Some Aspects of Improving Initial Filling Conditions and Steel Cleanliness by Flow Pattern Control Using a Swirling Flow in the Uphill Teeming Process

Zhe Tan

Doctoral Thesis

Stockholm 2013

Division of Applied Process Metallurgy
Department of Material Science and Engineering
School of Industrial Engineering and Management
Royal Institute of Technology
SE-100 44 Stockholm
Sweden

ISRN KTH/MSE--12/30--SE+APRMETU/AVH
Zhe Tan  

**Some Aspects of Improving Initial Filling Conditions and Steel Cleanliness by Flow Pattern Control Using a Swirling Flow in the Uphill Teeming Process**

Division of Applied Process Metallurgy  
Department of Material Science and Engineering  
School of Industrial Engineering and Management  
Royal Institute of Technology, KTH  
SE-100 44 Stockholm  
Sweden

ISRN KTH/MSE--12/30--SE+APRMETU/AVH  
© The Author
The Story of a Heart
Abstract

The flow pattern has widely been recognized to have an impact on the exogenous non-metallic inclusion generation in the gating system and mold flux entrapment in the uphill teeming process. Thus, a well-controlled flow pattern during the teeming process can improve the quality of ingots and further increase the yield during steel production. The current study focused on investigating and optimizing the flow pattern of steel in the gating system and molds to improve steel cleanliness during the initial filling moment. A mathematical model considering a trumpet was initially compared to a reduced model only considering part of the runner channel. Thereafter, the influence of swirl blades implemented at the bottom of the vertical runner on the improvement of initial filling conditions in the molds was investigated in a model considering the entire mold system including a trumpet. The effects of a swirl blade orientation on a swirling flow were further discussed. The simulation results, when utilizing swirl blades, were also verified by plant trials performed at Scana Steel. In addition, a new novel swirling flow generation component, TurboSwirl, was studied in a model considering the entire mold system including a trumpet. The model was based on modifications of the refractory geometry at the elbow of the runners near the mold without the usage of an inserted flow control device in the gating system. Owing to its great potential for improving the flow pattern of steel during the initial filling moment, the effect of TurboSwirl on steel cleanliness was also studied. The results showed that the initial filling conditions during the uphill teeming process can be improved by using a swirl blade or a TurboSwirl in the gating system. This makes it possible to further decrease the initial position of mold powder bags. In addition, it reduces the possibilities of exogenous non-metallic inclusion generation in the gating system as well as mold flux entrapment in the mold during the uphill teeming process. However, the utilization of swirl blades created a considerable amount of droplets when steel entered the molds during the first couple of seconds, which also was verified by the plant trials. The introduction of TurboSwirl showed a greater potential than a swirl blade due to a more evenly distributed swirling flow. The DPM model adopted in the simulations revealed that the TurboSwirl can improve steel cleanliness by increasing the non-metallic inclusion collision rate both with respect to Stokes and turbulent collisions.

Keywords: uphill teeming, ingot casting, flow pattern, swirl blade, TurboSwirl, realizable k-ε model, CFD.
Acknowledgements

I would like to express my heartfelt and sincerest appreciation to my dearest Prof. Pär Jönsson for your positive spirit, professional guidance and eternal encouragement through my entire research study. You are always like a guiding star showing me the way ahead.

I am sincerely grateful to my supervisor Dr. Mikael Ersson for his perpetual guidance, constant support and many valuable discussions throughout my work. Moreover, you are my mentor leading and guiding me in the world of simulations.

Docent Andrey Karasev is sincerely acknowledged for his consistent help and support regarding the sample analysis. Many thanks to Prof. Keiji Nakajima for the nice discussion and suggestion. Dr. Anders Tillander is gratefully acknowledged for his nice suggestions regarding my work. Prof. Hasse Fredriksson and Prof. Lage Jönsson are cordially appreciated for their kind encouragement. Prof. Sichen Du is gratefully thanked for arranging a great trip to Beijing.

I am thankful for the input from the members of the committee JK24053. Especially thanks to Mr. Lars-Henrik Österholm for his kind help and encouragement. I am very grateful to Mr. Peter Lidgren for all the kind help and support at Scana Steel. Mr. Johan Lönnqvist is acknowledged for the nice discussion and support. The foundry team at Scana Steel Stavanger is also acknowledged for the technical support and well cooperation during the plant trials.

Financial support from Jernkontoret (The Swedish Steel Producers’ Association), VINNOVA (Sweden’s Innovation Agency), Walfrid Peterssons minnesfond and Stiftelsen Axel Ax:son Johnsons Forskningsfond and Prytziska Fonden are greatly acknowledged.

Thanks to all my friends and colleagues at the department of Materials Science and Engineering. Especially thanks to Nils and Niloofar for sharing their great taste of music. Big thanks to Alicia for her nice tips on bowling to make a strike. Jesper, Zhi, Ola, Jennie, Kristofer and Abraham are acknowledged for the great time in sharing office during my Ph. D. study. Saman, Yuichi, Zhili, Lars, Björn, Fang, Arkadiy and Charlotte are also thanked for numerous great discussions. Thanks to Erik and Reza for sharing their nice sense of humor.

Last but not least, my sincerest gratitude and love to my parents in China, for your eternal love, support and encouragement through my whole life.

Zhe Tan, Stockholm, November 2012
Supplements

The present thesis is based on the following supplements:

**Supplement 1:** Mathematical Modeling of Initial Filling Moment of Uphill Teeming Process Considering a Trumpet  

**Supplement 2:** Modeling of Initial Mold Filling with Utilization of Swirl Blades  

**Supplement 3:** Plant Trials with Utilization of Swirl Blades at Scana Steel  

**Supplement 4:** Uphill Teeming Utilizing TurboSwirl to Control Flow Pattern in Mold  

**Supplement 5:** Effect of TurboSwirl on Steel Cleanliness during Ingot Filling  
Z. Tan, M. Ersson, P. G. Jönsson.

The contributions by the author to the different supplements of the thesis:

1. Literature survey, numerical calculations, major part of writing.
2. Literature survey, numerical calculations, major part of writing.
3. Literature survey, plant trials, part of sample analysis, numerical calculations, major part of writing.
4. Literature survey, numerical calculations, major part of writing.
5. Literature survey, numerical calculations, major part of writing.

Parts of this work have been presented in the following conference:

Contents
1. Introduction ......................................................................................................................... - 1 -
2. Mathematical Modeling .................................................................................................... - 5 -
   2.1. Numerical Assumptions ............................................................................................. - 7 -
   2.2. Transport Equations ................................................................................................. - 8 -
   2.3. Volume of Fluid (VOF) Model Theory ..................................................................... - 8 -
   2.4. Boundary Conditions ............................................................................................... - 9 -
   2.5. Properties for Materials ............................................................................................ - 10 -
   2.6. Method of Solution ................................................................................................... - 10 -
3. Experimental Work ............................................................................................................ - 11 -
4. Inclusion Collision Theory ............................................................................................... - 13 -
   4.1. Turbulent Collisions ................................................................................................. - 13 -
   4.2. Stokes Collisions ...................................................................................................... - 13 -
   4.3. Collision Design ...................................................................................................... - 14 -
5. Results .............................................................................................................................. - 15 -
   5.1. Flow Pattern ............................................................................................................ - 15 -
   5.2. Hump Height ............................................................................................................ - 22 -
   5.3. Wall Shear Stress ..................................................................................................... - 27 -
   5.4. Removal of Non-metallic Inclusions using TurboSwirl ............................................ - 33 -
   5.5. Plant Trials with Utilization of Swirl Blades ............................................................. - 39 -
      5.5.1. Teeming Process at Plant Trials ........................................................................ - 39 -
      5.5.2. Open-Eye Formation ......................................................................................... - 40 -
      5.5.3. Surface Quality .................................................................................................. - 43 -
      5.5.4. Sample Analysis ............................................................................................... - 47 -
6. Discussion ........................................................................................................................ - 50 -
7. Conclusions ....................................................................................................................... - 55 -
8. Future Work ...................................................................................................................... - 59 -
References ............................................................................................................................. - 60 -
1. Introduction

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

![Schematic diagram of the uphill teeming process.](image)

A schematic diagram of the uphill teeming process is shown in Figure 1. 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 prevents the steel from reoxidation and acts as a thermal insulator as well as a lubricant.

Steel cleanliness in the uphill teeming becomes even more critical as it directly affects the yield and quality of the final product. In order to meet this ever-increasing demand, stealmakers and researchers have spent great efforts on improving the process and technology of the uphill teeming process. It has long been recognized that the flow
pattern plays an important role during the teeming and mold filling process. Exogenous inclusion generation in the gating system and mold flux entrapment in the mold have been found to be closely related to the flow pattern in the uphill teeming process. Therefore, it is of great importance to improve the initial filling conditions and steel cleanliness by a flow pattern control in the uphill teeming process.

A systematical study of uphill teeming techniques based on experience and practice for producing high quality carbon and alloy steels was presented by Blank. He analyzed the development of mold fluxes based on theories and experiences. He also pointed out that an inappropriate ingot bottom design could give rise to the occurrence of entrapped mold flux in the ingots due to the resultant turbulence. In addition, many researchers investigated the phenomena of the entrapment of mold flux. The entrapment of mold flux in ingots was considered to be related to the flow pattern of steel in the mold.

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. 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 inclusion containing traces of mold flux are found in samples taken in the ingot mold during the filling process. In addition, Ragnarsson et al. found large macro inclusions generated by the flow in the horizontal runner. Also, the erosion of a refractory surface due to the flow-induced wall shear stress was studied by Singh et al. Therefore, as seen from these examples, it is of great interest to investigate the flow pattern in the uphill teeming process in order to improve the quality of ingots.

Many researchers have investigated the flow pattern in the uphill teeming process using both physical modeling and numerical simulations in order to find possible solutions to improve the filling conditions. Water modeling for the uphill teeming process has been carried out by a couple of researchers. A one quarter scale Plexiglas replica of one half of a 6 molds uphill teeming system was studied by Freborg, which also included 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 et al. to generate data for verification of CFD predictions. 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 and van der Graaf. In addition, Eriksson et al. have applied five different turbulence models to describe the ingot mold filling process and compared the predictions with water model measurements. Possible modifications including the flaring angle of an ingot mold entrance nozzle, a divergent entrance nozzle and an implementation of swirl blade in the gating system have also been suggested in previous
research. Enlighten by Blank’s research, Eriksson et al. found that a 25 degree angle resulted in the most even horizontal velocities, which was believed to minimize the steel/mold powder interactions. In addition, Yokoya et al. have studied the control of the flow pattern in the immersion nozzle using a swirl blade for continuous casting. Also, Hallgren et al. investigated the effect of nozzle type and swirl flow during the initial uphill teeming based on physical and mathematical modeling. It was found that the use of a divergent nozzle resulted in a smaller hump and a lower axial velocity compared to when using a straight nozzle. Moreover, a further velocity decrease could be achieved when a divergent nozzle was used in combination with a swirl generator. Later, Hallgren et al. studied the effect of a nozzle swirl blade on the flow pattern in a runner during uphill teeming. They found that the utilization of a swirl blade remarkably improved the flow conditions when a swirl blade is placed immediately after the runner elbow. Also, Zhang et al. discussed the effects of the implementation of a swirl blade at a vertical position at the inlet nozzle of a mold in the uphill teeming considering a runner and mold with a divergent nozzle. It was concluded that a uniform velocity distribution and a stable flow pattern can be obtained within a short time. In further studies, Hallgren et al. made a first attempt to implement a swirl blade in production of ingots. A calmer filling and a more uneven spreading of the mold flux were found in the plant trials. Moreover, the modeling work showed that the implementation of a swirl blade in the vertical runner resulted in a hump height decrease. Also, an increased inlet angle in combination with a swirl blade was found to further decrease the initial hump height.

