that an air-core vortex was formed during the filling process. Also, Tan et al.[19] simulated the initial mold filling process using a swirling blade, which was placed at the bottom of the vertical runner. The results showed that a calm free surface with fewer fluctuations was achieved during the filling. Recently, Jun et al.[20] presented mathematical modeling results where different angles between the trumpet and the horizontal runner were studied. They found that a $30^\circ$ angle between the trumpet and the horizontal runner can lead to a lower hump height and less fluctuations. Recently, Campbell[21] also recommended a swirl trap design to achieve calm filling conditions during the ingot filling.

Several studies focusing on a decrease in mold flux entrapments have been reviewed, as shown in Table 1. Although those suggested designs can reduce the mold flux entrapments to some extent, there are still some disadvantages. The TurboSwirl design can cause a generation of a vortex, which has the potential to generate mold flux entrapments. The swirl blade can cause severe erosion problems, when it was placed in the runner. The divergent nozzle and entrance nozzle designs can also lead to the formation of a hump at higher filling rates. Therefore, a design called the side teeming process (Figure 1c) was investigated in the present work. Several flow rates, including an industrial flow rate, were studied. It is expected that a calm free surface without a vortex formation can be generated in the mold. A water model was also built to observe the free surface in the side teeming process. An Ultrasonic Velocity Profiler (UVP) device was used to measure the vertical velocity in the mold. The measured results were compared with the simulation results for model validation. Moreover, a 3D mathematical model was simulated to investigate the Weber number at the free surface for the side teeming process. Finally, the wall shear stresses were numerically investigated.

| Author       | Design                  | Remark                     |
|--------------|-------------------------|----------------------------|
| Bai et al.[18]| TurboSwirl              | Numerical simulation,      |
|              |                         | physical model             |
| Hallgren et al.[17] | Swirl blade       | Numerical simulation,      |
|              |                         | physical model             |
| Eriksson et al.[15]| Entrance nozzle design| Numerical simulation       |
| Hallgren et al.[17]| Divergent nozzle  | Numerical simulation,      |
|              |                         | physical model             |

2. Experimental Section

Compared with complex and expensive industrial plant trials, water model experiments represent cheap alternatives to investigate the hump height and the flow pattern during the side

![Figure 1. Dimensions of the mold (mm): a) top view; b) front view; and c) 3D view.](image-url)
teeming process. The dimensions of the water model are shown in Figure 1, which is 1/5 size of 6.2 ton ingots. The divergent nozzle was modified to be a straight nozzle due to restrictions during manufacturing. Consequently, the bottom of the mold was made as a flat surface. One hole with a diameter of 70 mm was created at the mold’s side wall, which is used as an outlet to enable the system to reach a steady state. It is an artificial method to study the free surface at a given bath height experimentally. The mold was made of plexiglass, which is transparent, allowing visualization of the free surface inside the mold. A flange was made in the mold, which was used to connect the runner. Figure 1c shows the modified assembly of the runner and the mold, which is called the side teeming process in the current work. It should be noted that only the side teeming process was conducted in the present work; the results of the uphill teeming process were obtained from the previous work.

Figure 2a shows the total setup of the water model experiment for the side teeming process. During the experiment, water was transported from the reservoir to the mold by the pump, where the flow rate was controlled by the flowmeter. Table 2 shows the range of inlet velocities used to investigate the free surface for the side teeming process. The highest value, 1.05 m s\(^{-1}\), was calculated based on the filling rate. In addition, lower filling rates from 0.5 to 0.9 m s\(^{-1}\) were tested in the current work. During the experiment, water was injected into the mold through the vertical and horizontal runners. Then, water was discharged through the outlet at the side wall of the mold and transported back to the reservoir. It should be noted that the system was running for several minutes to reach a steady state before measurements began.

