INVESTIGATION OF MENISCUS REGION BEHAVIOR AND OSCILLATION MARK FORMATION IN STEEL CONTINUOUS CASTING USING A TRANSIENT THERMO-FLUID MODEL

by

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ABSTRACT

In the continuous casting of steel, many complex phenomena in the meniscus region of the mold are responsible for the formation of oscillation marks. Oscillation marks are depressions found around the perimeter of continuously cast steel slabs, which if too large can lead to cracking in steel slabs. Therefore, knowledge on how to minimize the size of oscillation marks is very valuable. A computational model was created of the meniscus region, which includes transient multiphase fluid flow of slag and steel, with low-Reynolds turbulence, heat transfer in the mold, slag, and steel, steel shell solidification, mold oscillation, and temperature-dependent properties. This model was first validated using previous experimental and plant data. The model was then used to study the impact of varying casting parameters, including oscillation frequency, stroke, modification ratio, casting speed, molten steel level fluctuations, and temperature-dependent slag properties and surface tension on the oscillation mark shape, and other aspects of thermal-flow behavior during each oscillation cycle, including heat flux profile, slag consumption and mold friction. The first half of oscillation marks were formed during negative strip time as the slag rim pushed molten steel away from the mold wall and that the second half of oscillation marks were formed during positive strip time as the molten steel is drawn near the mold wall due to the upstroke of the mold. Oscillation mark depth was found to decrease with increasing frequency, modification ratio, casting speed, and slag viscosity, while oscillation mark depth was found to increase with increasing stroke. Oscillation mark width was only found to increase due to increases in pitch, which can be contributed to decreasing frequency or increasing casting speed. While many observations were made in this study, in general, oscillation mark depth and total slag consumption increase with increasing negative strip time, while the average heat flux and average mold friction decrease with increasing negative strip time.
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CHAPTER 1
INTRODUCTION AND BACKGROUND

The quality and cost of steel is very important in the world today. Steel is important in many different industries across the globe. For example, steel is used heavily in the construction industry as a fundamental material used to build large buildings, such as schools, hospitals, and skyscrapers, and to build other structures such as bridges and railways. Another example of an industry that relies heavily on the use of steel is the transportation industry. Almost all forms of transportation use steel in some way, such as cars, trains, and ships. However, steel’s importance doesn’t stop there. Steel is also used in other kinds of critical infrastructure too, such as in oil rigs, pipelines, and can even be used in structures purposed for creating renewable energy. These are just a few ways that steel is used around the world.

It is fairly easy to see that steel touches the lives of almost all people on a daily basis. Therefore, it is important that the steel used in all of these systems is of the highest quality and manufactured as economically as possible. Research of the continuous casting process aims to achieve these two goals. Continuous casting was used in 2014 to produce 96% of the world’s steel, and therefore is the most commonly used method in the steel industry to manufacture steel slabs. [1] Therefore, any strides that can be made to increase the quality of continuously cast steel and decrease the cost of the continuous casting process will lead to many benefits.

1.1 History of Continuous Steel Casting

The roots of steel making processes trace back to 2000 BC, when iron products were made one at a time by a blacksmith. Over time the importance of steel was recognized and steel became a commodity in need of a mass production process. Initial methods of casting, such as ingot casting and slabbing processes were used to create steel products for about 200 years. [2] However, in the mid 1800s Henry Bessemer first came up with the idea of a continuous caster to manufacture long strands of steel. The technology took some time to progress, but its development was heavily spurred on by the motivation of World War II and was one of the many technologies to be greatly improved during this era. The technology made its way into plant production lines in 1970 and the idea took the industry by storm. In a very short time period Continuous Casting became the primary method for manufacturing steel strands. [2] [3]

There have been many advances in the continuous casting process since its introduction into steel plants. For example, the introduction of mold oscillation has minimized the occurrence of various defects, such as sticker defects, shell tearing, and breakouts, all of which are catastrophic failures that can occur in the continuous casting process. Additionally, the use of a concept called negative strip time (NST), which
is when the mold moves down faster than the casting speed for a portion of the oscillation cycle, has been found to decrease the likelihood of breakouts from occurring in the steel. [4] These two discoveries made modern commercial continuous casting possible and show the great importance of oscillation. Members of the Continuous Casting Center have utilized modeling techniques to investigate the fundamental phenomena associated with important advances, such as oscillation and negative strip time, since its formation in 1989. [5]

1.2 Overview of Continuous Casting

Continuous Casting is a midstream component of the overall steel-making process. Prior to casting, iron must go through a series of steps to be transformed into molten steel. Then the molten steel enters the casting process. A diagram illustrating this process can be seen in Figure 1.1. [5] The molten steel begins in the ladle, which is a storage container that transports the molten steel to the caster from upstream processes. From the ladle the molten steel flows into the tundish; a secondary intermediate storage container and secondary refining vessel. At the tundish exit a slide gate or stopper rod system is used to control the flow rate of the molten steel. The molten steel then enters the mold via a Submerged Entry Nozzle (SEN), which largely controls the flow pattern of the molten steel in the mold. Within the mold the molten steel will begin to solidify near the mold walls and a steel shell will grow as the steel cools. Once the solidified shell is thick enough to withstand the internal pressure from the remaining molten steel, it is pulled out of the bottom of the mold by a series of rollers. The steel continues to cool until the slab is completely solid. The slab is then cut into the appropriate length and sent to post-processing. [5]

