Effect of Swirling Blade on Flow Pattern in Nozzle for Up-hill Teaming

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Abstract

The fluid flow in the mold during up-hill teeming is of great importance for the quality of the cast ingot and therefore the quality of the final steel products. At the early stage of the filling of an up-hill teeming mold, liquid steel enters, with high velocity, from the runner into the mold and the turbulence on the meniscus could lead to entrainment of mold flux. The entrained mold flux might subsequently end up as defects in the final product. It is therefore very important to get a mild and stable inlet flow in the entrance region of the mold. It has been acknowledged recently that swirling motion induced using a helix shaped swirl blade, in the submerged entry nozzle is remarkably effective to control the fluid flow pattern in both the slab and billet type continuous casting molds. This result in increased productivity and quality of the produced steel. Due to the result with continuous casting there is reason to investigate the swirling effect for up-hill teeming, a casting method with similar problem with turbulence.

With this thesis we will study the effect of swirling flow generated through a swirl blade inserted into the entry nozzle, as a new method of reducing the deformation of the rising surface and the unevenness of the flow during filling of the up-hill teeming mold. The swirling blade has two features: (1) to generate a swirling flow in the entrance nozzle and (2) to suppress the uneven flow, generated/developed after flowing through the elbow. The effect of the use of a helix shaped swirl blade was studied using both numerical calculations and physical modelling. Water modelling was used to assert the effect of the swirling blade on rectifying of tangential and axial velocities in the filling tube for the up-hill teeming and also to verify the results from the numerical calculations. The effect of swirl in combination with diverged nozzle was also investigated in a similar way, i. e. with water model trials and numerical calculations.

KEY WORDS: swirling flow, up-hill teeming, nozzle, casting, fluid flow, modelling, CFD, LDA.
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Line Hallgren
Stockholm, December 2006
Supplements

The present thesis is based on the following papers:

Supplement 1:  “Effect of Nozzle Swirl Blade on Flow Pattern in Runner during Up-hill Teeming”  
*L. Hallgren, S. Takagi, R. Eriksson, S. Yokoya and P. Jönsson*  
Accepted for publication: ISIJ International, November 2006.

Supplement 2:  “Effect of Nozzle Type and Swirl on Flow Pattern for Initial Filling Conditions in the Mold for Up-hill Teeming”  
*L. Hallgren, S. Takagi, A. Tilliander, S. Yokoya, and P. Jönsson.*  
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2nd Nordic Symposium for Young Scientists, 22-23 Mars 2003, Stockholm, Sweden

Sohn International Symposium, 28-31 August 2006, San Diego, USA, Vol 2, p 471-484

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

1. Literature survey, major part of the writing and all of the numerical calculations, part of the water modelling.
2. Literature survey, major part of the writing and all of the numerical calculations.
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Up-hill teeming is a steel casting method where the steel is drained from the bottom of the teeming ladle into a refractory-lined runner system which feeds the steel into one or several ingot molds. Figure 1.1 (a) shows a schematic diagram of the ladle, runner system and the ingot mold. During the early stages of the mold filling a mold flux is added on top of the rising steel surface in the mold to protect the steel from reoxidation as well as act as a thermal insulator.

The flow pattern in the mold during filling has shown to be important to the quality of the steel, produced using up-hill teeming. Defects like exogenic inclusions (e.g. entrained mold flux) and surface cracks may occur in the lower regions of the ingot due to the flow pattern during the filling procedure. In the light of this, researchers have over the years tried to come up with different methods in order to reduce the velocity of the steel entering the mold. It has, for example, been shown in an earlier research that by flaring the upper diameter of the entrance by an angle of 6-12°, to the diameter of the running system, the velocity is reduced to about half of the initial value and the surface becomes more stable. This is generally used in ordinary runner systems, but the turbulent flow pattern can still cause damage to the produced ingot. Figure 1.1 (b) schematically shows a tapered inlet nozzle and the lower parts of an up-hill teeming mold.

Figure 1.1. Schematic description of (a) gating system of uphill teeming and (b) close up on the inlet nozzle.
One source of turbulence is the unevenness of the flow pattern during filling. This unevenness probably arises from the moment the ladle is opened and the melt starts to fill the runner system and is developed further as the melt passes at least two 90° bends before it enter the mold. Although the above described flaring of the nozzle does reduce the velocity of the steel that enters the up-hill teeming mold which would lead to a flatter and calmer rising steel surface, it does not produce any significant reduction in the observed unevenness of the flow.