The definitions of the hump height and the surface height are shown in Figure 3. \(H\) is the hump height, \(L\) is the surface height, and \(\Delta H\) is the height difference. A camera was used to record the formation of the free surface during the steady state. Also, an UVP, from Met-Flow, was used to measure the velocities in the mold. The UVP has a spatial resolution of 0.74 mm and a 19 ms sampling rate. The UVP method was developed by Takeda to measure the fluid velocity in liquid. The working mechanism of the UVP is that a pulse train of ultrasonic waves is transmitted from the transducer. Subsequently, the velocity through the flow channel is obtained by the Doppler shift of

![Diagram](image-url)

**Figure 2.** A schematic diagram of the water model apparatus: a) water model setup; b) UVP device setup in the mold; and c) measurement positions from a top view.

| Case | 1 | 2 | 3 | 4 | 5 | 6 |
|------|---|---|---|---|---|---|
| Flow rate \([\text{m}^3 \text{ h}^{-1}]\) | 2.73 | 3.28 | 3.83 | 4.38 | 4.92 | 5.74 |
| Velocity \([\text{m} \text{s}^{-1}]\)  | 0.50 | 0.60 | 0.70 | 0.80 | 0.90 | 1.05 |

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the reflected signal from particles in the fluid. In the present setup, a number of red color particles, which have a density of 1.03 g cm\(^{-3}\) and an average diameter of 0.3 mm, were evenly distributed in the water mold. An ultrasonic frequency of 4 MHz was implemented by considering the measuring distance and far-field beam divergence of the ultrasonic waves in the water.\(^{[24]}\) The data measured by the UVP were stored on a personal computer.

To validate the numerical model more comprehensively, the velocities in the mold were measured. Figure 2b shows the setup for measuring the vertical velocity using the UVP device. The holder with several holes was fixed at the mold to provide a suitable place for holding the transducer. The transducer was fixed at five positions in the holder, where the positions are shown in Figure 2c and the distance among each point is 150 mm. The transducer was mounted in a holder. Therefore, some distortions of the flow field could occur at the position close to the holder. However, the overall flow pattern is not believed to be affected to any significant extent by the insertion of the transducer. Thus, the measuring distance was from locations A to B, as shown in Figure 2b.

It should be noted that the side outlet at the side wall of the mold does not exist in the industrial ingot casting process. It is artificially made to study the free surface at a specific filling height because the transient filling process makes the observation of the free surface and measurement of the velocity more difficult. A steady state can be achieved by the side outlet, which makes the observation of the free surface and the measurement of the velocity more easily. However, the side outlet may also influence the formation of the free surface to some extent, which is discussed in Section 4.4.

3. Numerical Method

A 3D mathematical model of the side teeming process was built. The computational domain and boundary conditions are shown in Figure 4. Molten steel flowed into the horizontal runner with inlet velocities of 0.5, 0.6, 0.7, 0.8, 0.9, and 1.05 m s\(^{-1}\) and was drained from the side outlet. The normalized mass flux difference of the molten steel was monitored during the simulation, as shown in Figure 5. The results indicate a quasi-steady state in the uphill teeming process and a steady state in the side teeming process. The simulations were run until the system reached a steady state. Also, two turbulence models (realizable \(k\)--\(\varepsilon\) model and Reynolds stress model, RSM) were implemented in this work. The choice of the realizable \(k\)--\(\varepsilon\) model was due to its popularity in simulations of the ingot casting process.\(^{[16,17,22]}\) However, Bai et al.\(^{[18]}\) found that the RSM can better predict the strong swirling flow compared with the realizable \(k\)--\(\varepsilon\) model. Because moderate swirling flow is expected during the current side teeming process, consequently, the RSM was tested. The following assumptions were made in the mathematical modeling approach: 1) the fluid behaves as an incompressible Newtonian fluid; 2) heat transfer is not considered; 3) chemical reactions are neglected; 4) the material properties are assumed to be constant; 5) no initial entrapments of gas occurs at the trumpet and runner system; and 6) free surface; no addition of mold powder.

3.1. Transport Equation

The general conservation equation in Cartesian coordinates can be written in the following general form

\[
\frac{\partial (\rho \Phi)}{\partial t} + \frac{\partial (\rho U_i \Phi)}{\partial x_i} = \frac{\partial}{\partial x_i} \left( \frac{\partial k}{\partial x_i} \Phi \right) + S_{\Phi} \tag{1}
\]

The first and second terms on the left side are changes in \(\Phi\) with time and transport due to convection, respectively. The second term on the right side of Equation (1) presents the source term which can be added based on a specific process condition.

3.2. Realizable \(k\)--\(\varepsilon\) Model

The realizable \(k\)--\(\varepsilon\) model was proposed by Shih et al.\(^{[25]}\) to simulate turbulent flows. The transport equations for the realizable \(k\)--\(\varepsilon\) model are shown later. The dissipation rate \(\varepsilon\) was modified from an exact equation for the transport of the mean-square vorticity fluctuation.