The generation of exogenous inclusions in the gating system due to the erosion of the refractory surface is detrimental to the final quality of the steel. The erosion of refractory may occur due to a mechanical force, a thermal attack and chemical reactions. Singh et al. investigated the erosion of refractory surface due to the flow-induced wall shear stress. The predicted results were verified with the actual location of erosion. Therefore, the exogenous non-metallic inclusions could be generated in the regions where a high wall shear stress could be found. In addition, the magnitude of the maximum wall shear stress and its possible high magnitude regions are of importance to study.

The main purpose of this work is to investigate the flow pattern in the whole gating system and the molds by using mathematical modeling. Specifically, to improve the initial filling conditions and steel cleanliness with a swirling flow by minimizing the flow-induced mold flux entrapment in the mold and exogenous inclusion generation in the gating system. The outline of the present work is shown in Figure 2.
In **Supplement 1**, the emphasis of the study was focused on the flow pattern of the steel in the gating system and molds during the initial stage of the mold filling process. Compared to previous researchers' work, the model included both the trumpet, runner channel and the mold. A two molds runner system was adopted in the study. A reduced geometry including one mold and a runner was also used for the comparison. In addition, the predictions were compared to filling information from industrial trials and results from previous researches. In **Supplement 2**, the aim of the study was to investigate the flow pattern of steel in the gating system and molds with swirl blades implemented at the bottom of the vertical runners during the initial stage of the mold filling process. A two-mold gating system was adopted in the study and different orientations of the swirl blade were studied. In **Supplement 3**, the objective of the plant trials carried out at Scana Steel Stavanger was to make verifications for the simulations related to the flow pattern during the uphill teeming process. The effects of the swirl blade on the casting time, turbulence at initial casting, mold flux distribution, mold powder consumption and ingot surface defects due to mold flux entrapment were evaluated. In **Supplement 4**, a new novel swirling flow generation component, TurboSwirl, was studied to investigate the flow pattern of steel in the gating system and molds based on the authors' previous study. It was found that the initial filling conditions can be substantially improved by the use of a TurboSwirl flow pattern control. In **Supplement 5**, the potential of using TurboSwirl to obtain an improved steel cleanliness during filling of an ingot was studied by mathematical modeling using VOF and DPM models. It was concluded that the utilization of TurboSwirl can improve the steel cleanliness by reducing mold flux entrapment and by increasing non-metallic inclusions collision rate from both Stokes collisions and turbulent collisions.
2. Mathematical Modeling

A three dimensional model of a two-mold gating system for 6.2 ton ingots from Scana Steel was adopted in the present work. The size of the mold was set to 1/5 of the original mold height to observe the flow pattern at an initial filling stage. Typically, the diameter of a trumpet is 70mm and the diameter of runners is 45mm.\textsuperscript{27} A schematic description of the computational domain used in \textbf{Supplement 1} is shown in \textbf{Figure 3}. A reduced geometry including one mold and a runner is also shown in the figure, as indicated by the dashed line. This geometry was based on the method from previous researchers\textsuperscript{16,18,25,26} and was used for comparison to the current prediction results.

![Figure 3](image)

\textbf{Fig. 3.} Schematic diagram of the computational domain and boundary conditions used in the model, without a placement of swirl blades. The reduced geometry model bounds are indicated by the dashed line.

The schematic description of the computational domain for \textbf{Supplement 2} is illustrated in \textbf{Figure 4}. The possible modifications including a flaring angle at the mold entrance nozzle and swirl blades located at the bottom of vertical runner with different orientations were employed in the gating system. Based on the orientation relationship between the horizontal runner and the bottom edge of the swirl blades, parallel placement and perpendicular placements of the swirl blades were implemented at the bottom of two vertical runners. The swirl blade has a 60 degree twist angle and a 60mm length. The shape of the swirl blade is based on the studies from previous researchers.\textsuperscript{25,26}
Fig. 4. Schematic diagram of the computational domain and boundary conditions used in the model with a placement of swirl blades. The information of the flaring angle and the placement of the swirl blade bounds are indicated by the dashed line. A parallel placement of a swirl blade (P) is denoted. Moreover, a perpendicular placement of a swirl blade (V) is named.

Based on the geometric description from Supplement 2, a reduced geometry with possible modifications including a flaring angle at the mold entrance nozzle and swirl blades located at the bottom of vertical runner with different orientations was studied in Supplement 3.

The schematic description of the computational domain used in Supplement 4 is shown in Figure 5. The three dimensional model from Supplement 1 is modified with a flaring angle at the mold entrance nozzle and the new swirling flow generation component, TurboSwirl (TB), at the elbow of the runners near the mold. The mold entrance nozzle has a 52 degree flaring angle and a 35mm length. The TurboSwirl has a diameter of 150mm and a height of 50mm. In addition, the outlet nozzle of the TurboSwirl has a 49 degree flaring angle and a 20mm length. Compared to the gating system in Supplement 1, a total extra volume of 1.24dm³ is introduced.
Fig. 5. Schematic diagram of the computational domain and boundary conditions used in the model. The information of the flaring angle and the placement of the TurboSwirl bounds are indicated by the dashed line. A TurboSwirl with a clockwise/counter clockwise capability is denoted.

Based on the geometric description from Supplement 4, the radius of the TurboSwirl is reduced to 60mm. In addition, the mold entrance nozzle length is extended to 100mm. Moreover, a reduced geometry modified with the TurboSwirl at the elbow of the runners near the mold was also investigated in **Supplement 5**.

### 2.1. Numerical Assumptions

A compromise was made considering the balance between accuracy and time consumption. As the velocity of air is relatively low, there is no warrant to use the compressible flow unless considering thermal expansion effects. In addition, the coupling between temperature and pressure requests a considerable small time scale and an extremely fine mesh to capture the volume changes of air. Therefore, the density variation of air due to the heat transfer of the steel was neglected when the assumptions were made.

The following assumptions were made when developing the mathematical model:

A. The flow rate of steel is constant at the inlet of the trumpet;
B. Both air and steel are incompressible Newtonian fluids;
C. The physical property data are constant;
D. No chemical reactions take place;
E. Solidification and heat transfer are not considered;
F. The effect of interfacial tension on the mold flux distribution is not considered;
G. Clustering, coalescence and agglomeration of inclusions are neglected;
H. The removal of inclusions to the refractory surface is 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:

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

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.

Table 1. Conservation equations.

<table>
<thead>
<tr>
<th>Conservation of:</th>
<th>$\Phi$</th>
<th>$\Gamma$</th>
<th>$S_\Phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>x-momentum</td>
<td>$u$</td>
<td>$\mu$</td>
<td>$-\frac{\partial p}{\partial x}$</td>
</tr>
<tr>
<td>y-momentum</td>
<td>$v$</td>
<td>$\mu$</td>
<td>$-\frac{\partial p}{\partial y} + \rho g$</td>
</tr>
<tr>
<td>z-momentum</td>
<td>$w$</td>
<td>$\mu$</td>
<td>$-\frac{\partial p}{\partial z}$</td>
</tr>
<tr>
<td>Turbulent kinetic energy</td>
<td>$k$</td>
<td>$\mu + \frac{\mu_t}{\sigma_k}$</td>
<td>$G_k - \rho \varepsilon$</td>
</tr>
<tr>
<td>Turbulent dissipation rate</td>
<td>$\varepsilon$</td>
<td>$\mu + \frac{\mu_t}{\sigma_\varepsilon}$</td>
<td>$\rho C_1 \varepsilon - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{\mu/\rho \varepsilon}}$</td>
</tr>
</tbody>
</table>

Notes:

1. Turbulent viscosity: $\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}$
2. Molecular (dynamic/laminar) viscosity: $\mu$
3. Effective viscosity: $\mu_{eff} = \mu + \mu_t$
4. $\sigma_k = 1.0$ $\sigma_\varepsilon = 1.2$ $C_2 = 1.9$
5. $C_1 = \max[0.43, \frac{\eta}{\eta + 5}]$; $\eta = \frac{k}{\varepsilon} S = \sqrt{2} S_i S_{ij} S_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$

2.3. Volume of Fluid (VOF) Model Theory

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

$$\frac{\partial F}{\partial t} + u \frac{\partial F}{\partial x} + v \frac{\partial F}{\partial y} + w \frac{\partial F}{\partial z} = 0 \tag{2}$$

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

$$F = \begin{cases} 
0 & \text{Air phase only} \\
1 & \text{Liquid phase only} \\
0 < F < 1 & \text{At the interface} 
\end{cases} \tag{3}$$

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

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

where $\Phi_{\text{liquid}}$ and $\Phi_{\text{air}}$ are the physical properties of liquid (steel) and air, respectively.
2.4. Boundary Conditions

The top of the trumpet is a combined inlet (for steel) and outlet/inlet (for gas). 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 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 trumpet inlet surface. The gauge pressure was chosen to be zero.

A constant uniform velocity profile was also adopted for the reduced geometry model with a circle-shaped geometry for the whole cross section at the runner inlet, where the direction of the velocity was set normal to the runner inlet surface. This profile was calculated from the volumetric flow rate of the ladle and the cross sectional area of the two runners. In Supplement 3 and Supplement 5, the inclusions injected are assumed to be alumina particles with a spherical shape. The particles have a density of 3950 kg/m$^3$. The total flow rate of the inclusions was set to 0.001 kg/s.

The calculation methods are illustrated as follows and results for the velocity inlet conditions are summarized in Table 2.

<table>
<thead>
<tr>
<th>Model</th>
<th>$u$ (m/s)</th>
<th>$D_h$ (m)</th>
<th>Re</th>
<th>$I$ (%)</th>
<th>$k$ (m$^2$/s$^2$)</th>
<th>$l$ (m)</th>
<th>$\varepsilon$ (m$^2$/s$^3$)</th>
<th>$\mu_t$ (Pa•s)</th>
<th>$\mu_t/\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full</td>
<td>2.65</td>
<td>0.04</td>
<td>122019</td>
<td>3.70</td>
<td>1.44E-2</td>
<td>2.8E-3</td>
<td>0.102</td>
<td>1.27</td>
<td>212</td>
</tr>
<tr>
<td>Reduced</td>
<td>1.05</td>
<td>0.045</td>
<td>54228</td>
<td>4.10</td>
<td>2.76E-3</td>
<td>3.15E-3</td>
<td>7.6E-3</td>
<td>0.63</td>
<td>104</td>
</tr>
</tbody>
</table>

In addition, the following turbulence inlet conditions were used:

\begin{align}
  I &= 0.16Re^{-1/8} \\
  k &= 1.5(u \cdot I)^2 \\
  l &= 0.07D_h \\
  \varepsilon &= C_\mu \frac{k^{3/2}}{l}
\end{align}

where $I$ is the turbulence intensity, $Re$ is the Reynolds number at velocity inlet, $u$ is the inlet velocity, $l$ is the turbulence length scale and $D_h$ is the hydraulic diameter.

A pressure outlet boundary with a zero gauge pressure was used at the outlet of the mold. Moreover, a no-slip condition was applied to all the walls and a standard wall function was used with a logarithmic law to model the mean velocities near the wall.
2.5. Properties for Materials

The physical properties of steel used in the current calculations are shown in Table 3.31)

<table>
<thead>
<tr>
<th>Density (kg/m$^3$)</th>
<th>Dynamic viscosity (Pa•s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6900</td>
<td>0.006</td>
</tr>
</tbody>
</table>

In Supplement 3, the physical properties of mold flux can be seen in Table 4.32)

<table>
<thead>
<tr>
<th>Density (kg/m$^3$)</th>
<th>Dynamic viscosity (Pa•s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>270</td>
<td>63</td>
</tr>
</tbody>
</table>

In Supplement 3, the physical properties of inclusions are shown in Table 5.33)

<table>
<thead>
<tr>
<th>Density (kg/m$^3$)</th>
<th>Diameter (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3950</td>
<td>10</td>
</tr>
</tbody>
</table>

In Supplement 5, the physical properties of inclusions are presented in Table 6.