There are many phenomena happening within the mold. Some phenomena are natural occurrences. For example, within the mold there are multiple recirculation zones found due to the turbulent nature of the fluid flow. One bulk recirculation occurs below the SEN and one above the SEN. However, within these regions, depending on the angle of the spray from the SEN and many other factors, other recirculation zones can form. Additionally, the flow itself can cause waves at the surface of the molten steel. Another natural phenomena occurring in the mold, which was already mentioned, is the solidification and growth of the steel shell. However, some phenomena are the result of additional technologies being added into the process. For example, two mechanisms are used in order to keep the solidified shell from sticking to the mold. The first is the addition of a lubricant. Some billet casters utilize oil as a lubricant, while high quality billet casters and all slab casters utilize a mold flux, which begins as a powder that is placed on top of the molten steel, to act as a barrier between the steel and the air to prevent oxidation. Then as the powder sinters and melts, it forms a liquid slag, which flows into the slag gap, which is between the mold and the steel shell, and acts as a lubricant. Additionally, mold oscillation is used to further prevent sticking. The combinations
of these events can control the behavior of initial solidification of the steel shell. These are just a few examples of the complexities found in the mold.

![Diagram of the Continuous Casting Process](image)

**Figure 1.1 Diagram of the Continuous Casting Process[5]**

The complex phenomena found in the caster often cause defects to form in the steel in this region. Defects in steel can be problematic for two reasons. The first reason is that in some cases defects can decrease the yield of a batch of steel. Oftentimes post processing procedures are required in order to remove the defect, which often means removing steel from the slab and consequently lowering the yield. Secondly, defects, if severe enough, can lead to stress concentrations, which may lead to the steel cracking during future processing procedures, or worse after the final steel has already been put into service. If the steel fractures this can lead to catastrophic failures in the various kind of infrastructure mentioned previously. Some of the mechanisms that can lead to defects observed in continuously cast steels can be the entrapment of argon bubbles and/or inclusions, excessive mold level fluctuations, slag entrainment, deep oscillation marks, longitudinal cracks, and transverse cracks. The remainder of this thesis will focus on initial-solidification phenomena related to oscillation mark formation.
1.3 Background on Oscillation Marks

Oscillation marks are transverse depressions found extending around the perimeter of steel slabs. When oscillation marks become too deep they may cause cracking to occur in the steel slab. In the region where an oscillation mark is formed the local temperatures in the steel shell are higher, which can lead to larger grains forming during solidification. Due to the fact that the grain boundaries are weaker in the larger grains metallurgical embrittlement can occur. In addition, the thinner local shell can lead to stress concentrations and ultimately cracks. Therefore, regions that contain deep or wide oscillation marks are at higher risk for cracking than the rest of the steel slab. [6] In addition, oscillation marks associated with hooks can capture inclusions near the strand surface and lead to surface defects, and/or expensive grinding of the surface to remove them. [6]

Oscillation marks form in the meniscus region. The meniscus region is a small region near the top of the mold where the slag and steel come into contact with one another to create a curved shape. The meniscus shape forms due to the difference in surface tension between the slag and the steel. The mechanism responsible for the formation of an oscillation mark may differ depending on various casting conditions, such as casting speed, stroke, frequency, slag composition, and level fluctuations. There have been several other mechanisms that have been considered as the cause of oscillation marks, and these theories are discussed below:

- Meniscus Freezing and Overflow - During the casting process the meniscus region can cool down below the solidus temperature and create a curved solid tip, which is referred to as meniscus freezing. Then molten steel will overflow the frozen meniscus. [7] This process is shown in Figure 1.2. [8] This overflow can occur with or without mold oscillation. If the mold is not oscillating the meniscus can still freeze and if the steel level fluctuates molten steel is still able to overflow the frozen meniscus to form an oscillation mark. [9]

Hooks are another microstructural feature that are formed when an oscillation mark is formed due to meniscus freezing and overflow. The hook is the frozen portion of the meniscus that remains part of the existing solidified shell after overflow, and travels downward with the steel shell at the casting speed. Additional molten steel will then solidify around the hook. Hooks are visible in steel samples, due to the different grain structure seen in a hook in comparison to the remainder of the shell, which can be seen in Figure 1.3. [8] It has been found that hooks lead to an increased number of inclusion defects because as inclusions and inclusion-coated bubbles float to the surface they can be entrapped by the hook near the solidification front. [6]

- Shell Tip Bending - The theory of shell tip bending requires that the steel shell forms and then in-
creased pressure during negative strip time, causes the shell to bend away from the mold wall, which will create a hook. Then the shell will continue to grow vertically from the root of the hook forming an oscillation mark. While it is easy to bend the liquid meniscus, the theory that the solidified steel could bend was found to be unlikely due to evidence presented by several other researchers. [7] Badri found that the heat flux at the mold hot face tends to increase during negative strip time, proving that the steel must be near the mold at this time. [7]

