Mathematical Modeling of Initial Filling Moment of Uphill Teeming Process Considering a Trumpet

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The flow pattern in the uphill teeming process has been found to be closely related to the quality of ingots and further affects the yield of ingots production, which is crucial for steel making process. The formation of non-metallic inclusion and entrapment of mold flux has been considered to be affected by the flow pattern in the gating system and molds by many previous researchers. The emphasis of this study is focused on the flow pattern of steel in the gating system and molds during the initial stage of the mold filling process. A three dimensional model of two molds gating system for 6.2 ton ingots from Scana Steel is adopted in the present work. A reduced geometry including one mold and a runner is also used for comparison with the present results. In addition, the realizable k-ε model was used to study the flow pattern in uphill teeming process. The predictions were compared with practical filling information from industrial data and results from previous researches. It concludes that a reduced geometry with homogeneous inlet condition fails to describe the fluctuating conditions present as the steel enters the mold. However, the trends are very similar when comparing the (hump height-surface height) evolution over time. The maximum wall shear stress fluctuates with a descending trend. A special attention should be made in choosing refractory at center stone, the horizontal runner and the vertical runner at elbow, where the wall shear stress values are highest or with long exposure time.

KEY WORDS: gating system; uphill teeming; ingot casting; realizable k-ε model; CFD; mathematical modeling.

1. Introduction

The ingot production in the world has decreased to 7.0% of the total crude steel production in 2007, which comprises of 94.704 million metric tons. However, ingot casting is still a crucial process for making some grades of low-alloy steel and steel for special applications. Specific examples are high-carbon chromium-bearing steels, thick plates, seamless tubes, forgings, bars, and wire rods. In addition, it has long been widely recognized that the pouring method plays an important role in producing ingots. Due to much less turbulence compared to the top-pouring method, uphill teeming results in better internal and surface qualities. Therefore, the uphill teeming method is favored and prevailing in steel industry.

Figure 1 shows a schematic diagram of the uphill teeming process. The uphill teeming is a casting method in which liquid steel is drained by gravity from the bottom nozzle of the ladle into a refractory-lined trumpet. Thereafter, further into a runner system which distributes the liquid steel into one or more ingot molds. A paper bag of mold powder is hung close to the bottom of mold near the mold entrance. When liquid steel enters the mold, the paper bag is burned and thus releases the powder on the steel surface. This provides a flux, which will prevent the steel from reoxidation and act as a thermal insulator as well as a lubricating of the steel flow at the metal walls.

In order to meet the ever-increasing demands on improving the yield and quality of steel, steelmakers and researchers have spent great efforts on improving the process and technology in uphill teeming. A systematical study of uphill teeming techniques based on experience and practice for producing high quality carbon and alloy steels was presented by Blank. In addition, the control of non-metallic inclusion formation has been given much attention in recent years so as to further improve the quality of the steel. These non-metallic inclusions are primarily generated due to high-
oxygen-affinity metal additions during the ladle refining operation, entrapped ladle slag and eroded refractory.\textsuperscript{5)}

Before ladle teeming, for example, high-carbon chromium-bearing steel contains very few non-metallic inclusions and a low total oxygen concentration.\textsuperscript{6)} As the teeming starts, the potential exogenous inclusion formation/contamination sites were discussed by Freborg, which are the ladle-center runner junction and the steel-flux interface at the ingot mold.\textsuperscript{7)}

The Shrouding technique was implemented to prevent detrimental reoxidation inclusions at the ladle-center runner junction. The second source of exogenous inclusions indicated by Freborg was revealed by the recent studies, which shows that inclusions containing traces of mold flux are found in samples taken in the ingot mold during the filling process.\textsuperscript{8,9)} Many researchers investigated the phenomena of the entrapment of mold flux.\textsuperscript{2,4)} The entrapment of mold flux in ingots was considered to be related to the flow pattern of the steel in the mold.\textsuperscript{4,6,8,10)} The erosion of refractory surface due to the flow-induced wall shear stress was studied by Singh \textit{et al.}\textsuperscript{11)} Hence, it is of great interest to investigate the flow pattern in the uphill teeming process in order to improve the quality of ingots.