<table>
<thead>
<tr>
<th>Density (kg/m$^3$)</th>
<th>Diameter (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3950</td>
<td>2, 10, 30, 100, 200</td>
</tr>
</tbody>
</table>

2.6. Method of Solution

The governing equations were discretized by the finite volume method via using the commercial CFD software code ANSYS FLUENT 12.1/13.0®. The mesh of the full geometry model and the reduced geometry model was generated by using ANSYS WORKBENCH 12.1/13.0®. The VOF and DPM models were used. Moreover, the PRESTO discretization method was adopted to discretize the pressure. The PISO scheme was used to solve the 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. Experimental Work

The predictions and the experimental validations are both always essential to carry out when applying the results in industry. The aim of the experiment carried out at Scana Steel Stavanger was to verify the simulations related to the flow pattern during the uphill teeming process. Specifically, to evaluate the effects of the swirl blade on the casting time, turbulence at initial casting, mold flux distribution, mold powder consumption and ingot surface defects due to mold flux entrapment, etc. In addition, morphological and composition analysis for the samples collected from the ingots. It is important to carry out those analyses to have a close investigation on the effects from the centrifugal force provided by the swirl blade on the inclusions content in steel.

During the plant trials, a digital camera was used to capture the gating system assembly process. In addition, a HD-video recorder was used to record the flow pattern and mold flux distribution in the teeming process by using a mirror reflection from the mold. The videos were captured using a resolution of 1920x1080p and a frame rate of 25fps. Theoretically, the rising rate of the steel free surface in the mold can be calculated from the curvature of the convex mirror and the mounting angle of the mirror on the mold. It can be a part of on-line control during the teeming process in the future. Due to conditions restriction and certain uncertainties, it is hard to perform during this plant trial. The parallel placement of a swirl blade was chosen when performing the plant trials with implementation of the swirl blade, as can be seen in Figure 6. As full description of the experiment set-up is shown in Table 7.

![Fig. 6](image)

Fig. 6. Parallel placement of a swirl blade for all the placement of the swirl blades during the plant trials.

SEM/EDS were utilized to observe the morphological and composition improvements by using swirl technique in the control of inclusions. The sample analysis was performed at KTH.
Table 7. Experiment set-up description

<table>
<thead>
<tr>
<th></th>
<th>Reference 1</th>
<th>Reference 2</th>
<th>PB*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>2011-11-08 20:00</td>
<td>2011-11-09 12:00</td>
<td>2011-11-09 21:00</td>
</tr>
<tr>
<td>Steel Grade</td>
<td>A-21635/S165M/LowDF</td>
<td>A-21637/SAF Super Duplex 25% Cr</td>
<td>---</td>
</tr>
<tr>
<td>Weight of Casting Powder</td>
<td>2 kg</td>
<td>2 kg</td>
<td>---</td>
</tr>
<tr>
<td>Amount of Casting Powder Bags</td>
<td>6</td>
<td>6</td>
<td>---</td>
</tr>
<tr>
<td>Bag Placement</td>
<td>3+3</td>
<td>3+3</td>
<td>---</td>
</tr>
<tr>
<td>Bag Position</td>
<td>10cm/15cm</td>
<td>10cm/30cm</td>
<td>---</td>
</tr>
</tbody>
</table>

*Parallel placement of swirl blades
4. Inclusion Collision Theory

Due to the significance of turbulent collisions and Stokes collisions, these two collision theory models are of primary concern when designing a TurboSwirl concept to improve the steel cleanliness. Hence, the present work will mainly focus on turbulent collisions and Stokes collisions models.

4.1. Turbulent Collisions

The turbulent collisions model was originally developed to describe the collision of drops in turbulent clouds by Saffman and Turner. In this model, the Kolmogorov length scale was used to find the minimum size of an eddy in a local homogeneous turbulent flow. The Kolmogorov length scale is defined by:

$$\eta = (\nu / \varepsilon)^{0.25}$$ (1)

where $\nu$ is the kinematic viscosity of the fluid and $\varepsilon$ is the dissipation rate of the turbulence kinetic energy. Then, the frequency of collision (collision rate), $N_t$, is given by:

$$N_t = 1.3R^3n_in_j(\varepsilon/\nu)^{0.5}$$ (2)

where $R$ is the collision diameter, $n_i$ and $n_j$ are the number concentration of particles $i$ and $j$, respectively. Therefore, the collision rate of inclusions is proportional to the turbulence dissipation rate and the number concentration of inclusions. This means that a well-designed gating system can promote turbulent collisions by properly increasing the turbulence dissipation rate and the number concentration of inclusions in a relatively small volume, e.g. bringing inclusions close to the axis of a rotational flow.

4.2. Stokes Collisions

When an inclusion is submerged in steel, it experiences a greater pressure from the bottom side than its top side. This pressure difference results in a net force upward, i.e. buoyancy. Due to the nature of non-metallic inclusions, they normally have a density less than that of steel. This causes the floatation of the inclusion in steel. During its floatation, a terminal velocity, $v_t$, is reached when the frictional force combined with the gravitational force exactly balance the buoyancy force. This terminal velocity is given by the following expression:

$$v_t = \frac{2(\rho_p-\rho_f)}{9} \frac{\rho_f}{\mu} gR^2$$ (3)

where:

- $v_t$ is the terminal velocity,
- $\rho_p$ is the density of the inclusion,
• $\rho_i$ is the density of the steel,
• $\mu$ denotes the dynamic viscosity of steel,
• $g$ is the gravitational acceleration.

As can be seen from above, when two inclusions with different radii are subject to floatation, the inclusion with a greater size will have a larger terminal velocity. Moreover, this is quadratically proportional to the radius of the inclusion. Owing to this, the larger inclusion will catch up with the smaller inclusion. Hence, the larger difference in radius results in a faster collision.

When the reference frame is changed into a rotational field, the modified terminal velocity can be expressed as follows:

$$v_t' = \frac{2}{9} \frac{(\rho_p - \rho_f)}{\mu} a_c R^2$$  \hspace{1cm} (4)

where $a_c$ denotes the centripetal acceleration. In equation (4), the natural gravitational acceleration is not considered. The introduction of the modified terminal velocity depicts the tendency of inclusions with different sizes to gather towards the rotation center in a swirling flow. It can be found that an important factor which influences this tendency, besides the radius of inclusion, is the centripetal acceleration. The concept of a modified terminal velocity will be discussed later in this study.

The frequency of Stokes collisions, $N_s$, has been suggested by previous researchers as shown below:\textsuperscript{38)

$$N_s = \frac{2 \pi \Delta \rho g}{9 \mu} (r_1 + \eta_j)^3 |r_i - \eta_j|$$  \hspace{1cm} (5)

Here, it can be found that the collision rate can be drastically reduced when inclusions have a similar size.

4.3. Collision Design

As shown above, the aim of promoting an improved collision rate is to separate non-metallic inclusions from steel without them being entrapped inside ingots after stripping. This can significantly improve the steel cleanliness. The collision rate of a collision mechanism can be notably decreased under certain circumstances. However, the collision rate for the system should be kept or increased in order to maintain the capability of non-metallic inclusions separation. Therefore, the total collision rate, $N$, is of great concern and it can be written as:

$$N = N_t + N_s + N_{\text{other}}$$  \hspace{1cm} (6)

where $N_{\text{other}}$ denotes the collision rate due to other collision mechanisms which may contribute to inclusion collisions.
5. Results

5.1. Flow Pattern

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. up to several mm. 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 conditions.

![Figure 7](image)

**Fig. 7.** Contour of liquid steel during the ingot filling process at 5s from the teeming start in the model without a placement of swirl blades.

![Figure 8](image)

**Fig. 8.** Definition of the hump height ($H_h$), the surface height ($H_s$) and the steel height difference ($\Delta H$).

The flow pattern of steel during initial filling process in the model without a placement of swirl blades is shown in **Figure 7**. Around 0.5s, 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 1.5s. 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 starts to fall back after around 2.0s. Thereafter, the splashing steel height in the trumpet increases dramatically. The hump height increases significantly at 2.5s. 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 Figure 8. The steel height difference (ΔH) variation with filling time can be seen in Figure 9. It can be seen 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 a better understanding of the initial filling stage. Thus, they can 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.

![Steel height difference variation](image)

**Fig. 9.** Steel height difference (ΔH) variation between mold and trumpet with filling time. (N: without placement of swirl blade. P: parallel placement of swirl blade. V: perpendicular placement of swirl blade. TB: TurboSwirl.)

The flow pattern of steel during the initial filling process in the model with a placement of swirl blades is shown in Figure 10. The implementation of swirl blades in the gating system reduces the cross sectional area of the runners, where the swirl blade is located. Therefore, it causes a slight increase of the mean velocity as the steel passes the swirl blade. It also increases the macroscopic flow resistance in the system. The geometry of the center stone results in a steel flow divergence at the intersection, as shown in Figure 11. The main flow splashes upwards back to the trumpet and the minor flow hits the upper wall of the runners and then scatters. Thereafter, the minor flow reaches the end
of the horizontal runner and hits the swirl blades. The swirl blades hinder the steel coming into the vertical runner and cause a circulation flow.

Fig. 10. Contour of liquid steel during the ingot filling process at 5s from the teeming start in the model with a placement of swirl blades.

Fig. 11. Velocity vector plot of steel flow at the intersection of the center stone at 0.93s from the teeming start.

Fig. 12. Velocity vector plot at the top edge of the swirl blade in the vertical runner with a a) parallel b) perpendicular placement of a swirl blade at 5s from the teeming start. The presence of air phase introduces perturbations to the velocity vectors as shown in a).
This causes the horizontal runner to fill up faster compared to a case with no swirl blade. The splashing steel in the trumpet starts falling back at 1.1s, which results in a surge of waves in the horizontal runner. This results in more filled runners, which contain less entrapped air. The surge of steel in the horizontal runner along with the impact from swirl blades in the vertical runner results in a chaotic initial filling, when steel enters the molds at around 1.6s from the teeming start. In addition, the orientation of the swirl blade placement also affects the flow pattern of steel. In the reduced geometry model, without a swirl blade, a high velocity profile was observed at the outer part of the wall of the vertical runner in the elbow. Based on this, an investigation was performed to find out if the parallel placement or the perpendicular placement of the swirl blade was more optimal, as shown in Figure 12. In the mold with a parallel placement of a swirl blade, the mass flow of steel is evenly distributed. It enters the mold and small amounts of droplets are found, due to the tangential velocity given by the swirl blade. In the mold with a perpendicular placement of a swirl blade, the uneven distribution of mass flow separates the mass flow into opposite directions along with the droplets being splashed. The major flow is lead to the inner side of the mold and the minor flow is detached, which forms a surge towards the outer wall of the mold. The detached flow is of a considerable size and hits the wall of the mold, which may lead to abnormal erosion to the mold as can be seen in Figure 13. This erosion might be due to the mechanical and chemical reactions along with a quick solidification due to the high thermal conductivity of the mold. The abnormal erosion might also result in difficulties in detaching ingots from molds as well as to decrease the life cycle of the molds. Also, the initial droplets being splashed might have adverse effects on the wall of the mold by causing a degrading of the ingot surface quality.

As the filling process proceeds, the runners become more filled and less air is entrapped. Compared to previous work, which did not consider swirl blades, the amount of steel in the horizontal runner increases from 80.9% to 98.4% at 5s from the teeming start. This
results in a calmer filling condition, which makes it easier for operators to predict the flow and the placement of the mold powder. However, it needs to be mentioned that the accumulated air will form large air cavities, which is shown in Figure 14. Hence, an instantaneous high shear stress is expected in the horizontal runners, which might lead to a generation of exogenous inclusions. In addition, certain fluctuations of humps in the molds are also expected due to the escape of trapped air.

![Fig. 14. Contour of liquid steel during the ingot filling process at 1.9s from the teeming start.](image)

The variation of the steel height difference with filling time in the model with a placement of swirl blades is shown in Figure 9. It can be found that the perpendicular placement of the swirl blade causes slight steel height differences compared to a parallel placement of the swirl blade at the initial filling process in the molds. Also, a distinction of the steel height difference between a parallel and a perpendicular placement of swirl blades appears around 3s and lasts about 0.5s. However, the trend is quite similar. Compared to the model without a placement of swirl blades, the steel height difference in the present model with a swirl blade is much larger than for the model without a swirl blade. More specifically, the maximum magnitude is 475mm and 140mm, respectively. This is to be expected since the swirl blade will increase the flow resistance in the system. Also, from the hump height condition in the mold, it is hard to judge the steel height in the trumpet at the initial filling stage due to the unsymmetrical trend.