\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho k U_i)}{\partial x_i} = \frac{\partial}{\partial x_i} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_i} \right] + G_k - \rho \varepsilon \tag{2}
\]

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho \varepsilon U_i)}{\partial x_i} = \frac{\partial}{\partial x_i} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_i} \right] + \rho C_1 \varepsilon - C_2 \frac{\varepsilon^2}{k + \sqrt{\nu \varepsilon}} \tag{3}
\]

where

\[
C_1 = \max \left[ 0.43, \frac{\eta}{\eta + 5} \right], \quad \eta = \frac{k}{\varepsilon}, \quad S = \sqrt{2S_i S_j} \tag{4}
\]
3.3. Reynolds Stress Model

The eddy viscosity is not assumed to be isotropic for the Reynolds stress model. Instead, Reynolds stresses \( R_{ij} = \bar{u}_i \bar{u}_j \) are utilized in the transport equation to close the Reynolds-averaged Navier–Stokes equation, together with an equation calculating the dissipation rate. The transport equations for the transport of Reynolds stress can be written as follows:

\[
\rho \frac{\partial (\rho \bar{u}_i \bar{u}_j)}{\partial t} + \frac{\partial}{\partial x_k} \left( \rho \bar{u}_i \bar{u}_j \frac{\partial \bar{u}_k}{\partial x_k} \right) = -\frac{\partial}{\partial x_k} \left( \rho \bar{u}_i \bar{u}_k \frac{\partial \bar{u}_j}{\partial x_k} \right) + \frac{\partial}{\partial x_k} \left[ \mu \frac{\partial}{\partial x_k} (\bar{u}_i \bar{u}_j) \right] - 2\mu \frac{\partial \bar{u}_i}{\partial x_k} \frac{\partial \bar{u}_j}{\partial x_k} - 2\rho \frac{\partial}{\partial x_k} \left( \bar{u}_i \bar{u}_m \frac{\partial \bar{u}_m}{\partial x_k} + \bar{u}_j \bar{u}_m \frac{\partial \bar{u}_m}{\partial x_k} \right)
\]

where the local time derivative and convection terms are reported on the left-hand side. The terms representing turbulence diffusion, molecular diffusion, stress production, pressure strain, dissipation, and production by system rotation are shown on the right-hand side. Two new terms are added to the transport equation, namely, the pressure strain and rotation term.

3.4. Volume of Fluid Model

Water, molten steel, and air phases are presented in the current work. The results from the simulation of the water and air system were compared with the results from water model experiment for model validation. The molten steel and air system was used to study the free surface during the side teeming ingot casting process. Therefore, the volume of fluid method was implemented to capture the gas/liquid interface. The properties of air, water, and liquid steel are shown in Table 3. The volume of fluid, \( F \), is presented in the following equation:

\[
\frac{\partial F}{\partial t} + u \frac{\partial F}{\partial x} + v \frac{\partial F}{\partial y} + w \frac{\partial F}{\partial z} = 0
\]

\[
F = \begin{cases} 
0 & \text{Air phase only} \\
1 & \text{Liquid phase only} \\
0 < F < 1 & \text{At the interface}
\end{cases}
\]

3.5. Continuum Surface Force Model

Surface tension force term is considered by using the continuum surface force (CSF) model. The expression of surface tension force for a two-phase system is given by the following relationship

\[
F_s = \sigma \frac{\rho k \bar{v} \bar{a}_l}{0.5(\mu_g + \rho_l)}
\]

where \( k = \nabla \cdot \bar{n} \), \( \bar{n} = \frac{\bar{n}}{\|\bar{n}\|} \), \( \bar{n} = \nabla \bar{a}_g \).

Table 3. Physical properties of air, water, and molten steel.

|   | Density [kg m\(^{-3}\)] | Dynamic viscosity [Pa s] |
|---|--------------------------|---------------------------|
| Air | 1.23                     | 1.79 \times 10^{-3}       |
| Water | 998.20                   | 1.0 \times 10^{-3}       |
| Molten steel | 6900                      | 6.0 \times 10^{-3}       |
3.6. Boundary Conditions

A velocity inlet condition was applied at the entrance of the horizontal runner and the velocity was assumed to be constant. A parameter study was conducted to investigate the influence of the inlet velocity on the filling performance. Specifically, the test velocities of 0.5, 0.6, 0.7, 0.8, 0.9, and 1.05 m s\(^{-1}\) were implemented in the simulations. The top and side outlets of the computational domain were fixed as pressure outlets with a zero gauge pressure, as shown in Figure 4. No-slip boundary conditions were applied at the walls, and a standard wall function was also applied at the walls.