Water modeling for the uphill teeming process has been carried out by a few researchers. A one quarter scale plexiglas replica of one half of a 6 molds uphill teeming system was studied by Freborg\textsuperscript{5)} along with possible modifications in the runner system to decrease the turbulence. Later, an experimental study of the velocity field during filling of an ingot mold was done by Eriksson \textit{et al.} to generate data for verification of CFD predictions.\textsuperscript{12)}

Numerical simulations of flow patterns related to ingot casting process have been carried out by many researchers. As for filling of molds, cylindrical and thin rectangular molds were respectively investigated by Jönsson\textsuperscript{13)} and van der Graaf.\textsuperscript{14)} In addition, Eriksson \textit{et al.} have applied five different turbulence models to describe the ingot mold filling process\textsuperscript{15)} and compared the predictions with water model measurements.\textsuperscript{12)} Recently, Eriksson \textit{et al.} have also investigated the effect of a flaring angle of an ingot mold entrance nozzle on the fluid flow using a LES model. They found that a 25 degree angle gives the best result, leading to an almost-flat rising surface and low horizontal velocities.\textsuperscript{5)} In light of this, Hallgren \textit{et al.} investigated the effect of a nozzle swirl blade on the flow pattern in the uphill teeming process. In the cases, the geometry was adopted without considering the trumpet. Instead, a uniform velocity inlet boundary assumption was implemented for the whole cross section at the runner inlet. By the introduction of a swirl blade, a calmer filling with a lower hump height could be obtained in the filling process.\textsuperscript{16–18)}

The emphasis of this study is focused on the flow pattern of steel in the gating system and molds during the initial stage of the mold filling process. In addition, previous study has included both the trumpet, runner channel and the mold. A two molds runner system was adopted in the study.

\subsection*{2. Mathematical Modeling}

A three dimensional model of two molds gating system for 6.2 ton ingots from Scana Steel is adopted in the present work as shown in Fig. 2. The computation domain is optimized by comparing results to practical filling information from industrial trials. The size of the mold is thus set to 1/5 of the original mold to observe the flow pattern at an initial filling stage. Typically, the diameter of a trumpet is 70 mm and the diameter of runners is 45 mm.\textsuperscript{19)} In addition, a reduced geometry including one mold and a runner is also shown in the figure as indicated by the dashed line. This geometry is based on the method from previous researchers\textsuperscript{5,16–18)} and is used for comparison with the present prediction results.

\begin{table}[h]
\centering
\caption{Conservation equations.}
\begin{tabular}{|c|c|c|c|}
\hline
Conservation of: & $\Phi$ & $\Gamma$ & $S_\Phi$ \\
\hline
Mass & 1 & 0 & 0 \\
\hline
x-momentum & $u$ & $\mu$ & $-\frac{\partial p}{\partial x}$ \\
\hline
y-momentum & $v$ & $\mu$ & $-\frac{\partial p}{\partial y} + \rho g$ \\
\hline
z-momentum & $w$ & $\mu$ & $-\frac{\partial p}{\partial z}$ \\
\hline
Turbulent kinetic energy & $k$ & $\mu + \frac{\mu_t}{\sigma_k}$ & $\begin{aligned} & \rho C_f S_e - \rho C_i \left( \frac{1}{k} \frac{\partial u_i}{\partial x_i} \right) \\
& \sigma_k = 1.2 \quad C_2 = 1.9 \quad C_f = 0.09 \end{aligned}$ \\
\hline
Turbulent dissipation rate & $\varepsilon$ & $\mu + \frac{\mu_t}{\sigma_\varepsilon}$ & $p C_i S_e - \rho C_i \left( \frac{1}{\varepsilon} \frac{\partial u_i}{\partial x_i} \right)$ \\
\hline
\end{tabular}
\end{table}

Notes:
\begin{itemize}
\item (1) Turbulent viscosity: $\mu_t = \rho C_i \frac{\varepsilon^2}{k}$
\item (2) Molecular (dynamics/laminar) viscosity: $\mu$
\item (3) Effective viscosity: $\mu_{\text{eff}} = \mu + \mu_t$
\item (4) $\sigma_k = 1.0 \quad \sigma_\varepsilon = 1.2 \quad C_2 = 1.9 \quad C_f = 0.09$
\item (5) $C_i = \text{max}[0.43, \frac{\eta}{\eta + \frac{1}{2}}] \quad \eta = \frac{k}{\varepsilon} \quad S_e = \sqrt{2S_S S_S} \quad S_i = \text{max}[\frac{1}{S_S} \frac{\partial u_i}{\partial x_i} + \frac{1}{S_i} \frac{\partial u_i}{\partial x_i}]$
\end{itemize}
2.1. Numerical Assumptions

The following assumptions were made when developing the mathematical model:
A. Both air and steel are incompressible Newtonian fluids;
B. The physical properties are constant;
C. No chemical reactions take place;
D. Solidification and heat transfer are not considered.