The flow pattern of steel at the initial filling stage in the model with utilization of the TurboSwirl is shown in Figure 15. When the air-entrapped steel enters the TurboSwirl, the geometry of the TurboSwirl forces the flow streams circularly along the wall. This uses the axial velocity of the flow in the horizontal runners to create the tangential velocity of a swirling flow. In addition, the generation of a swirling flow in the TurboSwirl prolongs the resident time of the flow in the runners. This increases the resident time for the inclusions and promotes their separation from the steel, which makes the TurboSwirl to serve as an inclusion “collector”. Moreover, due to its geometry and the density difference between the steel and air, the entrapped air in the flow can be
separated in the upper center section of the TurboSwirl. Furthermore, the flaring-angled outlet nozzle improves the centering and swirling effect. This makes the TurboSwirl to also serve as a “separator”, which can be seen in Figure 16. Therefore, the outer and lower part of the TurboSwirl is always filled up with steel of a swirling flow. As shown in Figure 16, the magnitude of tangential velocity profile decreases in the radial direction towards the center of the TurboSwirl. This results in an even filled vertical runner when the steel enters the mold at around 2.1s from the teeming start. Due to the swirling effects, the steel spreads widely along the entrance nozzle and the bottom wall of the mold. This results in much calmer initial filling conditions in the molds. When a ferrostatic pressure gradually builds up in the molds, the entrapped air from the horizontal runners has a swirling motion in the upper section of the TurboSwirl due to the swirling flow of the steel. Due to the geometry of the TurboSwirl, the air cavity can gradually be released into the vertical runner with several air bubbles of a small volume as can be seen in Figure 17. Hence, the influence due to the perturbations of the entrapped air on the filling conditions of the steel flow in the molds can further be alleviated. As the teeming proceeds, the filling conditions in the molds are further improved as shown in Figure 18. This means the formation of a smaller hump and a more evenly distributed swirling flow. It is also necessary to mention that the introduction of the TurboSwirl increases the macroscopic flow resistance in the runners, which leads to more steel residing in the trumpet. This will alleviate the impact of the steel exerted on the horizontal runners at the center stone.

Fig. 15. Contour of liquid steel during the ingot filling process at 1.4s from the teeming start.
Fig. 16. Contour of liquid steel (a) and tangential velocity plot of steel flow (b) at the cross section of the TurboSwirl at 1.82s from the teeming start.

Fig. 17. Contour of liquid steel during the ingot filling process at 3.4s from the teeming start.

Fig. 18. Contour of liquid steel during the ingot filling process at 5s from the teeming start.
The variation of the steel height difference with filling time in the model with utilization of the TurboSwirl is shown in Figure 9. The macroscopic flow resistance in the gating system increases due to the formation of a swirling flow in the TurboSwirl. This leads to a continuous negative steel height difference value, i.e. the steel in the trumpet is higher than the steel in the mold. A large decrease of steel height difference value occurs around 2.3s from the teeming start. This happens when the initial entrapped air in the horizontal runners enters the mold. After that, the steel height difference keeps negative while the steel height in the molds increases as the teeming proceeds. Compared to the previous model, using a flow control device inserted in the gating system, it has a positive steel height difference value. Moreover, it clearly shows the difference of introducing the TurboSwirl concept, a model based on the modifications on the geometry of the refractory, at the elbow of the runners near the mold. Therefore, the teeming rate needs to be well-controlled to adjust the splashed steel height in the trumpet.

5.2. Hump Height

The concept of the hump height was initially introduced in the recent research by Hallgren et al.[26] This concept is of great practical significance in the steel production as the hump can directly be observed during the teeming process. In addition, the hump height ($H_h$) is closely related to the initial position of mold powder bags and the distribution of mold flux. The formation of a large hump during the teeming process results in a higher potential of mold flux entrapment. The definition of the hump height ($H_h$) and the surface height ($H_s$) for the present models is illustrated in Figure 8.

![Graph](image)

Fig. 19. Hump height ($H_h$) and surface height ($H_s$) variation with filling time in the model without a placement of swirl blades.

The hump height ($H_h$) in the model without a placement of swirl blades is shown in Figure 19. The steel enters the mold at around 1.5s from the teeming start, which leads
to the formation of a first hump with a height of 130mm. The steel jet then looses momentum and is forced back to the mold entrance by gravity. Thus, it forms the first noticeable surface height ($H_s$), which is around 12mm. 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 140mm can be found at times around 2.6s and 4.6s. Also, compared to the hump height curve, the surface height curve increases more steady and it contains less fluctuations.

![Graph of hump and surface heights](image)

**Fig. 20.** Hump height ($H_h$) and surface height ($H_s$) variation with filling time of the reduced geometry model.

The hump and surface heights in the reduced geometry model case, which represents the approach used by Hallgren, Eriksson and others,$^{16,18,25,26}$ are illustrated in **Figure 20**. Due to the absence of the trumpet in this simulation, the time for the steel to enter the mold is decreased by approximately 0.5s. 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 145mm at 1.3s followed by steel falling down to the bottom of the mold. This forms a first noticeable surface height of 10mm. 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. In addition, 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 a significant benefit with the model accounting for the trumpet is obvious because one can have the information of the variation of $\Delta H$ with time, as shown in **Figure 8**.
The comparisons of hump height predictions using different models can be seen in Table 8. Although the geometrical information of the computational domains is different, the data for the reduced model in the current study fits the results from previous researchers fairly well. 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.

<table>
<thead>
<tr>
<th>Surface height (mm)</th>
<th>Hump height I (mm)</th>
<th>Hump height II (mm)</th>
<th>Hump height III (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>82</td>
<td>75-90</td>
<td>85</td>
</tr>
<tr>
<td>20</td>
<td>86</td>
<td>76</td>
<td>60-130</td>
</tr>
<tr>
<td>30</td>
<td>88</td>
<td>76</td>
<td>90-110</td>
</tr>
<tr>
<td>40</td>
<td>92</td>
<td>84-87</td>
<td>90</td>
</tr>
<tr>
<td>50</td>
<td>98</td>
<td>92</td>
<td>90-100</td>
</tr>
</tbody>
</table>

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

The hump height variations with filling time for parallel and perpendicular placements of swirl blades are shown in Figure 21 and Figure 22, respectively. When swirl blades are used, a considerable amount of droplets are initially being formed in the molds. Also, the first noticeable hump forms in the molds around 2.4s from the filling start. Compared to the model without a swirl blade, the time for the first hump formation is delayed by 0.4s. In the mold with a parallel placement of a swirl blade, one distinctive hump with a largest hump height ($H_{\text{h max}}$) of 245mm forms around 3.2s. This leads to a height difference of 213mm compared to the steel surface in the mold. The maximum difference between the hump height and the surface height (Maximum $\Delta(H_{\text{h}}-H_{\text{s}})$) in the initial filling stage reaches 176mm. In the mold with a perpendicular placement of a swirl blade, three distinctive humps appear in the curve, as seen in Figure 22. The largest hump height of 170mm forms around 3.5s, giving a height difference of 141mm to the steel surface in the mold. The maximum difference between the hump height and the surface height in the initial filling stage reaches 106mm. When comparing the two different orientations of swirl blade placements, the parallel placement of a swirl blade may result in more entrapment of mold flux due to its huge hump formation at the initial filling stage. However, after the largest hump formation, the hump height curve for the parallel placement of a swirl blade varies ($\Delta H_{\text{h}}$) around 25mm (see Figure 21). Furthermore, for the perpendicular placement of the swirl blade it varies around 45mm after its largest hump formation (see Figure 22). This means that there is less risk of entrapment of mold flux with a parallel placement of the swirl blade compared to a perpendicular placement. In addition, compared to the model without swirl blades, the model with swirl blades might initially predict a larger hump height, but result in fewer
fluctuations as the casting proceeds. A summary of hump height comparison is shown in **Table 9**. Here, it can be seen that the utilization of swirl blades can reduce the fluctuations of the hump height.

**Fig. 21.** Hump height ($H_h$) and surface height ($H_s$) variation with filling time with parallel placement of swirl blade.

**Fig. 22.** Hump height ($H_h$) and surface height ($H_s$) variation with filling time with perpendicular placement of swirl blade.

**Table 9.** Hump height comparison.

<table>
<thead>
<tr>
<th>Case</th>
<th>$H_{h_{\text{max}}}$ (mm)</th>
<th>Number of Humps ($\geq 30$mm)</th>
<th>Maximum $\Delta(H_h-H_s)$ (mm)</th>
<th>$\Delta H_h$ after $H_{h_{\text{max}}}$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>140</td>
<td>8</td>
<td>87</td>
<td>60</td>
</tr>
<tr>
<td>V</td>
<td>170</td>
<td>3</td>
<td>106</td>
<td>45</td>
</tr>
<tr>
<td>P</td>
<td>245</td>
<td>1</td>
<td>176</td>
<td>25</td>
</tr>
</tbody>
</table>

N: without placement of a swirl blade.
V: perpendicular placement of a swirl blade.
P: parallel placement of a swirl blade.
The hump height variation with filling time in the model with utilization of the TurboSwirl and a comparison with previous studies data is shown in Figure 23. Compared to the previous study of the normal gating system model, the time for steel entering the mold is delayed by 0.6s. In addition, the first hump forms with a height of 112mm for the present model. However, the formation of the first hump in the normal gating system model has a height of 130mm. Then, the hump height decreases as the steel jet looses its momentum while the initial entrapped air in the horizontal runners is evacuated into the mold. After that, the hump height increases with a decreasing rate due to the swirling flow generated by the TurboSwirl along with the building up of the ferrostatic pressure in the mold. At 6s from the teeming start, it can be observed that the hump height for the present model has a value of 81mm while the value for the hump height in the normal gating system model is 140mm. Furthermore, a value of about 100mm with the utilization of swirl blades inserted at the bottom of the vertical runners is seen. This means that the initial position of the mold powder bags can further be lowered in the mold when using TurboSwirl compared to when using a swirl blade. This decreases the chances for reoxidation with air during the initial mold filling.6)

![Graph](image)

**Fig. 23.** Hump height ($H_h$) variation with filling time. (N: without placement of swirl blade. P: parallel placement of swirl blade. V: perpendicular placement of swirl blade. TB: TurboSwirl.)

The difference between the hump height and the surface height ($H_h - H_s$) is also of interest to investigate, as it is closely related to the mold flux entrapment. The difference between the hump height and the surface height variation with filling time for the present model along with its comparison with data from previous studies is shown in Figure 24. Compared to the previous models, it can be found that the current model with the utilization of the TurboSwirl results in a maximum value of 83mm in the difference between the hump height and the surface height. This is the lowest maximum value among all the other models. Moreover, the value of the difference between the
hump height and the surface height for the present model remains lower than the other models for most of the time and the fluctuations are less. This means a lower risk of mold flux entrapment in the present model with the utilization of the TurboSwirl compared to the other models.

**Fig. 24.** Difference between hump height ($H_h$) and surface height ($H_s$) variation with filling time. (N: without placement of swirl blade. P: parallel placement of swirl blade. V: perpendicular placement of swirl blade. TB: TurboSwirl.)

### 5.3. Wall Shear Stress

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. This is due to that 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.

The normalized maximum wall shear stress as a function of time in the model without a placement of swirl blades is plotted in **Figure 25.** The steel jet falls freely in the trumpet and reaches the center stone at around 0.5s. 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 splashed steel in the trumpet is reduced due to gravity. The normalized maximum wall shear stress then increases again as splashed steel in the trumpet falls back and starts filling the runners in the gating system. Around 1.5s, the steel enters the mold accompanied with a high
The 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 of the filling process.

![Normalized Maximum Wall Shear Stress](image)

**Fig. 25.** Normalized maximum wall shear stress variation with filling time of the model without a placement of swirl blades.