Another reason why the turbulence is so excessive is due to the small cross-section area of the inlet. A flaring of 6-12° does not increase the cross-section area fast enough for the velocity in the runner to decrease to an acceptable velocity. The velocity is especially large at the beginning of the filling of the ingot, due to the high ferrostatic head in the ladle. Increasing the area more does not give any effect on the velocity since the fluid leaves hold of the wall and does not fill out the whole cross-section area.1)

Therefore, other measures have to be taken in order to reduce the maximum velocity of the flow. One such method which has been proven to reduce the unevenness and decreased the maximum velocity of the flow entering continuous casting molds is the introduction of a helix shaped swirl blade in the submerged entry nozzle. For a clarification of the appearance of the swirl blade, the principle of its design is shown in Figure 1.2. The use of the swirl blade is well developed in the case with continuous casting. Several articles concerning the subject have been written by Yokoya et al 5-11. The positive findings in these concerning the use of swirling flow in reducing uneven flow in continuous casting molds serves as the motivation for this work where the use of swirl blades during up-hill teeming have been investigated.

Figure 1.2. Illustration of the principle of the helix shaped swirl blade. This swirl blade was not used in the trials.
To investigate how to make the flow into the mold calmer two studies have been carried out:
The first study was about the effect of nozzle swirl blade on flow pattern in runner during up-hill teeming, which is presented in more detail in Supplement 1.

The aim of this study was to investigate how the flow pattern, manipulated by a swirl blade, may affect the unevenness of the velocity profile. The purpose of the swirl blade is to disrupt the uneven flow and to create an axis-symmetric velocity. The uneven flow is developed when the steel passes through a sharp 90° bend, see Figure 1.3. A swirl blade, shaped like a 180° twisted tape placed right after the bend, introduce the rotating motion into the flow. The experimental equipment is designed to resemble the conditions that are present at the end gate of the running system, i.e. at the entrance to the mold, of an up-hill teeming system.

![Figure 1.3. Experimental setup for water modeling of flow through runner and inlet. The measuring points (1, 2, and 3) when using the LDA system are also marked in the figure.](image-url)
In this work, the effect of introducing a rotating motion to a flow with an uneven velocity profile has been investigated using both mathematical analysis and water model studies. The mathematical analysis has been carried out using numerical modeling and measurements of the fluid velocity, at several positions, in a transparent water model have been carried out using Laser Doppler Anemometer (LDA) in order to validate the results of the computations.

The second study, effect of nozzle type and swirl on flow pattern for initial filling conditions in the mold for up-hill teeming, had the aim to investigate the flow at the entrance of the mold when using a combination of swirl generator and diverged nozzle. The design of the swirl generator may bee seen in Figure 1.4, and may resemble a turbine. This study is presented in more details in Supplement 2.

The purpose with the diverged nozzle is to increase the cross-section area of the inlet more rapidly than what a tapered nozzle do (with the, in the introduction, suggested angles). The role of the swirl generator is to create a centrifugal force, forcing the fluid against the wall of the nozzle and hence hinder the detachment of the fluid from the wall.

The second study was also investigated with aid of mathematical analysis and water models. The mathematical analyses were validated by comparing the surface features of the water model.

![Figure 1.4. Sketch of main dimensions of swirl generator.](image)
2 Experimental Work

For both the studies water models have been used. The swirl flow has been created with two different items. In the first study a swirl blade, a blade shaped like a twisted tape, see Figure 1.2, has been used and in the second study a so called swirl generator, which resembles a turbine (as can be seen in Figure 1.4) was used. The flow pattern has been analyzed with a Laser Doppler Anemometer (LDA) in the first study and with help of video recordings in the second study.

2.1 Effect of Swirl on Uneven Velocity

Measurements of the fluid velocity using the LDA method have been carried out at several positions, with and without the presence of a swirl blade, in a physical model resembling the inlet used in the up-hill teeming mold. The model consists of a transparent pipe with a 90° degree bend and the swirl blade is placed down stream of the bend. The three positions of the measuring points are shown in Figure 1.3. In the upper part of the figure the experimental setup is shown from above and the direction of the positions where the measurements were taken is marked with an arrow.