2.2. Transport Equations

Based on the above mentioned assumptions, the transport of the fluid property $\Phi$ can be expressed in the following form:

$$\frac{\partial (\rho \Phi)}{\partial t} + \nabla \cdot (\rho \Phi \mathbf{u}) = \nabla \cdot (\Gamma \nabla \Phi) + S_\Phi \quad \ldots (1)$$

where $\rho$ is the density, $\Phi$ is the general fluid property, $t$ is time, $\mathbf{u}$ is the mean velocity vector, $\Gamma$ is the diffusion coefficient and $S_\Phi$ is the source term. A complete description of the mass and momentum equations are given in Table 1.

2.3. Volume of Fluid (VOF) Model Theory

The VOF method, developed by Hirt and Nichols, was adopted in the present work for tracking the free surface of the liquid at the air/liquid interface. The time dependent volume fraction occupied by fluid, $F$, is governed by the following equation:

$$\frac{\partial F}{\partial t} + \mathbf{u} \cdot \nabla F + v \frac{\partial F}{\partial y} + w \frac{\partial F}{\partial z} = 0 \quad \ldots (2)$$

The local value of $F$ in a control volume can be denoted for the following three conditions,

$$F = \begin{cases} 0 \quad \text{Air phase only} \\ 1 \quad \text{Liquid phase only} \\ 0 < F < 1 \quad \text{At the interface} \end{cases} \quad \ldots (3)$$

The material properties of the fluids can be computed as follows:

$$\Phi = F \Phi_{\text{liquid}} + (1-F)\Phi_{\text{air}} \quad \ldots (4)$$

where $\Phi_{\text{liquid}}$ and $\Phi_{\text{air}}$ are the physical properties of liquid and air, respectively.

2.4. Boundary Conditions

A constant uniform velocity profile corresponding to the volumetric flow rate and the cross sectional area of the ladle outlet was chosen as the inlet of the full geometry model. The velocity inlet was employed for the center part of the inlet boundary with a circle-shaped geometry. In addition, the direction of the velocity was set normal to the trumpet inlet surface. The pressure inlet boundary was adopted for the outer part of the inlet boundary as a ring-shaped geometry. The gauge pressure was chosen to be zero.

2.5. Properties for Materials

The physical properties of steel used in the current calculations are shown in Table 3.

2.6. Method of Solution

The governing equations were discretized by the finite volume method via using the commercial CFD software ANSYS FLUENT 12.1®. The mesh of the full geometry model and the reduced geometry model was generated with 225972 cells and 92199 cells, respectively. The mesh was done by using ANSYS WORKBENCH 12.1®. Moreover, the PRESTO discretization method was adopted to discretize the pressure. The PISO scheme was used to solve pressure-velocity coupling. First order upwind schemes were applied to the momentum, turbulent kinetic energy, and turbulent dissipation rate. In addition, the Geo-reconstruct was used to spatially discretize the volume fraction. Also, the courant number of VOF was fixed at 0.25. The calculations were carried out with a computer equipped with an Intel® Core™ i7-930, 8M Cache, 2.80 GHz and a 6.0 GB DDR-III RAM base on an OpenSUSE 11.2 system.
3. Results and Discussions

The flow pattern of steel is of great importance in the ingot casting process, since it directly affects the quality of the final product related to exogenous non-metallic inclusions whose sizes are relatively large, i.e., several mm in order. Here, non-metallic inclusions may be generated due to the wear of refractory materials or reactions with the mold flux. However, due to practical limitations, it is hard to observe the flow pattern of steel by performing experiments using industry trials. However, CFD simulations represent good possibilities to study the fluid flow.

The flow pattern of steel during initial filling process is shown in the Fig. 3. Around 0.5 s, the steel jet free falls in the trumpet and reaches the center stone while a noticeable droplet shape forms at the bottom of the steel jet. Due to the geometry of the center stone, the steel flow diverges into two parts at the center stone intersection. The main flow splashes upwards in the trumpet and the minor flow hits the upper wall of the runners and then scatters. The steel flow enters the molds with a large amount of air entrapped in the runner at 1.5 s. In addition, the splashing steel height in the trumpet is slightly lower than the steel height in the vertical runner of the base plate. The steel starts filling the molds after the first hump falls back after around 2.0 s. Thereafter, the splashing steel height in the trumpet increases dramatically. The hump height increases significantly at 2.5 s. After this point, the steel height difference between the steel in the molds and the splashing steel in the trumpet is roughly the same. The definition of the steel height difference is shown in Fig. 4. The steel height difference (ΔH) variation with filling time of the full geometry model can be seen in Fig. 5. It can be found that the steel height difference is large at the initial mold filling stage. The steel height difference damps when more steel fills up the molds. Basing on the steel height difference, the operators in the industry might get more understanding at initial filling stage and thus control the teeming flow rate of the steel to keep the steel height difference as low as possible to achieve a calm filling of the molds.