The possible regions where the maximum wall shear stress occurs during the initial filling process in the model without a placement of swirl blades are indicated in the **Figure 26.** 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 10.** 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 presents with more than $0.9\tau_{w \text{ peak}}$ of the maximum wall shear stress, which lasts for 0.1s. The normalized maximum wall shear stress ranges between $0.55\tau_{w \text{ peak}}$ 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 0.6s. The total simulation time for the filling process is 5s. Therefore, it lasts for 4.3s 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 (RI, RII, UI, 13, III2 and III3). A recent experimental study by Ragnarsson et al. 10) showed that the surface of a runner had been severely damaged by the mechanical force during the filling process. Furthermore, big macro inclusions generated by the flushing-off horizontal runner were 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 the magnitude of the wall shear stress and the exposure time. The erosion of the refractory surface formed with a low wall shear stress value in
Singh et al. work [11]. However, the wall shear stress is not easy to optimize, but it should be kept as low as possible when designing a new runner geometry.

Fig. 26. Maximum wall shear stress regions at the bends in the runner channel, see Fig. 3.

Table 10. Statistics of normalized maximum wall shear stress.

<table>
<thead>
<tr>
<th>Normalized Maximum Wall Shear Stress ($\tau_w$)</th>
<th>Regions</th>
<th>t (s)</th>
<th>t/t₀ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9$\tau_{w\text{ peak}}$ ≤ $\tau_w$</td>
<td>I₂/I₁</td>
<td>0.1</td>
<td>2</td>
</tr>
<tr>
<td>0.75$\tau_{w\text{ peak}}$ ≤ $\tau_w$ &lt; 0.9$\tau_{w\text{ peak}}$</td>
<td>I₂/I₃/I₁</td>
<td>0.3</td>
<td>6</td>
</tr>
<tr>
<td>0.65$\tau_{w\text{ peak}}$ ≤ $\tau_w$ &lt; 0.75$\tau_{w\text{ peak}}$</td>
<td>I₂</td>
<td>0.1</td>
<td>2</td>
</tr>
<tr>
<td>0.55$\tau_{w\text{ peak}}$ ≤ $\tau_w$ &lt; 0.65$\tau_{w\text{ peak}}$</td>
<td>I₂/I₂/I₁/I₂</td>
<td>0.2</td>
<td>4</td>
</tr>
</tbody>
</table>

$t$: the lasting time for the selected normalized maximum wall shear stress range.

$t₀$: the total simulation time for the filling process, i.e. 5s.

Fig. 27. Maximum wall shear stress variation with filling time in the model with a placement of swirl blades.
The maximum wall shear stress as a function of time in the model with a placement of swirl blades is shown in Figure 27. The possible regions where the maximum wall shear stress occurs are indicated in Figure 28. As the teeming starts, the steel falls freely in the trumpet. The steel jet strikes the center stone and causes a sudden increase of the wall shear stress at the bottom wall of the center stone (I). The splashing of steel in the trumpet exerts a transient impact on the lower part of the wall of the trumpet (II, V). This is followed by a consistent impact on the bottom wall of the center stone after 0.5s from the filling start. The splashed steel starts falling back around 1.1s. It is seen that the maximum wall shear stress regions appears in the lower part of the wall of the trumpet and spreads from the impact region to the horizontal runners close to the center stone (III). The impact region with the highest maximum wall shear stress value occurs at the swirl blades and the wall of the vertical runner close to the swirl blade (IV). During the rest of the filling process, the main regions under a high wall shear stress attack are the horizontal runner near the center stone and the lower wall of the center stone.

Generally speaking, compared to previous work, the implementation of a swirl blade can decrease and stabilize the wall shear stress value in the gating system. However, unstable fluctuations with sudden increases of the maximum wall shear stress are found at the swirl blades. The entrapped air in the runners leads to an unstable flow pattern and an instantaneous high shear stress giving a high erosion rate.

In the model with utilization of the TurboSwirl, the maximum wall shear stress value was normalized in comparison to the previous studies. The normalized maximum wall shear stress as a function of time for the present model is shown in Figure 29. It can be found that the curve for the present model follows a similar trend for the curve of the
normal gating system model. Moreover in general, the maximum wall shear stress value can be lowered with less fluctuations after the first hump formation in the mold after 2.5s from the teeming start. This results in a potential of a reduced macro inclusion formation originating from the gating system due to the flow-induced wall shear stress. However, the capability of suppressing the wall shear stress value fluctuations for the present model is not as good as that when using the swirl blades inserted at the bottom of the vertical runners.

The possible regions where the maximum wall shear stress takes place can be seen in Figure 30. The maximum wall shear stress region occurs in the lower part of the trumpet. This is due to that the introduction of the TurboSwirl leads to an increased macroscopic flow resistance in the runners, which results in that more splashed steel resides in the trumpet. However, this also alleviates the flow-induced wall shear stress exerted on the horizontal runners at the center stone. It thus reduces its impact region profile and its value on the horizontal runners at the center stone, as shown in Figure 31. At 5s from the teeming start, the highest maximum wall shear stress value exerted on the center stone in the TurboSwirl modified gating system can be reduced by 82.1% compared to that in the normal gating system in the previous study. When the ferrostatic pressure gradually builds up in the molds, the swirling steel flow in the TurboSwirl causes the entrapped air to have a swirling motion in the upper section of the TurboSwirl. This results in that the formation of a maximum wall shear stress region takes place at the upper part of the TurboSwirl and at the lower part of the vertical runner close to the TurboSwirl. Moreover, the highest maximum wall shear stress value exerted on the TurboSwirl can be reduced by 21.7% compared to that imposed on the swirl blades in the previous study by the authors. Therefore, considering the possible flow-induced erosion by the wall shear stress, a special attention should be made in choosing refractory in the lower part of the trumpet, the upper part of the TurboSwirl and the lower part of the vertical runner close to the TurboSwirl.
Fig. 30. Maximum wall shear stress regions at the bends in the runner channel, see Fig. 5.

Fig. 31. Bottom-viewed contour of maximum wall shear stress at the center stone with a a) normal gating system b) TurboSwirl modified gating system at 5s from the teeming start.
5.4. Removal of Non-metallic Inclusions using TurboSwirl

Although generations of researchers have been trying to reduce the non-metallic inclusions generation in gating systems, it is still not possible to fully eliminate them. However, the presence of TurboSwirl creates new possibilities. Here, a reduced model integrated with TurboSwirl was investigated with a DPM model. A reduced radius of 60mm was also adopted for the component. After 4s from the start of the filling process, particles were injected from the inlet of the Turboswirl for 0.1s. This corresponds to an addition of 0.1g of the total mass of injection. The total simulation time for the filling process is 8s.

After 8s from the filling start, the distribution of particles with different sizes is shown in Table 11. It can be found that the distribution of particles in the x-y plane, which is the radial direction of mold, generally has a diameter of 38-40cm. This is nearly equal to the half of the mold diameter, which is 84.6cm. However, it is also shown that the particles having a 30µm diameter are distributed with a diameter of 49-53cm, which is much larger than for the other diameters. In the z-direction, which is the axial direction of mold, it can be seen that the particles with a diameter of 200µm have the smallest range among others. In the present work, the size of particles is larger than 10⁻⁶m. Therefore, the process can be studied with Newtonian mechanics. Here, the terminal velocity \(v_t\) in Stokes’ law is only used for comparison though it is generally applied in a laminar flow.

By considering the terminal velocity, which is shown in Table 12, it can be found that the particles having a diameter of 200µm have the highest velocity value of 1.1cm/s. This means that the particles of a large size can be distributed close to the interface between the steel and mold flux by using Turboswirl. Thus, it promotes the removing rate of large non-metallic inclusions to the mold flux during the uphill teeming process.

<table>
<thead>
<tr>
<th>Diameter (µm)</th>
<th>2</th>
<th>10</th>
<th>30</th>
<th>100</th>
<th>200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle x-position distribution range (mm)</td>
<td>386</td>
<td>382</td>
<td>529</td>
<td>379</td>
<td>392</td>
</tr>
<tr>
<td>Particle y-position distribution range (mm)</td>
<td>377</td>
<td>377</td>
<td>493</td>
<td>377</td>
<td>398</td>
</tr>
<tr>
<td>Particle z-position distribution range (mm)</td>
<td>100</td>
<td>94</td>
<td>101</td>
<td>80</td>
<td>35</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Diameter (µm)</th>
<th>2</th>
<th>10</th>
<th>30</th>
<th>100</th>
<th>200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terminal velocity (m/s)</td>
<td>1.07E-06</td>
<td>2.68E-05</td>
<td>2.41E-04</td>
<td>2.68E-03</td>
<td>1.07E-02</td>
</tr>
</tbody>
</table>
As has been discussed in the previous research by the authors, the component can be served as a ‘collector’, which prolongs the residence time of inclusions and promotes the inclusion separation from steel. Therefore, the residence time for inclusions in the TurboSwirl also needs to be investigated when the DPM model is applied. The results are shown in Figure 32. It can be seen that the utilization of TurboSwirl can significantly increase the residence time for inclusions of a smaller size. For inclusions with a diameter of 2µm, the residence time can be up to 3.7s. It results from a very low terminal velocity in both the axial (v_t) and radial (v_t') directions. The modified terminal velocity in the radial direction is determined by the centripetal acceleration. The profile of the centripetal acceleration for the present model is shown in Figure 33. It can be seen that the centripetal acceleration can reach a value of 59.3m/s², which is more than five times higher than the gravitational acceleration. Therefore, the centripetal acceleration has a very strong influence on gathering non-metallic inclusions towards the rotational center of a swirling flow. The comparison of the maximum modified terminal velocity using a TurboSwirl can be seen in Table 13. Although the modified terminal velocity in the radial direction can be increased by six times compared to the terminal velocity in the axial direction, the tendency for particles of a 2µm diameter to gather towards the center and leaving for the mold is still very weak. Hence, the swirl generator component can be used as a ‘collector’ for non-metallic inclusions with a small size.
Fig. 33. Centripetal acceleration profile in TurboSwirl.

Table 13. Maximum modified terminal velocity for particles of different sizes.

<table>
<thead>
<tr>
<th>Diameter (µm)</th>
<th>2</th>
<th>10</th>
<th>30</th>
<th>100</th>
<th>200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terminal velocity (m/s)</td>
<td>6.48E-06</td>
<td>1.62E-04</td>
<td>1.46E-03</td>
<td>1.62E-02</td>
<td>6.48E-02</td>
</tr>
</tbody>
</table>

The non-metallic inclusions can also be removed due to turbulent collisions. As mentioned above, a well-designed gating system can promote turbulent collisions by properly increasing the turbulence dissipation rate and the number concentration of inclusions in a relatively small volume. Nowadays, it is a trend that some steel companies try to reduce the size of inclusion to an even smaller scale, i.e. a sub-micron size. Meanwhile, it is also necessary to remove non-metallic inclusion of a larger size, i.e. in the order of millimeter. Although the particle size of 200µm is larger than the Kolmogorov scale in the present model, recent experimental studies have shown that the acceleration and velocities of inertial particles with sizes larger than the Kolmogorov length scale in an intense turbulent flow can still be characterized by introducing a correction due to the particle Reynolds number. Therefore, inclusions with a diameter of 2µm and 200µm are investigated for both a setup with swirl (TB) and a setup with no swirl (L).

The average dissipation rate in the gating system during the filling process is shown in Figure 34. It can be seen that the average dissipation rate in a swirl setup is about 40% higher than that in a setup with no swirl, which can promote the removal of non-metallic inclusions due to turbulent collisions. In addition, it can also be noticed that the dissipation rate decreases as the filling proceeds. This indicates that the removal efficiency is reduced when the ferrostatic pressure builds up in mold. A comparison of the range of dissipation rate is shown in Table 14. It can be seen that the range of dissipation rate for the no swirl setup is much larger than that for the swirl setup. This
means that a much calmer filling condition is achieved in the swirl setup compared to the setup with no swirl.