- Freezing to the Mold and Stripping during NST - Another theory for oscillation mark formation proposes that if molten steel were to flow near the mold wall it can stick to the mold wall as it solidifies. Then during NST the piece of solidified steel shell will come back into contact with the remainder of the shell and the piece of solidified shell will weld onto the larger solidified steel shell strand, which is moving down at the casting speed. Thus, the shell will be stripped off the mold wall. The junction between the two pieces of the shell is pushed away from the mold wall during this compression to form a depression, which is considered an oscillation mark. However, while this is likely a mechanism for oscillation mark formation in casters that use oil lubrication it is unlikely in a caster that uses slag for lubrication. This is because when slag is present in the caster it is unlikely that the steel shell will come into contact with the mold wall. So while this is an important mechanism it is not a mechanism that can describe the formation of most oscillation marks. Since the model in the current study investigates solidification with a slag layer this mechanism is unlikely to occur. [8]

- Thermal Distortion of the Shell Tip - Thermal distortion of the shell due to steep temperature gradients found in the shell has been proposed as a mechanism that contributes to oscillation mark formation based on evidence found in a study performed by Sengupta et al. [11] It was found that as the
Figure 1.3 SEM Section View of Steel Including a Hook and Oscillation Mark [8]

shell cools thermal distortion can contribute to the depth of oscillation marks during the formation of the bottom half of the oscillation mark, but it is not the primary mechanism forming most oscillation marks.

1.4 Literature Review of Previous Work

For many years modelers have worked to gain insight into the many phenomena that occur in the meniscus region of the mold. Two of the recent modelers to contribute to this effort are Yan and Jonayat, who are the original developers of the model presented in this work. [12] [13] In the current work further validation of the model, study of the boundary conditions, and a parametric study have been done using the original and modified versions of the model developed by Yan. Yan’s model was developed based on a model created by Jonayat. [12] Jonayat primarily studied slag consumption using a model similar to Yan’s. Yan’s model is set apart from Jonayat’s because Jonayat’s model assumes a fixed slag gap and does not calculate the shape of the steel shell surface or oscillation marks. Therefore, Yan’s model is capable of predicting the more accurate fluid flow and heat transfer behaviors in the meniscus region, including the size
of the interfacial gap, as well as the formation of oscillation marks including their shape.

A comprehensive literature review of prior and similar modeling work has been published by Jonayat et al. [12] However, there are some modelers worth mentioning whose work specifically contributed to this body of work. One such modeler, Meng in conjunction with Thomas [14] developed a program called "CON1D", which is capable of calculating a 1-D transient model of the solidifying shell and 2-D steady state heat conduction in the mold. [11] This program can also calculate various steel and slag properties, heat flux and temperature profiles at various locations in the model, slag consumption, and various other parameters. This program serves as a simple and fast tool, for quickly determining which parameters to consider for parametric studies, as it provides an approximation of the results found by the present Fluent model. This program has been relied upon by many other researchers in previous work. [15] [16] [17] [18] [19] [20]

Plant experiments conducted by Shin et al. [21] at POSCO, measured slag consumption and determined the effect of various casting parameters on slag consumption. Shin separated consumption into solid slag consumption, liquid slag consumption, and consumption found within oscillation marks. Shin presented equations that describe how slag consumption varies with parameters such as casting speed and negative strip time. The data collected by Shin is useful for the validation of models, such as the one developed in the current work.

McDavid and Thomas’s [22] 3-D model of the top layer of mold powder and sintered slag calculates the coupled heat-transfer in all layers and fluid flow patterns found in the slag using a finite-element approach. McDavid developed temperature dependent slag viscosity, conductivity, and specific heat relationships, which have been built upon in the current work. McDavid’s model is capable of matching plant data for slag layer thicknesses. McDavid also proved the existence of a recirculation zone within the liquid slag, which was confirmed by work done by Zhao et al. [23]. Additional work has been done by Akhtar [24] to further understand the material properties of both mold powders and liquid slags. Akhtar’s experiments consist of nail board measurements performed in real casters and which were then modeled in ANSYS FLUENT. Akhtar’s powder and slag properties have been used to determine the reasonable properties to use in various parametric studies done using the current model.

Researchers Ojeda and Sengupta et al. [8] [25] [26] have both performed research to study the liquid slag layer above the molten steel, the slag rim, the profile of the steel/slag interface in the meniscus region, and the slag gap near the meniscus. They were able to study the fluid flow patterns of the molten steel and match their slag consumption data to that of plant measurements. [27] However, this study did not include the formation of the steel shell and it required a constant slag gap thickness be applied. Both of these fea-
tures are included in the current model.

Lastly, another recent model developed by Lopez et al.[28] [29] is able to model the fluid flow in the liquid slag and steel, the slag/steel interface, steel shell solidification, and mold oscillation. This model includes the VOF method to track the slag/steel interface and the enthalpy-porosity method to track the steel solidification, both of which are included in the current model. Furthermore, the mesh resolution does not allow this model to capture the details of oscillation mark formation in a quantitative manner. However, while the model includes temperature dependent viscosity for both the slag and the steel, the thermal conductivity of the slag remains constant in this model. The thermal conductivity of the slag is very important to the formation of oscillation marks and therefore is an important improvement included in the current model. The results published by Lopez did not report any information on slag consumption or oscillation mark shape. Additionally, Lopez’s model includes half of the caster, which extends 1.5 m below the slag/air interface. Therefore, it is very computationally expensive to run this model and it is not ideal for parametric studies.