Figure 2.1.1 shows the schematic of the experimental apparatus for the water model. By using an over flow tank a constant water velocity was obtained through the pipe system. The desired swirl flow was established using a fixed swirl blade inserted into the nozzle 35 mm above the symmetry plane of the horizontal runner, as shown in Figure 1.3. The thickness of the swirl blade was 7 mm. In order to study the velocity profile without the effect of swirl, the swirl blade could be removed, without otherwise changing the system. To obtain a steady state condition at the positions of measuring, the water level in the water jacket was kept at a constant level by assistance of a secondary over-flow tank. Figure 2.1.1 shows where the measurements of the velocities have been made using the LDA. A two-dimensional 4W Ar laser system made by Dantec Inc. has been used for measuring.

In this work, a constant water velocity at the inlet of the physical model was maintained at 0.7 m/s. This velocity corresponds to the average velocity during the filling of a 4.2
The resulting Reynolds number was 28000 (for water temperature of 20°C) giving a moderately turbulent flow.

2.2 Effect of Swirl on Flow Pattern in Mold

The water model for the tests of mold filling can be seen in Figure 2.2.1. It consists of a cylinder, with a diameter of 150 mm, with the entrance at the bottom. The water model was connected to a piping system with an overflow tank shown in Figure 2.2.2. The inlet to the cylinder could be varied between a straight nozzle and a diverged nozzle, which can be seen in Figure 2.2.3. The swirl was generated by a swirl generator, shown in Figure 1.4 and the experimental setup is shown in Figure 2.2.4.

The experiment was carried out for three versions; 1, with a straight nozzle, 2, with diverged nozzle and 3 with diverged nozzle and swirl. The cylinder was filled with water from the inlet with a velocity of 0.5 m/s. During the filling of the cylinder the flow
pattern created by the flow of water from the inlet was recorded with a video camera and the height of the hump was measured from the recordings.

**Figure 2.2.1.** Outline of experimental procedure for mold filling.

**Figure 2.2.2.** Sketch of experimental setup for water model of mold filling.
Figure 2.2.3 Schematic of straight nozzle and divergent nozzle.

Figure 2.2.4. Schematic of experimental setup of nozzle and mold for experiments using a straight nozzle and a divergent nozzle.
3 Mathematical Modeling

The flow in both of the water models, in part 2.1 and 2.2, was calculated numerically using the commercial computational fluid dynamics (CFD) code FLUENT\textsuperscript{12}, which uses the finite volume method with a staggered grid to discretize the equations and linearize the equations implicitly. The calculations were made by a computer with an Intel Xeon 3.2 GHz 800 MHz fsb processor and 4 GB DDR-RAM. The operative system of the computer was Windows 2000.

3.1 Mathematical Modeling of the Flow Pattern in the Bend

The grid used in the calculations was made in GAMBIT\textsuperscript{13} and had 90 000 cells, for the case with the swirl blade, and 55 000 cells for the case without swirl blade.

Governing Equations

In the present numerical model describing the flow of water through an elbow shaped pipe, the media have been assumed to be an incompressible Newtonian fluid with constant molecular viscosity. Furthermore, the effects of temperature and chemical reactions have been neglected. The governing equations for steady state flow in Cartesian coordinates can be written in the following general form

\[
\frac{\partial}{\partial x} \left( \rho u \phi - \Gamma_\phi \frac{\partial \phi}{\partial x} \right) + \frac{\partial}{\partial y} \left( \rho v \phi - \Gamma_\phi \frac{\partial \phi}{\partial y} \right) + \frac{\partial}{\partial z} \left( \rho w \phi - \Gamma_\phi \frac{\partial \phi}{\partial z} \right) = S_\phi
\]

(1)

where \( u, v, \) and \( w \) is the time averaged fluid velocity in the three directions of the Cartesian coordinate system, respectively and \( \rho \) is the density of the fluid. The variable \( \phi \) represents the various time averaged quantities i.e. mean velocity, production of turbulent kinetic energy and the dissipation rate of turbulent kinetic energy. Furthermore, the variable \( \Gamma_\phi \) is the effective diffusivity of the transported variable \( \phi \) and \( S_\phi \) is the source term which might contain pressure and body forces as well as
production. The various transport equations together with the realizable k-ε model are shown in Table 1 in Appendix. Unlike the standard k-ε model the parameters $C_1$ and $C_\mu$ are no longer constants in the realizable k-ε model formulation, as indicated in Table 1. The method used to calculate these two variables will not be elaborated further here; instead the reader is advised to consult the work by Shin et al.