![Graph showing dissipation rate over time](image)

**Fig. 34.** Average dissipation rate in swirl setup (TB) and no swirl setup (L) for 2 and 200µm inclusion sizes.

<table>
<thead>
<tr>
<th>Table 14. Comparison of the range of dissipation rate for 2µm inclusion size.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
</tr>
<tr>
<td>--------</td>
</tr>
<tr>
<td>Minimum dissipation rate (m²/s³)</td>
</tr>
<tr>
<td>Maximum dissipation rate (m²/s³)</td>
</tr>
</tbody>
</table>

The number concentration of non-metallic inclusions is another important factor which determines the collision rate of inclusions due to turbulent collisions. In the swirl setup, it can be divided into three parts, i.e. a generation part (component), a developing part (vertical runner) and a result part (mold). The developing part is of great interest to study as it is an essential region to control the distribution of inclusions as is shown in Figure 35. Owing to the nature of a swirling flow, the profile of the inclusion population in a vertical runner is different from that in a no swirl setup, as can be seen in **Figure 36**. Here, the percentage represents the inclusion population in the vertical runner out of the total inclusion population injected into the model. It can be seen that the inclusion population in the vertical runner of a no swirl setup decreases continuously whereas a mono-modal result appears in the vertical runner of a swirl setup due to a swirling flow. In the vertical runner of a no swirl setup, a higher value presents for particle with a diameter of 200µm. This results from a recirculation region in the elbow of the runners, which is due to an uneven flow distribution. In the swirl setup, the component prolongs the residence time for inclusions in the TurboSwirl. This leads to a more even profile for inclusions entering the vertical runner. In addition, the centripetal acceleration promotes non-metallic inclusions gathering towards the rotational center, which results in a nonlinear increase of the profile.
Due to the nature of a swirling flow, it causes the non-metallic inclusions to have a centering movement. An evaluation method was used based on the diameter variation of the analyzed volume in the vertical runner. The volume diameter is analyzed by 1cm, 2cm and 3cm in a concentric way. The diameter of the vertical runner is 45mm. The profile of inclusion population evolution in the vertical runner is studied. The results for 200µm and 2µm are shown in Figure 37 and Figure 38, respectively. It can be seen that a maximum value of 48% out of the total inclusion population of a 200µm size in the vertical runner can be concentrated in the volume that have a diameter of 1cm. Moreover, 51% of that for inclusions of a 2µm diameter. Here, the maximum efficiency takes place. In addition, inclusions of a 200µm size can be concentrated early. However, only 16% and 1.1% of the total inclusion population of sizes 200µm and 2µm, respectively, are concentrated in the analyzed volume center of 1cm in diameter. This, when the peak value of inclusion population occurs in the vertical runner. Considering the peak number concentration of inclusions within a diameter of 1cm, it occurs at 4.6s.
for inclusions of a 200µm diameter with a 33.7% value and at 4.8s for 2µm particles with a 34.8% value. Hence, a further optimization of the non-metallic inclusions concentration in the center is suggested in future work.

![Figure 37](image)

**Fig. 37.** Inclusion population evolution for inclusions of 200µm in the vertical runner.

![Figure 38](image)

**Fig. 38.** Inclusion population evolution for inclusions of 2µm in the vertical runner.

The profile of the number concentration of non-metallic inclusions within a diameter of 1cm of the vertical runner axis is shown in **Figure 39**. It can be found that the number concentration for the no swirl setup decreases very fast due to a lack of a centripetal acceleration. However, in the vertical runner, the number concentration for the swirl setup can reach up to 11.4% for inclusions of a 200µm size and 5.1% for inclusions of a 2µm diameter out of the total non-metallic inclusions presented in the gating system. It can clearly be seen that the utilization of TurboSwirl can increase the number concentration of non-metallic inclusions in the gating system, especially for inclusions of large sizes. Therefore, the collision rate of inclusions due to turbulent collisions can also be enhanced.
Fig. 39. Number concentration of non-metallic inclusions within a diameter of 1cm of the vertical runner axis.

5.5. Plant Trials with Utilization of Swirl Blades

5.5.1. Teeming Process at Plant Trials
The results of teeming process are based on the corresponding video files from the HD-video recorder.

Reference 1
Teeming started at 0s of the recording time. After 18s from the teeming start, the ladle outlet was centered at the trumpet. The steel entered the mold 1s later. The steel surface reached the lowest bag of the lower mold powder packages at 1min05s from the teeming start. The lower mold powder packages started floating up at 1m10s. At 1min40s from the teeming start, the upper mold powder packages started to float up and burn. The open-eye formed with a smaller size. At 3min10s from the teeming start, the open-eye disappeared. At 3min12s, the mirror was removed. At 6min33s from the teeming start, the ladle was moved away from the trumpet. At 8min10s, the teeming process finished.

Parallel placement of swirl blades (PA)
The ladle was moved to the trumpet at 27s from the teeming start. The steel entered the mold 3s later. At 34s from the teeming start, the lowest bag of the lower mold powder packages started to melt. At 38s, the middle bag of the lower mold powder packages started to melt. The steel surface reached the highest bag out of the three bags of the lower mold powder packages at 1min05s. At 1min48s, the steel surface reached the lowest bag of the upper mold powder packages. The open-eye stayed at the center of the mold. The mold flux distributed with a symmetrical pattern. But there were more mold flux residing at the location where the mold powder bags were initially placed. As the teeming proceeded, this phenomenon became more prominent with an oval-shaped
mold flux distribution. The mirror was removed at 3min55s. At 7min28s from the teeming start, the ladle was moved away from the trumpet. Finally, the teeming finished at 8min47s.

**Parallel placement of swirl blades (PB)**
The teeming process started at 50s from the video start. At 1min19s, the ladle was centered to the trumpet. The steel entered the mold at 1min35s. The steel surface reached the lower mold flux bags, which had a height of 10cm and with an amount of 2 x 2kg at 2min20s. At 2min57s, the steel surface reached the upper bags which had a height of 30cm and with an amount of 3 x 2kg. At 3min30s, the mold flux was distributed with an oval shape. More mold flux was located at the side where 3 bags initially hung. There was more mold flux residing at the location where the mold powder bags initially were placed. Furthermore, less mold flux at the other locations where no mold powder bags hung from the beginning. This phenomenon can be observed from 3min53s to 5min14s in the video. The mirror was removed at 5min38s. At 9min28s, the teeming rate was reduced and the ladle was moved away from the trumpet. At 11min28s, the teeming was finished.

5.5.2. Open-Eye Formation

**Reference 1**
The open-eye stays at the center. It has no contact with the mold walls. The size of the open-eye decreases till the steel surface was almost covered by the mold powder. The evolution process of the open-eye in reference1 can be seen from **Figure 40** to **Figure 42**. In **Figure 40**, the mold powder bags were hung at a similar height in the mold before steel enters the mold. After a short while, the mold powder bags released the mold flux without burning to flame. Meanwhile, the open-eye formed with a smaller size as can be seen in **Figure 41**. Later, the mold powder bags floated on the top of the flux layer and flamed as shown in **Figure 42**.

![Fig. 40. Placement of mold powder bags in reference 1.](image-url)
Parallel placement of swirl blades (PA)
The open-eye stays at the center. It has no contact to the wall of the molds. The size of the open-eye increases as the filling continues. This result may be due to that the amount of mold powder is conservative and that the diameter of the mold increases as the teeming proceeds. The swirling effect also contributes to the increase of the open-eye. An unevenness of the mold powder distribution can be observed and it has an oval shape. The site where the mold powder bags are located contains more mold powder. The evolution process of the open-eye in PA can be seen from Figure 43 to Figure 45.
Parallel placement of swirl blades (PB)
The open-eye stays at the center. It has no contact to the wall of the molds. Furthermore, the size of the open-eye increases as the filling continues. This may be due to that the amount of mold powder is conservative and that the diameter of mold increases as the teeming proceeds. The swirling effect also contributes to an increased open-eye. An unevenness of the mold powder distribution can be observed and it has an oval shape. The site where the mold powder bags were located has more mold powder. Moreover, the site where three bags were located contains more mold powder. The evolution process of the open-eye in PB can be seen from Figure 46 to Figure 48. The mold powder bags were hung at different heights in the beginning of the casting. The steel enters the mold with a small amount of splashed droplets. In the meantime, some droplets fall down into the mold from the ladle teeming stream due to the turbulence. This can be seen in Figure 46. Later, the lower packages of mold powder were fully released while the residual of higher packages floated on the top of the mold flux layer as shown in Figure 47. In addition, some freckle-like dark spots can be observed in the open-eye region, as seen in Figure 48.
5.5.3. Surface Quality
All the molds during the plant trials are used molds. For each trial, the surface quality of the mold and ingot were evaluated with respect to the influence of using a swirl blade at the vertical runner on the mold flux lubrication pattern during the uphill teeming process.

Reference 1
The ingots of reference 1 were directly placed at the yard after stripping without a further heat treatment. Hence, it was easy to measure and analyze the surface quality of the ingots. As can be seen in Figure 49 to Figure 51, no abnormal erosion on the ingot surface could be detected. In addition, the trace of mold flux ripples was in an interval
between 5-10mm. Moreover, there was no damage on the inner surface of the mold after the uphill teeming process, as shown in Figure 52.

Fig. 49. Surface quality of ingot in reference 1.

Fig. 50. Surface quality of ingot in reference 1.

Fig. 51. Surface quality of ingot in reference 1.
Parallel placement of swirl blades (PA)
The duplex stainless steel has a limited ideal hot forming temperature range. Therefore, an immediate heat treatment was required after stripping at night, due to the heats chemical composition. It was not possible to observe the ingots carefully and to measure the surface at room temperature. As shown in Figure 53, there was no existence of an abnormal erosion on the ingot surface. In addition, no damage on the inner surface of the mold was observed after the casting process, as is shown in Figure 54.
Parallel placement of swirl blades (PB)
An immediate heat treatment was required after stripping due to its composition. Therefore, it was not possible to observe the ingots carefully and to measure the surface quality at room temperature. As can be seen in Figure 55, there was no existence of an abnormal erosion on the ingot surface. Moreover, it is hard to find the trace of mold flux ripples on the ingots surface. This indicates that the utilization of the swirl blade at the vertical runner can result in a more even lubrication of mold flux between the ingot surface and the wall of mold compared to a normal casting. Furthermore, no damage on the inner surface of the mold was found after the teeming process, as shown in Figure 56.
Fig. 56. Surface quality of mold in PB.

5.5.4. Sample Analysis

The samples from industrial trials performed in November 2011 with utilization of a parallel placement of swirl blades in the gating system with implementation of nozzle B were investigated by using Scanning Electron Microscope (SEM). Two representative samples, i.e. B1-12109 (ingot bottom) and T1-12109 (ingot top), were chosen in the study. The aim of the sample analysis was to qualitatively determine the effects of using a parallel placement of swirl blades with implementation of the new entrance nozzle with a flaring angle of 52 degree on the morphological shape and the composition of the inclusions.

First of all, the composition of the metal matrix was analyzed as shown in Table 15. Later, the inclusions morphology and their compositions from Sample T1-12109 and B1-12109 were studied by using SEM/EDS, as can be seen from Table 16 to Table 19.

**Table 15. Steel composition in mass percent (%)**

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>C</th>
<th>O</th>
<th>F</th>
<th>Mg</th>
<th>Al</th>
<th>Si</th>
<th>S</th>
<th>Ca</th>
<th>Ti</th>
<th>Cr</th>
<th>Mn</th>
<th>Fe</th>
<th>Ni</th>
<th>Mo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matrix</td>
<td>3.71</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>22.59</td>
<td>-</td>
<td>62.70</td>
<td>8.51</td>
<td>2.50</td>
<td></td>
</tr>
</tbody>
</table>

As can be seen in Table 16, the morphological information of the inclusions from sample T1 shows that the inclusions have a length between 4.7μm and 24μm and a width between 3.55μm and 12.6μm. This means that no size larger than 24μm was observed. In addition, some inclusions show a structure which contains a light region in the inner layer and a darker region at outer layer. The compositions of the inclusions from sample T1 is illustrated in Table 17. The most frequent elements in the inclusions are oxygen, chromium, manganese, aluminum and carbon. The high content of chromium in the inclusions can be observed. In addition, more complex compositions of inclusions are presented in the dark region.
In addition, some inclusions show a structure which consists of two distinct regions, an outer light region and a darker region in the inner layer. Moreover, a dark region also presents at the center in some inclusions. The compositions of the inclusions from sample B1 is illustrated in Table 19. The most frequent elements in the inclusions are oxygen, chromium, manganese, aluminum, carbon and magnesium. A high content of chromium in the inclusions can also be observed. The present of magnesium may be due to the flow-induced wall erosion in the gating system or from ladle refractory. In addition, more complex compositions of inclusions are presented in the dark region.