1.5 Objectives of Current Work

The objectives of this work are to validate the use of the transient thermal-fluid model of the meniscus region developed by Yan using experiments performed on a mold simulator by Zhang and Wang et al. [30], and with plant experiments performed by Shin et al. [31] and others. In addition, this work aims to determine the effect of multiple casting parameters on the mechanism responsible for the creation of oscillation marks, the shape of oscillation marks that are formed, heat flux and mold friction profiles along the mold hot face, steel shell growth as the shell moves down the caster, and slag consumption. Specifically, the process parameters considered in this work include oscillation frequency, stroke, and modification ratio, casting speed, heat flux profiles in the meniscus region, slag lubrication, and level fluctuations.

1.6 Chapter 1 References


CHAPTER 2
TRANSIENT THERMAL-FLUID MODEL OF THE MENISCUS REGION

This section provides a description of the transient thermal-fluid model used to simulate the meniscus region and oscillation mark formation. This model has been built in ANSYS FLUENT, and leverages several built-in features. This section will summarize these built-in features. Additionally, this section will outline the governing equations, material properties, geometry, boundary conditions, and computational details used in this model.

2.1 Introduction

Previous models have been created to study the meniscus region. The works of Ojeda and Sengupta et al. [1] [2] [3] have summarized many possible mechanisms for oscillation mark formation. Mechanisms that were considered as possible sources of oscillation marks have been described in Section 1.4. This model attempts to provide quantitative results to support or refute these mechanisms and consider the possibility of new mechanisms. A model created by Jonayat utilized similar material properties, boundary conditions, and geometry to study slag consumption in the meniscus region. [4] However, in this model the steel shell was set to a fixed shape and therefore the natural occurrence of oscillation marks was not studied. The initial development of this current model was done by Yan and additional information on its development can be found elsewhere. [5] The mesh, user defined functions, and initial runs of this model were created by Yan and have been modified to perform parametric studies. The validation of the current model will be discussed in Chapter 3 and the details and results of the parametric studies will be discussed in Chapter 4.

2.2 Computational Model

This model simulates the fluid flow patterns, heat transfer, and steel shell solidification that occur in the meniscus region. This model includes both a solid copper mold and a fluid region. The domain is shown in Figure 2.1 The fluid region contains two different materials, steel and slag. The interface between the steel and the slag is solved for by the model. The model extends 150 mm below the slag/air interface and 100 mm from the mold hot face. The geometry of the mold domain will be discussed in Section 2.3.5. The mesh used for this model is a fixed structured mesh. The mesh used in the current model contains 87,862 elements, where the smallest element has a width and length of 50 µm. This mesh is shown in Figure 2.2.
This model was created using ANSYS FLUENT. This model includes four built-in FLUENT models, which are listed and explained below:

- **Energy Model** - The energy model in FLUENT turns on the energy equation. This allows the model to solve for temperature profiles, heat fluxes, and enthalpy profiles.

- **Solidification and Melting Model** - Use of the solidification and melting model allows the model to exhibit how the steel shell solidifies. Additionally, this model includes pull velocity, which allows the steel shell to be pulled out of the bottom of the domain in the same way as it would in a real casting process. This model requires one user input, the mushy parameter, $A_{mush}$, which can be described using a constant, but in this case a user-defined function was supplied to the model in order to define mushy parameters for different regions in the solidification zone. This user-defined function is called "solid_params" and can be found in Appendix A.
• Turbulence Model - Due to the turbulent Reynolds numbers that are found in some regions in the caster a turbulence model was included in this model. The Reynold’s number was found for three locations in the caster using Equation 2.1. Using the SEN flow rate equation, $Q_{SEN}$ [7], which is shown in Equation 2.2, the casting conditions of the base case, given in Chapter 3, and average SEN dimensions [8] the Reynolds number was calculated at three locations. First, the Reynolds number was calculated at the SEN exit based on a length scale of 80 mm, which is a standard SEN port diameter. The Reynold’s number was then calculated at the steel inlet of this model based on a length scale of 28 mm, which is the height of the steel inlet. Lastly, the Reynolds number was calculated near the solidifying steel shell. A 1 mm region was found near the steel shell where the average fluid velocity matches the casting speed. Therefore, the third location where the Reynold’s number was considered is in the fluid region adjacent to the solidified shell based on a 1 mm length scale, which roughly corresponds to the hook thickness, mushy-zone thickness, and/or the primary dendrite arm spacing in this region. The resulting Reynolds numbers are shown in Table 2.1. The results show that the flow is fully turbulent near the SEN and remain turbulent at the steel inlet of the domain. However, near the solidified steel shell the flow becomes completely laminar. The density for all calculations was set to the density of the steel, $\rho_{steel} = 7000\,[kg/m^3]$ and the viscosity was set to the viscosity of molten steel, $\mu = 6.3 * 10^{-3}\,[Pas]$. 
\[ Re = \frac{\rho_{\text{steel}}u l}{\mu} \]  