**Boundary Conditions**

The boundary conditions at the wall were set to no slip and the turbulence quantities $k$ and $\varepsilon$ were calculated from the assumption that the turbulent flow was fully developed. The flow at the wall was described with a logarithmic wall function. At the inlet the velocity, in the direction normal to the inlet, was set to 0.7 m/s and features was set to velocity inlet. The boundary condition of the outlet was set to pressure outlet.

### 3.2 Mathematical Model of the Flow Pattern in and at the Entrance of the Vessel

A numerical model was made of the cylinder. Due to symmetry of the cylindrical vessel a 2D axis-symmetric model was made with GAMBIT and had 12000 cells.

**Governing Equations**

The same assumptions made in section 3.1.1 are also made here. That means that the fluid is assumed to be an incompressible Newtonian fluid with constant molecular viscosity and that the effects of temperature and chemical reactions have been neglected. The flow was described in an axisymmetric domain, where the axial and tangential velocities were solved in a transient solution mode. In the case with a swirling flow, the domain was set to axisymmetric with swirl, which means that there were no circumferential gradients, but non-zero velocities.

**Boundary Conditions**

The boundary conditions at the wall were set to no slip and the turbulence quantities $k$ and $\varepsilon$ were calculated from the assumption that the turbulent flow was fully developed. The flow at the wall was described with a logarithmic wall function. At the inlet the
velocity, in the direction normal to the inlet, was set to 0.5 m/s, and for the case with
swirl a function file describing the tangential velocity was added. The features of the inlet
were set to velocity inlet. The boundary condition on the upper part of the vessel was set
to pressure outlet.
4 Results and Discussion

4.1 Flow Pattern after the Bend

Flow Field without Swirl Blade

In Figure 4.1.1 the development of the velocity, on the plane through the horizontal and vertical axis, in the runner is shown in form of the radial profile of the velocity vector plot before and after the elbow for the case without swirl blade. The flow in the horizontal runner resembles a typical turbulent flow in a pipe\(^{16}\). After the elbow, the flow becomes non-uniform with the highest velocities closest to the left side of the vertical runner, such as an impinging flow. As the distance to the bend increase the difference between maximum and minimum velocity decreases.

![Velocity vector plot when not using a swirl blade. [mm]](image)

In Figure 4.1.2 a-c) a comparison between the result from the water model and the numerical calculations of the axial velocity in the runner for the case without swirl blade is shown. The positions of the measurements are at the positions of 1 to 3 in Figure 1.3. The agreement between the result from the numerical calculations of the axial velocity and the measurements from the water model of the axial velocity is good, as can be seen in Figure 4.1.2. More specifically, the mean deviation of the predictions from the
measurements is within 10 % of the mean axial velocity. The figure also confirms the velocity profile in Figure 4.1.1; that the velocity is higher at one side of the wall and lower at the opposite side. However, the radial profiles of the axial velocity component become also little more flatter with the flow passing downstream.

![Graph of Axial Velocity vs. Radius for different positions](image)

**Figure 4.1.2** Predicted and measured axial-velocity values in nozzle at positions (referring to Figure 1.3); (a) 1, (b) 2 and (c) 3 for the case with no swirl blade.
Flow Field with Swirl Blade

The development of the radial profile of the velocity vectors, before and after the runner bend, for the case with swirl is shown in Figure 4.1.3. The flow changes from a typical turbulent flow in a pipe, before the bend to an uneven velocity just after the bend, as for the case without swirl shown in Figure 4.1.1 and 4.1.2. The flow is, however, changed to an axis-symmetric flow after the flow passing through the swirl blade. Figure 4.1.3 also show that the difference of the velocities at the wall and in the center decrease as the distance from the swirl blade increases.

![Velocity vector plot when using a swirl blade placed after the elbow.](Figure 4.1.3)

Figure 4.1.3 Velocity vector plot when using a swirl blade placed after the elbow. [mm]

Figure 4.1.4 shows the, by the swirl blade developed, tangential velocity at the three positions, 1 to 3 shown in Figure 1.3, where the velocity was measured. Figure 4.1.4 does also show a comparison between the numerically calculated tangential velocities and the experimental result measured from the water model. The figure show that the calculated and the measured results coincide fairly well with each other. The mean deviation of the predictions and the experiments was 18%, of the mean tangential velocity, for the studied conditions. The radial profile of the tangential velocity is approximately axis-symmetric within short distance from the outlet of the swirl blade.
Figure 4.1.4 Comparison of the predicted and experimentally determined tangential velocity as a function of position in the vertical direction. The height is (a) 85 mm, (b) 105 mm and (c) 125 mm above the symmetry line for the horizontal runner.