### Table 16. Inclusion Morphology in T1-12109

<table>
<thead>
<tr>
<th>No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>L (µm)</td>
<td>5.9</td>
<td>8.57</td>
<td>8.57</td>
<td>4.7</td>
<td>10.03</td>
<td>10.81</td>
<td>9.19</td>
<td>15</td>
<td>9.88</td>
<td>24</td>
<td>15.5</td>
</tr>
<tr>
<td>W (µm)</td>
<td>5.6</td>
<td>5.57</td>
<td>6.64</td>
<td>4.46</td>
<td>7.7</td>
<td>5.97</td>
<td>3.55</td>
<td>12.6</td>
<td>8.24</td>
<td>5.2</td>
<td>10.32</td>
</tr>
<tr>
<td>Shape</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
<td><img src="image9.png" alt="Image" /></td>
<td><img src="image10.png" alt="Image" /></td>
<td><img src="image11.png" alt="Image" /></td>
</tr>
</tbody>
</table>

### Table 17. Composition of T1-12109 in Mass Percent (%)

<table>
<thead>
<tr>
<th>No.</th>
<th>type</th>
<th>C</th>
<th>O</th>
<th>F</th>
<th>Mg</th>
<th>Al</th>
<th>Si</th>
<th>S</th>
<th>Ca</th>
<th>Ti</th>
<th>Cr</th>
<th>Mn</th>
<th>Fe</th>
<th>Ni</th>
<th>Mo</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Light</td>
<td>2.89</td>
<td>33.16</td>
<td>-</td>
<td>-</td>
<td>4.56</td>
<td>-</td>
<td>-</td>
<td>1.11</td>
<td>35.11</td>
<td>23.17</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>Light</td>
<td>2.27</td>
<td>31.96</td>
<td>-</td>
<td>-</td>
<td>4.63</td>
<td>-</td>
<td>-</td>
<td>0.88</td>
<td>34.31</td>
<td>22.14</td>
<td>3.82</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>Light</td>
<td>3.03</td>
<td>33.10</td>
<td>-</td>
<td>-</td>
<td>5.38</td>
<td>-</td>
<td>-</td>
<td>0.49</td>
<td>34.51</td>
<td>23.3</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>Light</td>
<td>3.08</td>
<td>34.99</td>
<td>-</td>
<td>-</td>
<td>5.63</td>
<td>-</td>
<td>-</td>
<td>0.71</td>
<td>32.86</td>
<td>22.73</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>Light</td>
<td>3.95</td>
<td>34.40</td>
<td>-</td>
<td>-</td>
<td>7.51</td>
<td>-</td>
<td>-</td>
<td>0.59</td>
<td>30.63</td>
<td>22.92</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>Light</td>
<td>2.77</td>
<td>32.91</td>
<td>-</td>
<td>-</td>
<td>3.87</td>
<td>-</td>
<td>-</td>
<td>0.92</td>
<td>33.21</td>
<td>20.73</td>
<td>5.05</td>
<td>0.54</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>Dark</td>
<td>1.58</td>
<td>41.74</td>
<td>3.12</td>
<td>1.32</td>
<td>5.82</td>
<td>9.57</td>
<td>0.26</td>
<td>18.29</td>
<td>-</td>
<td>3.48</td>
<td>13.03</td>
<td>1.78</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>Light</td>
<td>2.72</td>
<td>37.21</td>
<td>-</td>
<td>1.13</td>
<td>10.08</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>26.88</td>
<td>21.98</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>Dark</td>
<td>2.03</td>
<td>20.19</td>
<td>2.36</td>
<td>0.44</td>
<td>4.09</td>
<td>4.87</td>
<td>0.63</td>
<td>7.50</td>
<td>-</td>
<td>15.01</td>
<td>5.81</td>
<td>32.55</td>
<td>4.11</td>
<td>-</td>
</tr>
<tr>
<td>10</td>
<td>Dark</td>
<td>1.89</td>
<td>42.94</td>
<td>-</td>
<td>1.17</td>
<td>8.41</td>
<td>10.41</td>
<td>1.17</td>
<td>12.05</td>
<td>0.73</td>
<td>16.89</td>
<td>18.43</td>
<td>3.43</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>11</td>
<td>Light</td>
<td>3.34</td>
<td>36.13</td>
<td>-</td>
<td>1.58</td>
<td>8.55</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>29.72</td>
<td>20.69</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>12</td>
<td>Dark</td>
<td>1.98</td>
<td>26.60</td>
<td>-</td>
<td>0.94</td>
<td>6.23</td>
<td>7.69</td>
<td>0.50</td>
<td>8.78</td>
<td>-</td>
<td>12.90</td>
<td>6.21</td>
<td>25.33</td>
<td>2.84</td>
<td>-</td>
</tr>
</tbody>
</table>

As shown in Table 18, the morphological information of the inclusions from sample B1 shows that the inclusions have a length of between 8.48µm and 22µm and a width between 6.7µm and 15.14µm. This means that no size larger than 22µm was observed.

In addition, some inclusions show a structure which contains a light region in the inner layer and a darker region in the outer layer. Moreover, a dark region also presents at the center in some inclusions. The compositions of the inclusions from sample B1 is illustrated in Table 19. The most frequent elements in the inclusions are oxygen, chromium, manganese, aluminum, carbon and magnesium. A high content of chromium in the inclusions can also be observed. The present of magnesium may be due to the flow-induced wall erosion in the gating system or from ladle refractory. In addition, more complex compositions of inclusions are presented in the dark region.

### Table 18. Inclusion Morphology in B1-12109

<table>
<thead>
<tr>
<th>No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>L (µm)</td>
<td>8.48</td>
<td>10</td>
<td>16.07</td>
<td>21.43</td>
<td>13.7</td>
<td>22</td>
</tr>
<tr>
<td>W (µm)</td>
<td>6.7</td>
<td>10</td>
<td>11.8</td>
<td>13.43</td>
<td>13.7</td>
<td>15.14</td>
</tr>
<tr>
<td>Shape</td>
<td><img src="image12.png" alt="Image" /></td>
<td><img src="image13.png" alt="Image" /></td>
<td><img src="image14.png" alt="Image" /></td>
<td><img src="image15.png" alt="Image" /></td>
<td><img src="image16.png" alt="Image" /></td>
<td><img src="image17.png" alt="Image" /></td>
</tr>
</tbody>
</table>
Table 19. Composition of B1-12109 in Mass Percent (%)

<table>
<thead>
<tr>
<th>No.</th>
<th>type</th>
<th>C</th>
<th>O</th>
<th>F</th>
<th>Mg</th>
<th>Al</th>
<th>Si</th>
<th>S</th>
<th>Ca</th>
<th>Ti</th>
<th>Cr</th>
<th>Mn</th>
<th>Fe</th>
<th>Ni</th>
<th>Tl</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Light</td>
<td>3.80</td>
<td>34.87</td>
<td>-</td>
<td>-</td>
<td>4.24</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.74</td>
<td>33.70</td>
<td>22.65</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>Light</td>
<td>4.85</td>
<td>37.29</td>
<td>-</td>
<td>0.68</td>
<td>5.48</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.48</td>
<td>30.84</td>
<td>20.39</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>Light</td>
<td>-</td>
<td>38.03</td>
<td>0.79</td>
<td>8.72</td>
<td>0.71</td>
<td>-</td>
<td>1.22</td>
<td>-</td>
<td>28.89</td>
<td>21.65</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>Light</td>
<td>3.33</td>
<td>42.34</td>
<td>-</td>
<td>0.58</td>
<td>6.71</td>
<td>7.62</td>
<td>-</td>
<td>12.30</td>
<td>-</td>
<td>11.74</td>
<td>12.50</td>
<td>2.89</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>Light</td>
<td>3.22</td>
<td>35.38</td>
<td>-</td>
<td>-</td>
<td>5.38</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.56</td>
<td>32.19</td>
<td>23.27</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>Light</td>
<td>2.24</td>
<td>36.15</td>
<td>-</td>
<td>1.37</td>
<td>6.44</td>
<td>0.67</td>
<td>-</td>
<td>0.90</td>
<td>-</td>
<td>31.94</td>
<td>20.08</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>Medium</td>
<td>-</td>
<td>39.51</td>
<td>1.22</td>
<td>9.73</td>
<td>9.23</td>
<td>-</td>
<td>9.86</td>
<td>-</td>
<td>15.36</td>
<td>14.90</td>
<td>-</td>
<td>-</td>
<td>0.19</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>Dark</td>
<td>2.24</td>
<td>36.22</td>
<td>3.09</td>
<td>1.02</td>
<td>4.81</td>
<td>7.10</td>
<td>0.30</td>
<td>11.44</td>
<td>-</td>
<td>12.82</td>
<td>12.04</td>
<td>7.98</td>
<td>0.94</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>Dark</td>
<td>3.30</td>
<td>43.53</td>
<td>-</td>
<td>0.96</td>
<td>7.79</td>
<td>11.96</td>
<td>-</td>
<td>17.64</td>
<td>-</td>
<td>2.92</td>
<td>10.46</td>
<td>1.45</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

As shown in the tables above, the utilization of a parallel placement of swirl blades with an implementation of the new entrance nozzle with a flaring angle of 52 degree results in the following features. Firstly, from a morphology aspect, the inclusions from the B series have a spherical and round shape. Some inclusions from the T series have an elongated shape with a high aspect ratio, even though most of them have a spherical shape. In addition, no inclusion size larger than 30μm was found in neither of the samples. Furthermore, the compositions of the inclusions in both samples are complicated. Most of the inclusions contain a darker region in the outer layer and a lighter region in the inner layer. However, the inclusions from the B series also contain a darker region in the center of the lighter region in the inner. This may result in a higher density of the inclusions. Moreover, fluoride, sulfur and titanium appear more frequently in the T series than in the B series.
6. Discussion

The results from Supplement 1 and Supplement 2 summarize that, it is desirable to achieve a calm flow in the mold filling process. This results in less entrapped mold flux in the ingots and therefore less chances for reoxidation and a cleaner steel. It is also important to study the possibilities to obtain an inclusions control mechanism in the gating system, which reduces non-metallic inclusion generation. More specifically, due to the wear on the refractory materials and the growth and transportation of inclusions.

It is found that the implementation of a swirl blade in a runner channel can reduce the fluctuations of the hump height by 79% compared to a case without a swirl blade implementation, after 4.5s from the teeming start. Furthermore, it is also possible to decrease the highest maximum wall shear stress value by 54% and to reduce the fluctuations of the maximum wall shear stress value by 69% after 3.5s from the teeming start. However, the initial filling conditions in the molds are degraded. Overall, it is still promising to use swirl blades in uphill teeming casting. One possible solution to improve the benefits of using a swirling flow is to extend the vertical runner length. This helps the flow pattern to become fully developed, as shown in Figure 57. It can be seen in both cases, parallel and perpendicular placements of the swirl blade, that a more even axial velocity profile is achieved by increasing the vertical runner length from 20cm to 30cm.