3.7. Solution Method

In the current work, all simulations were conducted using ANSYS Fluent 2019R2. The number of cells used in the simulation work is 268,520, which was evaluated by a grid convergence method (GCI) mesh sensitivity study.[27] The PRESTO! discretization method was applied to discretize the pressure. The pressure–velocity coupling was solved by the coupled scheme. A second-order upwind scheme was adopted to solve the momentum equation. In addition, second-order upwind schemes were used to calculate the turbulent kinetic energy and turbulent dissipation rate. The variable time step method was used, adopting a Courant number of 0.25. Transient calculations were done up to several seconds until the normalized mass flux difference reaches a steady-state condition, as shown in Figure 5b.

4. Results and Discussion

4.1. The Experimental Free Surface

In previous studies,[17,20,22,28] it is shown that a hump is formed at the free surface in the center of the mold during the uphill teeming process. A higher height and higher fluctuation of the hump can result in a higher degree of mold flux entrapments.[28] The formation of the hump is mainly due to the strong vertical flow velocity from the inlet to the mold, which contributes to strong turbulence at the gas/liquid interface. Also, the hump height fluctuates during the filling process due to the unevenness of the flow after the bend.[29]

Table 4. Hump heights (\(H\)), surface heights (\(L\)), and standard deviations (\(\sigma\)) in both cases (mm) for the case with an inlet velocity of 1.05 m s\(^{-1}\).

|              | \(H\) | \(\sigma_H\) | \(L\) | \(\sigma_L\) |
|--------------|-------|--------------|-------|--------------|
| Uphill teeming process | 135   | 8.1          | 81.2  | 9.7          |
| Side teeming process   | No hump | 0            | 74    | 0            |

The proposed side teeming method decreases the potential of mold flux entrapments. Figure 6 shows the water/air interface for a flow velocity of 1.05 m s\(^{-1}\), where Figure 6a shows the uphill teeming process and Figure 6b shows the side teeming process. Specifically, Figure 6a was taken at an instantaneous time when the system reaches a quasi-steady state, and it was obtained from the previous work.[23] Figure 6b is based on the result from the current work. It was found that a much calmer free surface was formed in the side teeming process compared with that in the uphill teeming process. Table 4 shows the hump height and surface height in both processes. Both Table 4 and Figure 6 show a highly turbulent free surface in the uphill teeming process and a calm free surface in the side teeming process. The uphill teeming process has a dynamic change in the free surface, which means that a quasi-steady state can be achieved. The results show that the side teeming process has a much more stable free surface (no hump is formed), and a steady state can be formed. This difference can also be seen from the normalized mass flux results in Figure 5, where the normalized mass flux regularly fluctuates in the uphill teeming process. However, it approaches zero in the side teeming process, when time is sufficiently long. This is because of the direction of the flow and subsequent oscillations of the free surface. For the uphill teeming process, incoming water directly passes from the bottom of the mold to the free surface through the vertical runner. The formation of the oscillating hump results in a dynamic motion of the free surface. For the side teeming process, water comes from the horizontal runner to the mold, where it needs to be transported from the edge of the mold to the middle of the mold. Thus, the water jet is not directly in contact with the free surface, which results in less turbulence at the free surface. Consequently, it is expected that the side teeming process should generate less mold flux entrapments compared with the uphill teeming process. On the contrary, some nonmetallic inclusions may be generated by the erosion of the refractory. This will be discussed in Section 4.5.

Figure 6. The interface behavior for both the uphill teeming process and the side teeming process for the case with an inlet velocity of 1.05 m s\(^{-1}\): a) the uphill teeming process.[23] Reproduced under the terms of the Creative Commons Attribution 4.0 International License; b) the side teeming process.
Although most parts of the free surface are flat, surface disturbances are formed near the side wall during the side teeming process, as shown in Figure 7. This is due to the higher velocity near the side wall, which generates turbulence at the free surface. This may lead to mold flux entrapments. However, the problem is less important because this effect occupies a limited area of the free surface. Overall, the side teeming process has a much more stable surface compared with the uphill teeming process. Moreover, it was found that the surface disturbances at the edge of the mold disappeared when the flow rate was less than 0.7 m s⁻¹. In addition, the free surface remains flat in the side teeming process as the inlet velocity decreases.