The height of the hump is one of the important properties in the ingot filling process which indicates the possible distribution of mold flux. Moreover, it can be directly observed by the operators in industry during production. The parametric studies for the height of the hump with swirl blade implemented for the reduced geometry ingot filling system were investigated by Hallgren et al.\textsuperscript{17) In the present work, a full scale ingot filling system was adopted along with a reduced geometry system for comparison. The definition of the hump height can be seen in Fig. 4.

The hump height (H\textsubscript{h}) in the full scale model case is shown in Fig. 6. The steel enters the mold around 1.5 s which leads to the formation of a first hump with a height of 130 mm. The steel jet then loses momentum and is forced back to the mold entrance by gravity. Thus, it forms the first noticeable surface height (H\textsubscript{s}) which is around 12 mm. Then the steel starts to spread out on the bottom plane of the molds, which results in a further decrease of the
surface height. Meanwhile, the second hump begins to form, which leads to an increase of the surface height. In addition, due to the existence of entrapped air, fluctuations of the hump height can be seen. Two peak values of the hump height of 140 mm can be found around 2.6 s and 4.6 s. Also, compared to the hump height curve, the surface height curve increases more steady with less fluctuations.

The hump and surface heights in the reduced geometry model case, which represents the approach used by Hallgren, Eriksson and others,\textsuperscript{5,16–18} are illustrated in Fig. 7. Due to the absence of the trumpet in this simulation, the time for the steel to enter the mold is decreased by approximately 0.5 s. This roughly equals to the time it takes for the steel to freely fall down to the center stone from the ladle teeming gate. The first hump reaches a height of 145 mm at 1.3 s followed by steel falling down to the bottom of mold. This forms a first noticeable surface height of 10 mm. No distinct fluctuations of the hump form after the second hump. Also, it can be found that the height difference between the hump and the steel surface in the molds decreases as the filling process proceeds. Both the hump height curve and the surface height curve increase steadily. This is due to lack of entrapped air in the runner system, which was not taken into account in these particular simulations. It should be noted that significant benefit with the model accounting for the trumpet is obvious because one can have the information of variation of $\Delta H$ as time as shown in Fig. 5.

The comparisons of the hump height with different models can be seen in Table 4. Although the geometrical information of computational domains is different, the data for the reduced model in the current study fits the results from previous researchers fairly well.\textsuperscript{17} In the current study, the comparison between a full geometry model and a reduced geometry model clearly shows that the reduced geometry experiences less fluctuations in the hump height. The cause of the differences is mainly due to the existence of a trumpet and the boundary conditions considering the presence of air. The main trends are, however, very similar. Mold powder will be added to the model to investigate the possible distribution of mold flux and the phenomena of mold flux entrapment in the near future, but until then it is the authors suggestion that a reduced geometry approach can be used when looking for the mechanisms to reduce the hump height. Such mechanisms might be swirl, flaring angle of the mold inlet etc.\textsuperscript{5,16–18}

The wall shear stress which the steel exerts on the refractory materials in the runner channel is another important property during the initial filling process. Non-metallic inclusions may be generated in regions where a high wall shear stress takes place due to the wear of refractory materials. Therefore, the magnitude of the maximum wall shear stress and its possible high magnitude regions are important to investigate. In the present study, the maximum wall shear stress in the full scale model is studied.

The normalized maximum wall shear stress as a function of time is plotted in Fig. 8. The steel jet falls freely in the trumpet and reaches the center stone at around 0.5 s. This exerts a peak value of the normalized maximum wall shear stress ($\tau_{w \text{ peak}}$) on the center stone. Thereafter, the normalized maximum wall shear stress rapidly decreases to 0.65 $\tau_{w \text{ peak}}$ due to the formation of a stagnation point. After that, the steel splashes in the gating system which leads to an increased normalized maximum wall shear stress. The normalized maximum wall shear stress dramatically decreases when the upward velocity of splashing steel in the trumpet is reduced due to gravity. The normalized maximum wall shear stress then increases again as splashing steel in the trumpet falls back and starts filling the runners in the gating system. Around 1.5 s, the steel enters the mold accompanied with a high normalized maximum wall shear stress value reaching 0.66 $\tau_{w \text{ peak}}$. The normalized maximum wall shear stress is then maintained below 0.55 $\tau_{w \text{ peak}}$ for the remainder