Fig. 57. Axial velocity profile at the entrance of mold with different height of vertical runner in steady state of reduced geometry. a) a parallel swirl blade placement with a 20cm height of vertical runner; b) a parallel swirl blade placement with a 30cm height of vertical runner; c) a perpendicular swirl blade placement with a 20cm height of vertical runner; d) a perpendicular swirl blade placement with a 30cm height of vertical runner;
One should keep in mind that the orientation of a swirl blade is important. It will affect the flow pattern, which is coupled to the design of the gating system. An improper placement of the swirl blade can cause reverse effects related to the flow pattern, inclusion generation and distribution, and the mold flux distribution.

**Supplement 3** focused on the teeming process and the flow pattern simulations showed that the initial splashing of droplets takes place when steel passes through the swirl blade and enters the mold. This can be seen in **Figure 14**. The initial filling moment recorded by a HD-recorder also captured the initial droplets splashed when steel entered the mold as shown in **Figure 58**. The flow pattern simulated by using the CFD technology was thus verified by the observations in the plant trials.

![Initial splashing of droplets](image)

Fig. 58. Initial splashing of droplets

In addition, the open-eye evolution at the initial filling moment was also captured by the HD-recorder. It shows a mold flux distribution with a ring shape and that the open-eye stays at the center of the mold, as can be seen in **Figure 44** and **Figure 47**. The CFD simulations also predicted a similar phenomenon of mold flux distribution as shown in **Figure 59** and **Figure 60**. As shown in **Figure 59**, the mold flux (red) was distributed by the steel flow (yellow) with a ring shape. The information about the thickness of the mold flux layer can be found in **Figure 60**. It can be seen that the mold flux distribution in the simulations fit the actual mold flux distribution in the teeming process quite well.
The complex compositions of the inclusions in the samples may be verified by the simulation as mentioned above. It may be due to the present of a swirling flow introduced by the swirl blade along with its interaction with the mold flux during filling process. The simulation shows that a much higher inclusion concentration is present in the case with a parallel placement of a swirl blade in comparison to a normal gating system without utilization of a swirl blade, as shown in Figure 61. The maximum concentration of inclusions presented in Figure 61 for a normal gating system and a parallel placement of a swirl blade are 2.17kg/m³ and 7.57kg/m³, respectively. This means that the utilization of a swirl blade in the vertical runner may promote the agglomeration/aggregation of inclusions during the uphill teeming process.
In Supplement 4 and Supplement 5, it was found that with proper modifications of the geometry of the refractory at the elbow of the runners near the mold by using the axial velocity of the flow in the horizontal runners, to create the tangential velocity, can generate a swirling flow. The introduction of the TurboSwirl can further improve the initial filling conditions during the uphill teeming process. The tendency of mold flux entrapment during the mold filling process may also be determined by using the Weber number.\textsuperscript{16) Here, the critical value of a mold flux entrapment is 12.3. By using the same method and assumptions, the results is shown in Figure 62. It can be seen that the utilization of the TurboSwirl can reduce the risk for a mold flux entrapment within about 1s after the steel jet enters the mold.}

The effect of the radius (R) and mold entrance nozzle length (H) variation on the hump height ($H_h$) as well as on the difference between hump height and surface height ($H_h - H_s$) can be seen in Figure 63 and Figure 64, respectively. It can be found that the possibility
of mold flux entrapment can further be reduced by properly reducing the radius of TurboSwirl or by using a proper tapered mold entrance nozzle with an adequate developing region.

Fig. 63. Effect of radius and mold entrance nozzle length variation on hump height.

Fig. 64. Effect of radius and mold entrance nozzle length variation on difference between hump height and surface height.

It was also found that the uneven profile of the inclusion population evolution and the maximum efficiency of inclusion removal can further be improved.
7. Conclusions

In **Supplement 1**, the study was aimed at implementing a full scale gating system and molds in a mathematical model based on industrial trials. 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 study in **Supplement 1**:  
(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 when 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 they prevail during a long time;  
(4) The simulations show that the (hump height-surface height) difference is approximate 80mm as the steel enters the mold and then decreases to approximate 40mm 3.5 seconds later.

In **Supplement 2**, the study focused on the flow pattern of steel in the gating system and molds with swirl blades inserted at the bottom of the vertical runners with different orientations during the initial stage of the mold filling process. Based on the orientation relationship between the runner and the bottom edge of the swirl blades, a parallel placement and a perpendicular placement of the swirl blades were simulated. The following specific conclusions may be summarized from the study in **Supplement 2**:  
(1) The implementation of swirl blades gives a chaotic initial filling condition with a considerable amount of droplets being created when steel enters the molds during the first couple of seconds.  
(2) The introduction of swirl blades to the gating system results in more filled horizontal runners with less entrapped air. Compared to previous work without swirl blades, the amount of steel in the horizontal runner increases from 80.9% to 98.4% at 5s from the teeming start. In addition, a more calm filling condition with less fluctuations is achieved at the molds after a short while.  
(3) The orientation of the swirl blades affects the flow pattern of the steel. A proper placement of a swirl blade improves the initial filling conditions. In the current model, a parallel placement of the swirl blade is better than a perpendicular placement of the swirl blade. This is due to that a parallel placement of a swirl blade gives an evenly distributed mass flow of the steel.  
(4) The steel height difference (ΔH) in the present simulations with swirl blade placement is much larger with a maximum magnitude of 475mm than that in the
simulations without swirl blades with a maximum magnitude of 140mm. This is due to the increased flow resistance in the system due to the incorporation of a swirl blade.

(5) Compared to a simulation without swirl blades, a simulation with swirl blades might initially result in larger hump heights. However, it gives fewer fluctuations as the casting proceeds. This, in turn, means less risks of mold flux entrapment.

(6) The implementation of a swirl blade can decrease and stabilize the wall shear stress value in the gating system. In the model without swirl blades, the maximum wall shear stress varies in the range between 300Pa and 1200Pa after the steel enters the molds. Compared to that, the maximum wall shear stress when using swirl blades mainly has a variation in the range between 200Pa and 600Pa after the steel enters the molds. However, unstable fluctuations with sudden increases of the maximum wall shear stress are found at the swirl blades and the wall of the vertical runner close to the swirl blades. This is due to that the entrapped air in runner system passes through the swirl blades.

In Supplement 3, the experiment performed at Scana Steel focused on verifying the simulations related to the flow pattern during the uphill teeming process. During the experiment, a total number of 4 ladles were teemed. This includes two heats that were teemed using the normal gating system without using swirl blades and two heats casted with the utilization of swirl blades with a parallel placement orientation. The following specific conclusions may be summarized from the study in Supplement 3:

(1) The filling conditions were improved by using the new nozzle with a flaring angle of 52 degree compared to the old nozzle with a 62 degree flaring angle. This is verified by the videos of the teeming process captured by a HD-recorder. No flow interference occurs when steel enters the mold. Only a small amount of droplets were created due to an initial impingement between the steel and the swirl blade.

(2) All ingots could easily be removed from the molds. No additional equipment was needed during stripping and all the ingots could be stripped by their gravity.

(3) No damage to the walls of the molds. Neither could any abnormal erosion on the wall of molds be found, which was also confirmed by the operators.

(4) No distinctive defects on the ingot surface could be found. The surface of ingots was observed after stripping. There was no tendency for that the mold was burnt into the ingots. The utilization of the swirl blade at the vertical runner might have resulted in a more even lubrication mold flux between the ingot surface and the wall of mold.

(5) The inclusions from the B series show a spherical and round shape. Some of the inclusions from the T series have an elongated shape with a high aspect ratio. No inclusion size larger than 30 μm was found in both samples. The composition of the inclusions in both samples is complex. The swirl blade may promote the
agglomeration/aggregation of inclusions. Fluorine, the sulfur and titanium contents appear more frequent in the T series than in the B series.

In **Supplement 4**, the study was aimed at using a swirling flow to improve the initial filling conditions without the usage of an inserted flow control device in the gating system. The specific conclusions for the study in **Supplement 4** may be summarized as follows:

1. The initial filling conditions can further be improved with a swirling flow by using the TurboSwirl setup. A much calmer filling condition was achieved in the mold with less fluctuations.
2. A continuous negative steel height difference value appeared in the present model. The teeming rate needs to be well-controlled to adjust the splashed steel height in the trumpet due to the increased macroscopic flow resistance in the runners.
3. The hump height in the present model was lower than in the previous studies by the authors. At 6s from the teeming start, the hump height for the present model had a value of 81mm. Moreover, while the value for the hump height in the normal gating system model was 140mm. Furthermore, the value was about 100mm with the utilization of swirl blades inserted at the bottom of the vertical runners. This makes it possible to further decrease the initial position of the mold powder bags.
4. The difference between the hump height and the surface height in the present model has a maximum value of 83mm, which is the lowest maximum value among all the other models studied. The Weber number goes below 12.3 within about 1s after the steel jet enters the molds. Therefore, a lower risk of the mold flux entrapment with the utilization of the TurboSwirl, is seen.
5. The maximum wall shear stress value can generally be lowered with less fluctuations after the first hump formation in the mold after 2.5s from the teeming start. However, the capability of suppressing the wall shear stress value fluctuations for the present model is not as good as that obtained by using the swirl blades inserted at the bottom of the vertical runners. Depending on refractory material, this might not be an issue.

In **Supplement 5**, the present study focused on revealing the effects TurboSwirl has on improving steel cleanliness. It is found that the utilization of TurboSwirl can improve the steel cleanliness by reducing mold flux entrapment and increasing non-metallic inclusions collision rate from both Stokes collisions and turbulent collisions. The following specific conclusions may be summarized from the study in **Supplement 5**:

1. The possibility of mold flux entrapment can further be reduced by properly reducing the radius of TurboSwirl or a proper tapered mold entrance nozzle with an adequate developing region for the steel flow in a swirl setup. The steel cleanliness can further
be improved in the mold when the mold powder release time and the release method are adjusted to the current casting system.

(2) The removal rate of large non-metallic inclusions by mold flux in the uphill teeming process can be promoted by using TurboSwirl. For inclusions of small sizes, the component can serve as a ‘collector’, which prolongs the residence time of inclusions and promotes inclusion separation from the steel. The residence time for inclusions with a diameter of 2µm can be up to 3.7s.

(3) The utilization of TurboSwirl can promote turbulent collisions by properly increasing the turbulence dissipation rate and the number concentration of inclusions in a relatively small volume. The average dissipation rate in the swirl setup is about 40% higher than that in a setup without swirl. The maximum efficiency for gathering inclusions towards the center volume within a diameter of 1cm can be up to 48% out of the total inclusion population in the vertical runner for inclusions in size of 200µm. Moreover, 51% of that for inclusions with a diameter of 2µm. The number concentration for the swirl setup can reach up to 11.4% for inclusions of a 200µm size and 5.1% for inclusion with a diameter of 2µm. This compared to the total non-metallic inclusions present in the gating system.

In summary, the present model reveals a great potential for improving the steel cleanliness. The inclusions distribution and collision rate are related to the Kolmogorov scale in the filling process. The boundary conditions, i.e. teeming rate, has great influence in removing non-metallic inclusions in uphill teeming process. Therefore, it is highly desirable to perform plant trial or physical modeling verification for the model in future.
8. Future Work

Following points are suggested for future work:

1. To add the effects of refractory erosion due to thermal attack and chemical reactions to the ingot filling model. Also, to consider the influences owe to composition variation and surface condition of refractory. This will enhance the understanding of macro non-metallic inclusion generation from refractory in the gating system.

2. Further improve the evenness of swirling flow generated by the TurboSwirl. This means a further optimization of TurboSwirl design, e.g. inlet flow condition design, evenly increase the number of inlets, a neat gas/steel phase separation, etc.

3. To improve the removal efficiency of inclusions and a further optimization of non-metallic inclusions concentration in the center by using the TurboSwirl. The number concentration of inclusions of small sizes should further be increased in the center of the vertical runner. As the removal efficiency is related to the flow condition and inclusion characteristic, a statistic parametric study is suggested.

4. Compatible design of the base plate, which fits the modularization of refractories.

5. An in-depth study of interaction between mold powder/flux and flow pattern in the teeming process is suggested. A flow pattern coupled releasing method of mold powder bags and solid/liquid transition of mold powder/flux could be added to the ingot filling model.
References


32) Swerea KIMAB.