4.2. Model Validation (Water–Air System)

The aforementioned experimental results show that a calm free surface is formed in the side teeming process. A numerical model was performed to investigate the fluid flow in the side teeming process. Here, a selection of an appropriate turbulence model is very important. The Realizable k–ε turbulence model has been used by many researchers [15,17,22,28–30] to model the ingot casting process. However, they did not carry out model validation. Recently, Bai et al. [18] implemented the standard k–ε, realizable k–ε model, and Reynolds stress turbulence models to simulate the swirling flow generated by TurboSwirl during the uphill teeming process. They found that the RSM showed a good agreement to the experimental results in predicting the swirling flow compared with other tested models. Also, Jakirlic [31] and Escue [32] studied several types of rotating and swirling flows. They reported that the RSM was superior to other tested turbulence models. Therefore, the realizable k–ε model and the Reynolds stress model were used to simulate the side teeming process.

As shown in Figure 7 and Figure 8a, the experimental results show that a flat free surface with surface disturbances is formed at the edge of the mold during the side teeming process. Both the realizable k–ε model and the RSM show a similar phenomenon as the experimental results. However, the surface disturbances at the edge of the mold in the RSM simulations are more similar to the experimental results compared with the results using the realizable k–ε model, as shown in Figure 8b,c. In other words, the surface disturbances at the edge of the mold predicted by RSM are in better agreement with visual observations.

Figure 9 shows the average velocities along line AB at five positions for both experimental and numerical results. The

![Figure 7](image1)

**Figure 7.** Close-up of the small surface disturbances at the edge of the side wall for the case with an inlet velocity of 1.05 m s⁻¹.

![Figure 8](image2)

**Figure 8.** Surface disturbance at the free surface in the side teeming process for the case with an inlet velocity of 1.05 m s⁻¹: a) experiment; b) RSM; and c) realizable k–ε.
4.3. Weber Number (Molten Steel–Air System)

From the above water–air system, the numerical simulations show a reasonably good agreement compared with the experimental results. Therefore, the RSM was used to simulate the molten steel–air system. The tendency for mold flux entrapments can be estimated using the Weber number, representing the ratio of the inertial forces to the interfacial tension force. The equation for calculating the Weber number is expressed as follows:

\[
We = \frac{v_{\text{steel}}^2 \gamma_{\text{steel}}}{\sqrt{2g (\rho_{\text{steel}} - \rho_{\text{slug}})}}
\]  

Xia et al.\textsuperscript{[34]} conducted physical and numerical modeling to study the oil droplet entrainments into the liquid phase. The results showed that the oil droplet dispersed into the water when a critical interfacial velocity of 0.233 m s\textsuperscript{-1} was exceeded, corresponding to a Weber number of 12.3. Jönsson et al.\textsuperscript{[35]} also studied the Weber number at the steel/slag interface in a gas-stirred ladle by using this critical Weber number. Moreover, Eriksson et al.\textsuperscript{[36]} investigated the mold flux entrapments in an ingot casting process using this critical Weber number. From a practical point of view, a similar discussion can be presented. The free surface can be divided into two regions: the risk region and the safe region. The risk region is defined as the area at the free surface with a Weber number higher than 12.3, and the safe region is defined as the area at the free surface with a Weber number lower than 12.3. The risk region has a higher tendency for mold flux entrapments and the safe region has a low tendency for mold flux entrapments.

The density of the steel is assumed to be 6900 kg m\textsuperscript{-3}\textsuperscript{[22]} and the density of the slag is defined as 2600 kg m\textsuperscript{-3}\textsuperscript{[36]} The value of the interfacial tension has a dynamic change over time, which has been confirmed by Tanaka et al.\textsuperscript{[37]} This is because of the reactions between the slag and the liquid steel. Riboud et al.\textsuperscript{[38]} show that the interfacial tension decreases sharply when the mass transfer is intensive during initial deoxidation, while it increases to a high value and remains stable as the mass transfer slows down to a stable value. The interfacial tension between liquid Fe alloy and molten slag is around 1.3 N m\textsuperscript{-1} in an equilibrium state.\textsuperscript{[38]} However, the interfacial tension for most killed steels can be less than 0.4 N m\textsuperscript{-1} during an initial deoxidation.\textsuperscript{[19]} In the current work, the interfacial tension values were set as 0.5, 1, and 1.5 N m\textsuperscript{-1}.
Figure 11 shows the values of Weber number for a 1.05 m s$^{-1}$ inlet velocity with a 0.5 N m$^{-1}$ interfacial tension force at the free surface during a steady state. It can be seen that the highest Weber number is found near the side wall of the mold. This is natural because the tangential velocity is highest near the side wall of the mold. The velocity decreases as the distance to the center of the mold decreases. It can be observed that the safe region is located at the center of the mold. This region occupies 66.8% of the total free surface area, indicating a lower tendency for mold flux entrapments at the majority of the free surface.