(2.1)

where:

\( \rho_{\text{steel}} \): Density of the steel \([\text{kg/m}^3]\)

\( u \): Velocity of the steel in the flow direction \([\text{m/s}]\)

\( l \): Characteristic length scale \([\text{m}]\)

\( \mu \): Dynamic viscosity \([\text{Pas}]\)

\[ Q_{\text{SEN}} = \frac{dh_l}{dt} (WT - \frac{\pi}{4} D_o^2) + v_c WT \]  

(2.2)

where:

\( \frac{dh_l}{dt} \): The average rate of steel level change \([\text{m/s}]\)

\( W \): Width of the caster \([\text{m}]\)

\( T \): Thickness of the caster \([\text{m}]\)

\( D_o \): Diameter of the SEN \([\text{m}]\)

\( v_c \): Casting speed \([\text{m/s}]\)

Table 2.1 Calculated Reynolds Numbers

<table>
<thead>
<tr>
<th>Location</th>
<th>( u ) [\text{m/s}]</th>
<th>( l ) [\text{mm}]</th>
<th>Re [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEN Exit</td>
<td>1.00</td>
<td>80</td>
<td>88889</td>
</tr>
<tr>
<td>Model Steel Inlet</td>
<td>0.29</td>
<td>28</td>
<td>9022</td>
</tr>
<tr>
<td>Near Solidified Shell</td>
<td>0.01</td>
<td>1</td>
<td>11</td>
</tr>
</tbody>
</table>

FLUENT has several turbulence models to choose from. In this model the k-\( \omega \)-SST model was used. The k-\( \omega \)-SST model features a two equation turbulence model that captures laminar behavior near the solidified shell and the fully turbulent behavior, according to the k-\( \epsilon \) model, in the free stream near the bulk fluid flow inlet in the domain. This model requires many empirical constants. The default model constants provided by FLUENT are all very well defined constants for fully turbulent flow found from experimental data. Additionally, as the turbulent region in the domain is found away from solidification zone, which is the region of interest for this study, it was determined that additional investigation into the turbulence model constants was not necessary. Therefore, the standard constants were adopted in this work with no modification. Further information on the constants used can be found elsewhere. [4] [5] [6] Due to the low velocities found in the domain as a whole the Low-Re Correction was turned on. The Low-Re Correction damps the turbulent kinetic energy by altering the turbulent kinematic viscosity \( \nu_t \) [\( \text{m}^2/\text{s} \)], shown in Equation 2.3, where the viscosity
changes based on the blending function $F_2$. More information on this function can be found in the
FLUENT manual. This is done by including the coefficient $\alpha^*$, which is set to 1 when the Low-Re
Correction is not used. Further details on the definition of $\alpha^*$ can be found in the FLUENT manual.

A sensitivity study was performed on the turbulent parameters and will be discussed in Chapter
3. Additionally, due to the large velocity gradients found at the interface of the slag and the steel in
order to avoid unnatural turbulence from being created at the interface between the slag and the steel
the Turbulence Damping option was also turned on. Due to the fact that the viscosity of the slag is
so high, and so much higher than that of the steel, it is not appropriate to model turbulence in the
slag near the interface. The turbulence damping feature includes an additional source term in the dis-
sipation equation of turbulence model which will be defined in the governing equations sections of
this report.

$$
\nu_t = \frac{k}{\omega} \frac{1}{\max\left(\frac{1}{\alpha^*}, \frac{SF_2}{\alpha^*\omega}\right)}
$$

(2.3)

where:

$\alpha^*$: Low-Re correction factor [-]

$k$: Turbulent kinetic energy $[\frac{J}{kg}]$

$\omega$: Turbulent dissipation rate $[\frac{1}{s}]$

$S$: Strain rate magnitude $[\frac{1}{s}]$

$F_2$: The blending function [-] [6]

- Multiphase Model - FLUENT also has multiple built-in multiphase models. The Volume of Fluid
  Method was used in this model. This method essentially tracks what fraction of any given cell is the
  primary phase and applies properties to this cell based on this volume fraction. The solution method
  for this model was chosen as the explicit method.

2.2.1 Governing Equations

Due to the presence of turbulence in the model, the Reynolds Averaged Navier Stoke Approach (RANS)
is used to solve for the 2-D momentum and mass balance equations for this model. These equations are
shown below in Equations 2.4, 2.5. [6]

The Continuity Equation

$$
\nabla \cdot (\vec{v}) = 0
$$

(2.4)

where:
\( \bar{v} = \text{Mean velocity vector} \left[ \frac{m}{s} \right] \)

The Navier-Stokes Equations

\[
\frac{\partial \bar{v}}{\partial t} + \bar{v} \cdot \nabla \bar{v} = -\frac{1}{\rho} \nabla \bar{p} + \nabla \cdot [\nu_T (\nabla \bar{v} + \nabla^T \bar{v})] + g + \frac{F_\sigma}{\rho} - \frac{S_{\text{mush}}}{\rho} \tag{2.5}
\]

where:
\( \bar{v} \): The mean velocity vector \( \left[ \frac{m}{s} \right] \)
\( \bar{p} \): The mean pressure \( [Pa] \)
\( \nu_T \): Turbulent Kinematic Viscosity \( \left[ \frac{m^2}{s} \right] \)
\( g \): Gravity vector \( \left[ \frac{m}{s^2} \right] \)
\( \rho \): Density of the mixture \( \left[ \frac{kg}{m^3} \right] \)
\( F_\sigma \): Surface tension defined as 1.3 \( \left[ \frac{N}{m} \right] \) for this case \([4]\) \([5]\)
\( S_{\text{mush}} \): Sink term to account for solidification, shown in Equation 2.17 \( \left[ \frac{m}{s} \right] \)

In addition, to the equations shown above. Additional governing equations were utilized in this model to describe the built in FLUENT models listed in Section 2.3.1.