Figure 4.1.5 shows the radial profile of the axial velocity at the first position in the runner. The diagram show a comparison of the numerically calculated tangential
velocities and the experimental result measured from the water model. The numerical calculations deviate a little from the measured values, but it has the same tendency.

![Graph showing predicted and measured axial velocity values in nozzle at position 1](image)

**Figure 4.1.5.** Predicted and measured axial-velocity values in nozzle at position 1 (referring to Figure 1.3)

**Unevenness of Velocity**

The unevenness of the fluid velocity is defined by the following relationship

\[
\text{uneven velocity} = \left(\frac{\Delta u}{V}\right) \times 100\% \quad (2)
\]

where \(V\) is the mean axial velocity and \(\Delta u\) is difference of the axial velocities at the distances \(r\) from the center of the runner. **Figure 4.1.5** illustrates the definition.

![Diagram illustrating the definition of mean velocity, V, and axial velocity difference, \(\Delta u\).](image)

**Figure 4.1.5** Definition of mean velocity, \(V\), and axial velocity difference, \(\Delta u\).

The uneven velocities for the experimental and calculated results are shown in **Figure 4.1.6 a-c**. The figures show a comparison of the uneven velocity for the cases with and without swirl blade (in the figure referred as s b). Both numerically calculated and
measured values from the water model are presented. Figure 4.1.6 a) show some agreement between the calculated and experimental result for the case without swirl. The agreement for the case with swirl is, however, not so good and that might arise from that it is very close to the swirl blade. The thickness of the swirl blade causes separation at the downstream end of the swirl blade. This is a phenomenon difficult to simulate, and though leads to less good agreement between the calculated and experimental result. The figure also shows that the unevenness of the velocity is bigger for the case without swirl. Figure 4.1.6 b) shows a good agreement between the measured and calculated result both for the case with and without swirl. The uneven velocity is lower for the case with swirl. Figure 4.1.6 c) do also show a good agreement between the calculated and the measured result and the unevenness for the case with swirl is still lower than for the case without swirl. Figure 4.1.6 a-c) do all show a trend of decreasing unevenness as the distance to the bend increases for the case without swirl. For the case with swirl the unevenness is lower for the two upper positions but it does not vary much after the first position, i.e. the unevenness is abruptly rectified by the swirl blade.
Figure 4.1.6 (a)-(c) Predicted and measured uneven flow distribution as function of vertical position; (a) 85 mm, (b) 105 mm and (c) 125 mm above horizontal runner’s line of symmetry. [%]

4.2 Flow Pattern in and at the Entrance of the Vessel

The flow pattern in the vessel was investigated by studying the behavior of the water surface, both from water models and numerical models, and plots of velocity and kinetic energy of turbulence from numerical models. The water models did not only give information of how the fluid behaved for the three cases but also gave a validation of the numerical model.

Surface Profile

In Figure 4.2.1, digital photographs of the physical model’s water vessel are shown for three configurations: a) a straight nozzle without swirl (from here on referred to as “straight nozzle”); b) a divergent nozzle without swirl; and c) a divergent nozzle with swirl. In Figure 4.2.1(a) it can be seen that there is a lot of activity on the water surface. A feature that is especially pronounced is the hump at the center of the vessel above the inlet. It is created by the water jet entering the vessel. The hump not only affects the surface at the center, but generates movement all over the surface as the water flows into the bath. In Figure 4.2.1(b), the case with divergent nozzle without swirl, it can be seen that the surface is calmer than with the straight inlet. A hump can still be seen at the center, but it is much smaller than with the straight nozzle. Figure 4.2.1(c) shows that the combination of swirl generator and divergent nozzle has a pronounced effect on the surface movement. The surface is very calm and there is almost no trace of any hump.
above the inlet. As can be seen, the hump disappears at an early stage in the filling. The height of the surface from the bottom of the vessel is approximately 15 mm.

![Figure 4.2.1](image)

**Figure 4.2.1.** Digital photos of hump on free surface of water bath when using: (a) straight nozzle, (b) divergent nozzle, and (c) combined divergent nozzle and swirl generator. Inlet axial velocity 0.5 m/s and swirl velocity 0.43 m/s. Photo backgrounds edited to show clear surface profile. Diagram at left indicates photo position in model setup. Diagram at right shows simplified outline of surface shape.