Figure 12 shows the proportion of the risk region at the free surface for different interfacial tension forces. It demonstrates that higher interfacial tension can decrease the tendency of mold flux entrapments. In addition, the inlet velocity dramatically influences the formation of the risk region, which has a sharp decrease at an inlet velocity of a 0.7 m s$^{-1}$. This is because the main value of the tangential velocity at the risk region is around 0.49 m s$^{-1}$ for the case with 0.7 m s$^{-1}$ inlet velocity, resulting in a Weber number of 11 with an interfacial tension of 0.5 N m$^{-1}$. This indicates a low tendency of mold flux entrapments for the case with an inlet velocity of 0.7, 0.6, and 0.5 m s$^{-1}$. The experimental results also show a flat free surface without forming surface disturbances near the side wall of the mold for lower filling rates. It is important to note that these observations are qualitative. Therefore, the critical Weber number may be different for a liquid metal system.

4.4. Influence of the Side Outlet on the Flow Pattern (Molten Steel–Air System)

The side outlet was used in the water model experiment to investigate the free surface during a steady state. However, the side outlet may influence the formation of the free surface. Figure 13 shows the free surface formation for the case without using the side outlet at the same filling height as the case when using the side outlet. Compared with Figure 8b, the free surface looks even calmer, and fewer surface disturbances can be found at the edge of the mold. This is because a large pressure difference at the side outlet results in surface disturbances near the side outlet for the case with the side outlet. This makes the free surface at the edge of the mold experience more curvature. The remaining area (in the middle of the mold) at the free surface is identical to the case with the side outlet. Table 5 shows the proportion of the risk region at the free surface for different cases (with and without the side outlet). It can be concluded that the differences between the transient case and the artificial steady-state case are tiny.

4.5. Wall Shear Stresses (Molten Steel–Air System)

The shear stresses are also essential parameters to evaluate the side teeming process. The liquid phase moves along the refractory wall, where friction is generated at the refractory wall. If the wall shear stress is large enough, erosion problems could occur at the refractory wall. This could contribute to additional

| Interfacial tension [Nm$^{-1}$] | 0.5 | 1  | 1.5 |
|----------------------------------|-----|----|----|
| With the side outlet [%]         | 33  | 26 | 22 |
| Without the side outlet [%]      | 34  | 27 | 23 |
inclusions being generated. Thus, it is of great interest to investigate where the shear stresses are generated as well as their magnitude in the side teeming process. The average shear stresses in the mold are shown in Figure 14. It should be noted that the average shear stresses are computed by dividing the summation of the product of the wall shear stress and facet area by the total area of the surface. It can be noted that the shear stress increases as the inlet velocity increases. To express the average erosion rate of the mold wall, a quantitative analysis approach for erosion is applied. Recently, Huang et al. also used this approach to investigate the refractory erosion characteristics of the refining ladle. The erosion rate can be expressed by the loss of the thickness of refractory per unit time:

$$H_{sl} = \int (\tau, I) = -2.061 \times 10^{-13} (\tau \times I)^2$$

$$+ 2.642 \times 10^{-7} (\tau \times I) + 5.636 \times 10^{-4}$$  \hspace{1cm} (14)

The calculated erosion rate is around $5.6 \times 10^{-4}$ mm h$^{-1}$ for all the cases (different inlet velocities), which indicates a low erosion value. This manifests a low risk for erosion problem with the side teeming process. To conclude, if Equation (13) is valid, this clearly shows that a mechanical erosion will not be a problem for the current setup.