![Fig. 7. Hump height ($H_h$) and surface height ($H_s$) variation with filling time of the reduced geometry model.](image)

![Table 4. Comparison of hump height with different models.](image)

| Surface height (mm) | Hump height I (mm) | Hump height II (mm) | Hump height III (mm) |
|---------------------|-------------------|---------------------|---------------------|
| 10                  | 82                | 75–90               | 85                  |
| 20                  | 86                | 76                  | 60–130              |
| 30                  | 88                | 76                  | 90–110              |
| 40                  | 92                | 84–87               | 90                  |
| 50                  | 98                | 92                  | 90–100              |

I: Reference model from Hallgren et al. with a 1 m/s uniform velocity inlet;
II: Reduced geometry model;
III: Full geometry model.

![Fig. 8. Normalized maximum wall shear stress variation with filling time of the full geometry model.](image)
of the filling process.

The possible regions where the maximum wall shear stress occurs during the initial filling process are indicated in the Fig. 9. As can be seen, the highest values can be found at the center stone, the horizontal runner nearby the center stone and at the vertical runner at the elbow. In addition, the statistics of the normalized maximum wall shear stress are shown in Table 5. It can be found that the first knock of the steel impacts on the middle part of the pit bottom and the wall of the pit (I2, II) in the center stone. Moreover, it presences with more than 0.9 \( \tau_w \text{peak} \) the maximum wall shear stress, which lasts for 0.1 s. The normalized maximum wall shear stress ranges between 0.55 \( \tau_w \text{peak} \leq \tau_w < 0.65 \tau_w \text{peak} \) and 0.9 \( \tau_w \text{peak} \). It is found in the regions mentioned above, the center part of the pit bottom and the lower wall of the center stone nearby the runner (I2, II, I1 and III1). In addition, it lasts for 0.6 s. The total simulation time for the filling process is 5 s. Therefore, it lasts for 4.3 s for the normalized maximum wall shear stress less than 0.55 \( \tau_w \text{peak} \). This occurs at the horizontal runner nearby the center stone, the vertical runner at elbow, the outer part of the pit bottom and the upper wall of the center stone (I1, III, UI, I3, II1 and II11). A recent experimental study by Ragnarsson et al.\textsuperscript{24} showed that the surface of runner had been severely damaged by the mechanical force during the filling process. Furthermore, those big macro inclusions generated by the flushing-off horizontal runner are present in the steel samples from the horizontal runner. However, the erosion of the center stone and the end stone was negligible. In general, the mechanical erosion of refractory depends both on magnitude of wall shear stress and the exposure time. The erosion of the refractory surface formed with low wall shear stress value in Singh \textit{et al.} work.\textsuperscript{11} However, wall shear stress is not easy to optimize, but it should be kept as low as possible when designing new runner geometry. This was the potential to lead to a reduced macro inclusion formation originating from the runner system.

Summarizing the present study, It is desirable to achieve a calm flow in the mold filling process, which results in less entrapped mold flux in the ingots and therefore a clean steel. It is also important to study possibilities to obtain an inclusions control mechanism in the gating system, which reduces non-metallic inclusions generation. More specifically, due to the wear on the refractory materials and the growth and transportation of inclusions. Currently, as a part of the project research, the experiments and industrial trials data collection are performed at Scana Steel. Therefore, possible modification on the gating system and the implementation of flow pattern control devices (i.e. swirl blade) based on the information from industrial trials will be investigated in the future research.

4. Conclusions

This study was aimed at implementing a full scale gating system and molds in a mathematical model based on industrial data. In addition, the purpose was to study filling conditions in ingot casting. Both a full geometry model including the trumpet, runners and molds as well as a reduced geometry model including only part of the runner and the mold were studied. The following specific conclusions may be summarized from the current study:

1) Using a reduced geometry with a homogenous inlet condition fails to describe the fluctuating conditions present as the steel enters the mold;

2) The trends are very similar when comparing the (hump height-surface height) evolution over time;

3) The maximum wall shear stress fluctuates with a descending trend. This indicates that a special attention should be made in choosing refractory at the center stone, the horizontal runner and the vertical runner at elbow. In these regions, the wall shear stress values are highest or prevail during a long time;

4) The simulations show that the (hump height-surface height) difference is approximate 80 mm as the steel enters the mold and then decreases to approximate 40 mm 3.5 seconds later.

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