The plot in **Figure 4.2.2** allows for comparison of the height of the hump formed above the inlet of the vessel for the three different cases (**Figure 4.2.1 (a)-(c)**). The mathematical modeling results were evaluated by comparing the predicted hump height with the height of the hump created by the jet from the inlet in the water model.

The results of the measured values in **Figure 4.2.2** concur with what can be seen in the digital photos in **Figure 4.2.1**. More specifically, the maximum hump height for the case with the divergent nozzle and swirling flow (dn/swirl) is only about 30% that of the straight nozzle (sn) and 40% that of the divergent nozzle (dn) without swirl. It can also be seen that the hump disappears after the surface has risen about 5mm (0.03 D_vessel) in the vessel for the case with the divergent nozzle and swirl generator. For the case with the divergent nozzle without swirl, the hump disappears only when the surface has reach
a height of about 90mm (0.6 $D_{\text{vessel}}$), and in the straight-nozzle case, the hump still remains visible when the water surface has reached a height of 170mm (1.13 $D_{\text{vessel}}$).

![Graph showing hump height (H) at center of water-bath free surface for different filling heights (L).](image)

**Figure 4.2.2** Hump height (H) at center of water-bath free surface for different filling heights (L). Data from all three experimental cases: straight nozzle (sn), divergent nozzle (dn), and combined divergent nozzle and swirl generator (dn/swirl). Axial velocity 0.5 m/s at entrance.

*Flow Pattern in the Vessel; Velocity Vector Plot*

A vector plot of a vertical cross section through the center of the vessel from mathematical modeling of the filling of the ingot can be seen in **Figure 4.2.3**. It shows that there is much less movement in the mold for the case with the divergent nozzle and this is especially true for the case with the swirl generator. In **Figure 4.2.3 (a)** a strong jet, formed at the inlet, can be seen. The high velocity at the inlet causes a lot of turbulence in the mold. A vortex is formed in the vertical plane in the mold, with a downward motion near the wall and the opposite direction close to the inlet jet. In **Figure 4.2.3 (b)** the jet from the inlet can still be seen, but the flow is much calmer. The velocity close to the wall of the divergent inlet is very low and the widening of the nozzle has little effect on lowering the velocity of the jet from the inlet. The reason for the low velocity at the wall is the rise of a separation flow. The case with the divergent
nozzle and swirl generator can be seen in Figure 4.2.3 (c) and the most pronounced feature of the flow pattern is that it is very calm in the whole vessel. The fluid is pressed towards the wall of the nozzle, due to the centrifugal force caused by the swirl effect, and it is evenly distributed when it enters the vessel.

Figure 4.2.3 Vector plots of velocity in water in upper part of nozzle and mold for the three cases: (a) straight nozzle (b) divergent nozzle and (c) divergent nozzle with swirl. Swirl velocity 0.43 m/s. Velocity at entrance 0.5 m/s.

Turbulence in the Vessel

Figure 4.2.4 depicts the kinetic energy of the turbulence in the vertical center plane in the vessel as predicted by the mathematical model. The magnitude of the kinetic energy of the turbulence is about the same for the three cases, but the distribution in the vessel differs. In Figure 4.2.4 (a), the case with the straight inlet, it can be seen that the turbulence is distributed mainly in the middle of the vessel and it is highest at the surface of the fluid. For the case of the divergent nozzle without swirl, Figure 4.2.4 (b), the distribution is similar to the case with a straight nozzle, i.e. the highest turbulence is at the surface and in the middle of the vessel. However, the areas of greater magnitude are smaller than for the case with the straight nozzle. Figure 4.2.4 (c) shows the case with the divergent nozzle combined with swirl; here the turbulence is very low in the vessel. The areas of high turbulence kinetic energy are mainly concentrated at the walls of the inlet. There is also some turbulence at the surface, as for the case with swirl, but it is of a lower magnitude and extends over a smaller area. The turbulence is therefore lower for the case of the divergent nozzle with swirl compared with the cases of straight nozzle and divergent nozzle without swirl.
4.3 Concluding Discussion

During teeming steel into molds during up-hill teeming there is a lot of turbulence in the mold at the initial stage, i.e. when the steel melt enters the mold. The steel melt is forming a fountain from the inlet to the mold and slopping and splashing occur. The rapid movement of the steel melt may lead to mold powder being dragged down into and trapped in the melt and finally result in formation of inclusions. This is a serious problem since the possibilities to remove these inclusions, at this late stage, are small. The quality of the final steel product do indeed depend on, among other things, the distribution of inclusions. Especially big inclusions, so called macro inclusions, must be avoided.