5. Conclusions

In this article, the ingot casting process has been investigated. A side teeming process was adopted, which introduces the melt into the mold in a horizontal fashion rather than using the standard vertical uphill teeming fashion. Water model experiments were performed together with numerical simulations to study the free surface formation during the process. In addition, the Weber number was calculated to analyze the tendency of mold flux entrapments and the shear stresses were used to evaluate the friction at the refractory wall. Both the physical and numerical model results confirm that a less turbulent free surface is generated for the side teeming process compared with the uphill teeming process. Thus, decreased mold flux entrapments are expected in the side teeming process. Overall, the following specific conclusions were obtained: 1) A much less turbulent free surface was found for the side teeming process compared with the uphill teeming process. Some surface wiggles can be seen close to the wall of the mold, but they are small and vanish at lower teeming velocities. 2) Considering the surface disturbance and the vertical velocity measurement at five positions, the Reynolds stress turbulence model shows a better agreement with the experimental results compared with the realizable $k$-$

6. Nomenclature

| Symbol | Definition |
|--------|------------|
| $\omega$ | Angular velocity [rad s$^{-1}$] |
| $x$ | Coordinate direction [x, y, or z] |
| $C_1$ | Constant value [1.9] |
| $\rho$ | Density [kg m$^{-3}$] |
| $\Gamma_D$ | Diffusion coefficient [m$^2$ s$^{-1}$] |
| $\mu$ | Dynamic viscosity [Pa s] |
| $\rho_g$ | Density of gas phase [kg m$^{-3}$] |
| $\rho_l$ | Density of liquid phase [kg m$^{-3}$] |
| $\rho_{steel}$ | Density of steel [kg m$^{-3}$] |
| $\rho_{slag}$ | Density of slag [kg m$^{-3}$] |
| $\eta$ | Effectiveness factor [dimensionless] |
| $H_{sl}$ | Erosion rate [mm h$^{-1}$] |
| $g$ | Gravitational acceleration [m s$^{-2}$] |
| $\gamma$ | Interfacial tension [N m$^{-1}$] |
| $\nu$ | Kinetic viscosity [m$^2$ s$^{-1}$] |
| $S_0$ | Source term [kg m$^{-1}$ s$^{-1}$] |
| $\sigma$ | Surface tension coefficient [N m$^{-1}$] |
| $\sigma_{h}^{\text{st}}$ | Standard deviation of the hump height |
| $\sigma_{l}^{\text{st}}$ | Standard deviation of the surface height |
| $\tau$ | Shear stress [Pa] |
| $t$ | Time [s] |
| $k$ | Turbulent kinetic energy [m$^2$ s$^{-2}$] |
| $\mu_t$ | Turbulent viscosity [m$^2$ s$^{-1}$] |
| $\sigma_k$ | Turbulent Prandtl numbers for $k$ [constant value 1] |
| $\epsilon$ | Turbulent dissipation rate [m$^2$ s$^{-3}$] |
| $\sigma_\epsilon$ | Turbulent Prandtl numbers for $\epsilon$ [constant value 1.2] |
| $l$ | Turbulent intensity |
| $\nu_{steel}$ | Tangential velocity of molten steel [m s$^{-1}$] |
| $\Phi$ | Various time-averaged quantities, i.e., mean velocity, mass, production of turbulent kinetic energy, the dissipation rate of turbulent kinetic energy etc. |
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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

Research data are not shared.

Keywords

computational fluid dynamics, mold flux entrapments, mold filling, side teeming process, water model