**k-\( \omega \)-SST Equations**

The turbulent kinetic energy equation and the turbulent specific dissipation energy equation are shown in Equations 2.6 and 2.7, which describe the turbulent behavior seen in the k-\( \omega \)-SST model. \([6]\)

\[
\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_j} (\rho_k u_j) = \frac{\partial}{\partial x_j} \left( \Gamma_k \frac{\partial k}{\partial x_j} \right) + G_k - Y_k + S_k \tag{2.6}
\]

where:
\( \Gamma_k \): Effective diffusivity of the turbulent kinetic energy \( \left[ \frac{kg}{ms} \right] \) \([6]\)
\( G_k \): Generation of turbulent kinetic energy \( \left[ \frac{kg}{m^3s^2} \right] \) \([6]\)
\( Y_k \): Dissipation of turbulent kinetic energy \( \left[ \frac{kg}{m^3s} \right] \) \([6]\)
\( D_k \): Cross-diffusion of turbulent kinetic energy \( \left[ \frac{kg}{m^3s^2} \right] \) \([6]\)
\( S_k \): A User defined source term, which was set to zero for this model \( \left[ \frac{kg}{m^3s^2} \right] \) \([6]\)

\[
\frac{\partial}{\partial t} (\rho \omega) + \frac{\partial}{\partial x_j} (\rho \omega u_j) = \frac{\partial}{\partial x_j} \left( \Gamma_\omega \frac{\partial \omega}{\partial x_j} \right) + G_\omega - Y_\omega + S_\omega \tag{2.7}
\]

where:
\( \Gamma_\omega \): Effective diffusivity of the specific dissipation \( \left[ \frac{kg}{ms} \right] \) \([6]\)
\( G_\omega \): Generation of the specific dissipation \( \left[ \frac{kg}{m^3s^3} \right] \) \([6]\)
\[Y_\omega: \text{Dissipation of the specific dissipation } \left( \frac{kg}{m^3 s^2} \right) \] [6]

\[D_\omega: \text{Cross-diffusion of the specific dissipation } \left( \frac{kg}{m^3 s^2} \right) \] [6]

\[S_\omega: \text{A User defined source term, which is defined in Equation 2.8 for this model due to the use of the turbulence damping feature } \left( \frac{kg}{m^3 s^2} \right) \]

\[S_i = A_i \Delta n \beta_t \rho_i \left( \frac{B \mu_i}{\beta_t \rho_i \Delta n^2} \right)^2 \] (2.8)

where:

\[A_i: \text{Interfacial area density for phase i } [-] \] [6]

\[\Delta n: \text{Cell height normal to the interface } [m] \]

\[\beta_t: \text{ } k - \omega \text{ model closure coefficient, equal to 0.075 } [-] \] [6]

\[\rho_i: \text{Density of phase i } [\frac{kg}{m^3}] \]

\[B: \text{Damping factor, set to the FLUENT default value of 10 } [-] \] [6]

\[\mu_i: \text{Viscosity of phase i } [Pa - s] \]

The Volume of Fluid Method Equations

The Volume of Fluid Method (VOF) solves Equation 2.9 to determine the volume fraction of the primary phase, in this case steel is the primary phase. In this equation \(q\) is the steel and \(p\) is the slag. In this equation \(\alpha_q\) is the volume fraction of the cell in the \(q\) phase. [6] Then Equation 2.10 can be used to determine the volume fraction of the slag, or phase \(p\).

\[\frac{1}{\rho_p} \left[ \frac{\partial}{\partial t} \left( \alpha_q \rho_q \right) + \nabla \cdot \left( \alpha_q \rho_q \vec{v}_q \right) \right] = S_{\alpha_q} + (\dot{m}_{pq} - \dot{m}_{qp}) \] (2.9)

where:

\(q\): An index representing the fluid in question, steel

\(p\): An index representing all other phases present in the model, slag

\(\alpha_q\): Volume fraction in the cell in the \(q\) phase

\(\rho_q\): Density of the \(q\) phase, in this case 7000 [\(\frac{kg}{m^3}\)]

\(S_{\alpha_q}\): A source term which allows a source term to be included in the model