The turbulence is a result of the high velocity in the steel melt as it is transferred from the ladle to the mold in the runner system. The high velocity is, in its turn, a result of the ferrostatic head, unevenness buildup due to bends in the runner system and last but not least the small cross section area of the inlet to the mold. This study, consisting of two parts; tries to minimize the turbulence by minimizing the effects of the two phenomena of uneven velocity and a small cross section area. Both these phenomenon are in this work suppressed by the presence of swirl.

The unevenness is rectified by the swirl blade as it interrupts the velocity peaks and forms a more uniform and axisymmetric velocity profile in the inlet to the mold. The swirl does also enable the use of a wider inlet. The flaring of inlets used today is limited
by the fact that separation occurs between the wall and the fluid and the whole cross section area is not used. When a swirl blade is used a centrifugal force is created in the fluid and the fluid is pressed against the wall. The fluid will therefore fill the whole cross section area and the velocity is allowed to decrease.
5 Conclusions

The conclusions that can be drawn from these studies are that the swirl flow, combined with a diverged inlet, has a positive effect on the flow into the mold, since the turbulence is decreased. The reasons for an improved flow are that two of the issues that contribute to turbulence at the bottom of the mold are treated. The two sources of turbulence that are referred to is the unevenness of the flow and the small cross section area at the inlet of the mold. The swirl flow rectifies the uneven flow pattern in the runner and distributes the fluid in the whole inlet, making it possible to use a larger cross section area and hence lowering the velocity of the fluid into the vessel.

Conclusions of the Effect of the Swirl on Flow Pattern at the Bend

The effect of using a swirl blade in a runner on the flow in an uphill-teeming nozzle was studied both using mathematical and physical modeling. The main finding was that the swirl blade was found to create fluid flow conditions that are beneficial during uphill teeming. The following specific conclusions were found:

The numerical calculations turned out to coincide well with the experimental result for both the case with and without swirl as can be seen in Figure 4.1.2 a-c and Figure 4.1.4 a-c. The numerical result has a mean deviation of 13% from the experimental result. Figure 4.1.2 a-c and Figure 4.1.4 a-c also show that:

- The maximum velocity decreases as the distance from the swirl blade increases.
- The minimum velocity increases as the distance from the swirl blade increases for the axial velocity.

Concerning the uneven velocity, shown in Figure 4.1.6 the conclusion is summarized as follows:

- The uneven velocity calculated from the numerical result coincides well with the uneven velocity of the experimental result.
• The general tendency when the swirl blade is not used is that the unevenness of the velocity is higher at all three of the positions where measurements have been taken.
• The unevenness of the velocity decreases as the distance to the swirl blade increases.

The uneven flow pattern developed in the fluid, after it passes through the elbow, is abruptly rectified, and considerable axis-symmetric flow in both axial and tangential velocity can be obtained within a short distance from the swirling blade. Accordingly, setting the swirling blade just beneath the elbow is a very effective way to get a uniform fluid flow pattern in the nozzle during up-hill teeming.

Conclusions of the Effect of Swirl on the Flow Pattern in the Vessel

Physical and mathematical modeling were used in studying the effect of nozzle type and swirl flow on the resulting flow pattern in the ingot mold during the initial filling period in uphill teeming. Good agreement was observed between the corresponding results from the water model and mathematical model. Both divergent and straight nozzles were investigated. It was found that the use of a divergent nozzle without swirl resulted in a smaller hump and lower axial velocities in the bath than the straight nozzle without swirl. The hump and the axial velocities were found to decrease even more when the divergent nozzle was used in combination with a swirl generator. The overall conclusion drawn from the study’s findings was that the combination of swirl generator and divergent nozzle will result in calm initial filling conditions. The specific findings of the study were the following:

• The combination of swirl and divergent nozzle had a substantial effect on the movement of the free surface in the water vessel. The hump, which was present for the straight and divergent nozzle cases without swirl, disappeared at an early stage of the filling, which can be seen in Figure 4.2.2. More specifically, the disappearing of the hump occurred after a filling height of only 5mm (0.03 Dvessel) for the case with swirl and divergent nozzle, compared with 90mm (0.6 Dvessel) for the divergent nozzle without swirl and 170mm (1.13 Dvessel) for the straight nozzle without swirl.