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[1] C. P. Zhang, A. Loucif, M. Jahazi, R. Tremblay, L. P. Lapierre, Appl. Sci. 2018, 8, 1878.
[2] N. Tripathi, D. Sichen, Scand. J. Metall. 2004, 33, 362.
[3] L. Zhang, B. Rietow, B. G. Thomas, K. Eakin, ISIJ Int. 2006, 46, 670.
[4] Z. Liu, B. Li, A. Vakhrushev, M. Wu, A. Ludwig, Steel Res. Int. 2018, 90, 1800017.
[5] Z. Liu, Z. Sun, B. Li, Metall. Mater. Trans. B 2016, 48, 1248.
[6] L. Zhang, B. G. Thomas, Metall. Mater. Trans. B 2006, 37, 733.
[7] L. Zhong, X. Zhou, P. Jiang, H. Wang, L. Pang, P. Hao, Ironmaking Steelmaking 2017, 46, 431.
[8] X. Zhou, L. Zhong, P. Ni, N. Deng, Metals 2019, 9, 238.
[9] P. K. Trojan, ASM Handbook, ASM International, Metals Park, OH 1988, p. 88.
[10] L. F. Zhang, B. G. Thomas, ISIJ Int. 2003, 43, 271.
[11] H. J. T. Ellingham, J. Soc. Chem. Ind 1944, 63, 125.
[12] J. Frustherofer, L. Schottler, S. Dudczig, G. Schmidt, P. Gehre, C. G. Aneziris, J. Eur. Ceram. Soc. 2016, 36, 1299.
[13] K. C. Mills, C.-Å. Däcker, The Casting Powders Book, Springer, New York, NY 2017, p. 535.
[14] R. Eriksson, P. Jonsson, A. Gustafsson, Scand. J. Metall. 2004, 33, 106.
[15] R. Eriksson, L. Jonsson, P. G. Jonsson, ISIJ Int. 2004, 44, 1358.
[16] L. Ragnarsson, M. Ek, A. Eliasson, D. Sichen, Ironmaking Steelmaking 2013, 37, 347.
[17] L. Hallgren, S. Takagi, A. Tilliander, S. Yokoya, P. Jonsson, Steel Res. Int. 2007, 78, 254.
[18] H. T. Bai, M. Ersson, P. G. Jonsson, ISIJ Int. 2016, 56, 1404.
[19] Z. Tan, M. Ersson, P. G. Jonsson, ISIJ Int. 2012, 52, 1066.
[20] J. Yin, M. Ersson, H. H. Mao, P. G. Jonsson, Metals 2019, 9, 693.
[21] J. Campbell, Complete Casting Handbook: Metal Casting Processes, Metallurgy, Techniques And Design, Butterworth-Heinemann, Oxford, UK 2015.
[22] Z. Tan, M. Ersson, P. G. Jonsson, ISIJ Int. 2011, 51, 1461.
[23] J. Yin, S. Guo, M. Ersson, P. G. Jonsson, Steel Res. Int. 2020, 91, 1900069.
[24] Y. Takeda, Int. J. Heat Fluid Fl 1986, 7, 313.
[25] T.-H. Shih, W. W. Liou, A. Shabbir, Z. Yang, J. Zhu, Comput Fluids 1995, 24, 227.
[26] A. Fluent, ANSYS Inc, Canonsburg, PA 2012.
[27] I. B. Celik, U. Ghia, P. J. Roache, C. J. Freitas, J Fluid Eng-T Asme 2008, 130, 078001.
[28] L. Hallgren, A. Tilliander, S. Yokoya, P. G. Jonsson, S. Hagman, ISIJ Int. 2010, 50, 1763.
[29] A. Pola, M. Gelfi, G. M. La Vecchia, Materials 2016, 9, 256.
[30] L. Hallgren, S. Takagi, R. Eriksson, S. Yokoya, P. Jonsson, ISIJ Int. 2006, 46, 1645.
[31] S. Jakirlic, K. Hanjalic, C. Tropea, AIAA J. 2002, 40, 1984.
[32] A. Escue, J. Cui, Appl. Math. Model. 2010, 34, 2840.
[33] H. T. Bai, M. Ersson, P. Jonsson, Metall. Mater. Trans. B 2015, 46, 2652.
[34] Z. Xiao, Y. Peng, C. Liu, Chin. J. Mater. Sci. Technol. 1987, 3, 187.
[35] L. Jonsson, P. Jonsson, ISIJ Int. 1996, 36, 1127.
[36] Y.-B. Kang, M.-S. Kim, S.-W. Lee, J.-W. Cho, M.-S. Park, H.-G. Lee, Metall. Mater. Trans. B 2012, 44, 309.
[37] T. Tanaka, H. Goto, M. Nakamoto, M. Suzuki, M. Hanao, M. Zeze, H. Yamamura, T. Yoshikawa, ISIJ Int. 2016, 56, 944.
[38] P. V. Riboud, L. D. Lucas, Con. Metall. Q. 1981, 20, 777.
[39] P. Sulasalmi, V. V. Visuri, T. Fabritius, Mater. Sci. Forum. 2013, 762, 242.
[40] Z. Dai, X. Niu, S. Shen, J. Petrochem. Univ. 2007, 20, 85.
[41] A. O. Huang, H. Gu, M. Zhang, N. Wang, T. Wang, Y. Zou, Metall. Mater. Trans. B 2013, 44, 744.