• Figure 4.2.2 do also show that the maximum hump height for the case of divergent nozzle and swirl was only about 30% that of the straight nozzle without swirl and 40% that of the divergent nozzle without swirl.
• The vector plots a-c) in **Figure 4.2.3** shows that the velocity is dramatically decreased when swirl is used.

• As can be seen in **Figure 4.2.4**, the kinetic energy of the turbulence was very low, compared to the other cases, at the surface for the divergent nozzle/swirl combination.

The addition of swirl to the inlet flow seems to be important to get a calm flow into a mold. It is however important to get a suitable swirl for the system so that it is strong enough to press the melt against the wall but not too large, since a vortex is created at the inlet. When a vortex is created there is an increased risk for the mold powder to be dragged down into the melt.
6 Future Work

The results from this dissertation have shown that it is beneficial from a theoretical point of view to use a swirl blade in a runner during filling of an ingot. In order to further improve the theoretical knowledge regarding the use of swirl technique in ingot casting the following theoretical studies are suggested:

- Optimization of the combination of swirl blade and diverged nozzle.
- Effect on swirl strength due to velocity
- Effect on flow pattern when the swirl blade is placed in the horizontal part in the runner system, before the bend.
- Adaptation of the swirl – nozzle design to current existing runner design.

In order to test the swirl technology in production the following plant trials are suggested:

- Effect on the size distribution and composition of inclusions when a swirl blade is added to the runner system.
Reference

11) S. Yokoya, S. Takagi, Y. Kudou, Y. Sasaki, M. Iguchi, Tetsu-to-Hagane: 90 (2004), No. 6
12) FLUENT incorporated, FLUENT 6.1 User’s Guide
13) http://www.fluent.com/software/gambit/index.htm
## Appendix

### Table 1. Conservation equations and turbulence model constants.

<table>
<thead>
<tr>
<th>Conservation of</th>
<th>$\Phi$</th>
<th>$\Gamma_\Phi$</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-direction momentum</td>
<td>u</td>
<td>$-\frac{\partial}{\partial x}\left(p + \frac{2}{3}\rho k\right) + \frac{\partial}{\partial y}\left(\mu \frac{\partial u}{\partial y}\right) + \frac{\partial}{\partial z}\left(\mu \frac{\partial w}{\partial z}\right)$</td>
<td></td>
</tr>
<tr>
<td>y-direction momentum</td>
<td>v</td>
<td>$\mu_l + \mu_t$</td>
<td>$-\frac{\partial}{\partial y}\left(p + \frac{2}{3}\rho k\right) + \frac{\partial}{\partial x}\left(\mu \frac{\partial v}{\partial x}\right) + \frac{\partial}{\partial z}\left(\mu \frac{\partial w}{\partial z}\right)$</td>
</tr>
<tr>
<td>z-direction momentum</td>
<td>w</td>
<td>$\mu_l + \mu_t$</td>
<td>$-\frac{\partial}{\partial z}\left(p + \frac{2}{3}\rho k\right) + \frac{\partial}{\partial x}\left(\mu \frac{\partial w}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu \frac{\partial w}{\partial y}\right)$</td>
</tr>
<tr>
<td>Turbulent kinetic energy</td>
<td>$k$</td>
<td>$\mu_l - \frac{\mu_t}{\sigma_s}$</td>
<td>$G_k - \rho \varepsilon$</td>
</tr>
<tr>
<td>Turbulent dissipation rate</td>
<td>$\varepsilon$</td>
<td>$\mu_l - \frac{\mu_t}{\sigma_s}$</td>
<td>$\rho C_s \varepsilon - \rho C_e \frac{\varepsilon^2}{k + \sqrt{\mu_t / \rho \varepsilon}}$</td>
</tr>
</tbody>
</table>

### Notes

1. $\mu_t = \rho C_{\mu} \frac{k^2}{\varepsilon}$
   - turbulent viscosity

2. $\sigma_k \quad \sigma_{\varepsilon} \quad C_1 \quad C_2 \quad C_{\mu}$
   - N/A* \quad 1.9 \quad N/A*  

3. $G_k = \mu_t S^2$  
   - $S = \sqrt{2S_{ij} S_{ij}}$  
   - $S_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$

4. $\mu_l$  
   - laminar (dynamic) viscosity

5. $\mu_e = \mu_l + \mu_t$  
   - effective viscosity

*Variables calculated using the method specified by Shin et al.\textsuperscript{13}