\(\dot{m}_{pq} - \dot{m}_{qp}\): Mass balance between the slag and the steel [\(\frac{kg}{s}\)]

\[\alpha_q + \alpha_p = 1 \] (2.10)
Surface Tension Equations

In using the VOF method the option to define parameters along the interface of the two phases, slag and steel, becomes available. This allows the user to specify details related to interfacial surface tension and wall adhesion. In the base case of this model a constant interfacial surface tension was defined by Equation 2.11 developed by Girfalco and Good. [9] In this equation the parameter $\phi$ is defined by Equation 2.12. [10] For the base case, which will be discussed more in Chapter 3, the values of $\phi$, $\gamma_{Fe(l)-gas}$, and $\gamma_{sl-gas}$ were set to 0.4281, 1.6 N/m, and 0.419 N/m, respectively. This resulted in an interfacial surface tension between the slag and the steel of 1.3 N/m. In addition, the contact angle for wall adhesion was specified based on works done by Ojeda [12], using an equation developed by Young to describe the ternary slag system, [13] this value is specified as $\theta_{eq} = 160^\circ$. Further information on the surface tension can be found in Section 4.6.

\[
\gamma_{steel-slag} = \gamma_{steel-gas} + \gamma_{slag-gas} - 2\phi\sqrt{\gamma_{steel-gas}\gamma_{slag-gas}}
\]  

(2.11)

where:

- $\gamma_{steel-slag}$: The surface tension between steel and slag [N/m]
- $\gamma_{steel-gas}$: The surface tension between steel and an inert gas [N/m]
- $\gamma_{slag-gas}$: The surface tension between slag and an inert gas [N/m]
- $\phi$: A constant defined by Equation 2.12

\[
\phi = 0.003731(\text{wt.}\%Al_2O_3) + 0.005973(\text{wt.}\%SiO_2) + 0.005806(\text{wt.}\%CaO)
\]  

(2.12)

Solidification and Melting Equations

The Solidification and Melting model determines how solidified a material is and influences the momentum, energy, and turbulence equations appropriately. The Solidification and Melting model relies upon the liquid fraction, $\beta$, which is defined for the steel phase in Equation 2.13. This liquid fraction dictates the amount of latent heat present in the material mixture at any given time step, as shown in Equations 2.14 and 2.15. The energy balance for models including the Solidification and Melting model is solved using Equation 2.16. In Equation 2.17 a momentum sink term is defined, which is included in the Navier-Stokes equations to cause the steel to behave as a solid or partially solidified material. A similar sink term can also be included in the turbulence equations when the Solidification and Melting model and a Turbulence model are used together, which can be seen in 2.18. The enthalpy-porosity technique causes the region that is between solid and liquid, often referred to as the "mushy region", to be treated as a porous medium.
Therefore, when a region is completely solid the porosity is set to zero. The parameter $A_{mush}$ dictates how closely a region’s heat transfer, fluid flow, and turbulence behave as if the region were a pure solid.[6] This parameter is defined for this model, which varies from $10^7$ in the solid steel to $10^4$ in the dendrite region, according to the location of the shell, using a user-defined function, and can be found in Appendix A.

$$\beta = \frac{T - T_{solidus}}{T_{liquidus} - T_{solidus}} \alpha_q$$ \hspace{1cm} (2.13)

where:

$T_{solidus}$: The solidus temperature $[K]$

$T_{liquidus}$: The liquidus temperature $[K]$

$$H = h + \Delta H$$ \hspace{1cm} (2.14)

where:

$H$: Enthalpy in a given cell $\left[ \frac{J}{kgK} \right]$

$h$: Sensible enthalpy $\left[ \frac{J}{kgK} \right]$

$\Delta H$: Latent heat $\left[ \frac{J}{kgK} \right]$

$$\Delta H = \beta L$$ \hspace{1cm} (2.15)

where:

$L$: Latent heat of the material $\left[ \frac{J}{kgK} \right]$

$$\frac{\partial}{\partial t}(\rho H) + \nabla \cdot (\rho \vec{v} H) = \nabla \cdot (k\nabla T)$$ \hspace{1cm} (2.16)

where:

$\rho$: Density of the material $\left[ \frac{kg}{m^3} \right]$

$H$: Total Enthalpy $\left[ \frac{J}{kgK} \right]$

$k$: Thermal Conductivity $\left[ \frac{W}{mK} \right]$

$$S = \frac{(1 - \beta)^2}{(\beta^3 + \epsilon)} A_{mush} (\vec{v} - \vec{v}_p)$$ \hspace{1cm} (2.17)

where:

$A_{mush}$: Mushy parameter [-]
\( \vec{v} \): Fluid velocity \([ \frac{m}{s} ]\)
\( \vec{v}_p \): Pull velocity \([ \frac{m}{s} ]\)

\[
S = \frac{(1 - \beta)^2}{(\beta^3 + \epsilon)} A_{mush} \phi \tag{2.18}
\]

where:

- \( A_{mush} \): Mushy parameter [-]
- \( \phi \): Represents the turbulence parameter being solved

### 2.2.2 Boundary Conditions

Each boundary in this model was defined by a fluid flow boundary condition and a thermal boundary condition. These boundary conditions are shown in Figures 2.3 and 2.4, respectively. Each of these boundary conditions are explained below:

#### Fluid Flow Boundary Conditions

- **Pressure Inlet** - The top long horizontal boundary at the top of the fluid domain, which is within the slag/powder region, just below the interface between the slag and air in a real caster, was defined as a pressure inlet. This gauge pressure inlet was set as as 0 Pa, or atmospheric pressure. The direction of fluid flow is specified as normal to this boundary. The turbulence parameters set at all boundaries were the turbulent intensity, calculated using Equation 2.19, [6] and the hydraulic diameter. For the pressure inlet the turbulent intensity was set to 5 \%, which corresponds to medium intensity, and the hydraulic diameter was set to 0.1 m.

\[
I = 16 \times \text{Re}_d^{-\frac{1}{8}} \tag{2.19}
\]

where:

- \( I \): Turbulent intensity [%]
- \( \text{Re}_d \): Reynold’s number found using the hydraulic diameter [-]

- **Symmetry Planes** - Three boundaries in the fluid domain were defined as symmetry planes. Two of these boundaries are along the right plane of the domain and the third is along the bottom of the domain. These three boundaries can be set as symmetry boundary conditions because relative to the bulk fluid flow in the domain the velocities in both the x and y directions are negligible. By calling these boundaries symmetry planes the velocity perpendicular to the plane was set equal to zero, i.e. \( u = 0 \) for the right plane and \( v = 0 \) for the bottom plane. Also, the gradient of the velocity parallel to the wall in the direction perpendicular to the wall in question was also set to zero, i.e. \( \frac{\delta u}{\delta x} = 0 \) for
the right plane and \( \frac{\delta u}{\delta y} = 0 \) for the bottom plane.

- **Steel Inlet** - The steel inlet was defined as a mass flow inlet flowing entirely in the negative x-direction. The mass flow in this region was defined by a user-defined function named steel ”steel_inlet_mass”, which can be found in the Appendix A. This user defined function calculates the mass flow across the steel and slag outlet boundaries and then assigns the sum of these two flows as the total mass flow of steel into the domain. The turbulent intensity for the steel inlet was set to 5 \% and the hydraulic diameter was set to 0.027 m.

- **Slag and Steel Outlets** - There are two boundaries, which allow slag and steel to exit the domain, named slag outlet and steel outlet. Steel is still able to exit the slag outlet and slag is still allowed to exit the steel outlet, which is important because in this model the slag gap is able to move, and the thickness of that gap is an important output of the model. These outlets were defined as pressure outlet conditions. The static pressure specified at a pressure inlet or outlet in FLUENT is equivalent to the ferrostatic pressure, but in a multiphase model, the default way that FLUENT calculates the static pressure in the domain is by using the average density of all fluids present in the domain. Therefore, in order to properly account for the two different densities present in the current model an ”operating density” is used, which means that one density is chosen for the entire domain and all pressure boundaries must be set to pressures that take this into account. The relationship between the pressure that is specified at a boundary, \( p'_s \), and the operating density \( \rho_o \) is shown in Equation 2.20. In this model the pressure of the steel outlet is set to 4700 Pa, and the pressure of the slag outlet is set to 4500 Pa. The pressure at the slag outlet is governed by lubrication theory which dictates that the pressure across the gap is the same at any given x-position. The pressure here is influenced heavily by the ferrostatic pressure of the steel, and is therefore set to 4500 Pa. Further information on the slag outlet boundary condition can be found in Section 2.3.5. The direction of fluid flow for both boundaries is set normal to the boundary. At the slag and steel outlets the turbulent parameters were set to a backflow turbulent intensity of 5 \% and a backflow turbulent viscosity ration of 10, which is defined as a medium turbulent viscosity ratio. [6]

\[
p'_s = p_s - \rho_ogh \tag{2.20}
\]

where:
- \( p_s \): Actual pressure [Pa], which is \( \rho_{steel}gh \)
- \( \rho_o \): Operating density, which was set to the slag density, 2500 [\( \frac{kg}{m^3} \)] for this case
**h**: Distance below the slag/air interface [m]

- **Mold Hot Face** - The Mold hot face was defined as a moving wall boundary. This boundary was defined by a user-defined function named “mold_oscillation”, which allows the mold to oscillate in the y-direction, while remaining stationary in the x-direction. This user-defined function can be found in Appendix A. The equation used to specify the oscillation profile of the mold is shown in Equation 2.21, where \( v_m(t) \) is the velocity of the mold at time \( t \). The position of the mold is defined by Equation 2.22 where \( y(t) \) is the mold’s vertical position at time \( t \).

\[
v_m(t) = \pi stf \cos(2\pi ft)
\]

\[
y(t) = \frac{st}{2} \sin(2\pi ft)
\]

where:

- \( st \): Stroke [mm], which is half the amplitude of the oscillation
- \( f \): Frequency [Hz]

- **Mold Top, Bottom, and Cold Faces** - Due to the fact that the mesh in the mold region is oscillating with the Mold Hot Face boundary, the mold top, bottom, and cold faces were all defined as stationary walls because they move in the same fashion as the Mold Hot Face.

- **Steel Shell Velocity** - The viscosity of the steel shell cannot be set to its realistic value due to convergence issues. Therefore, an ”adjust” function is used to set the y-velocity, \( v \), to the casting speed, and the x-velocity, \( u \), to zero in order to essentially make the viscosity of the steel shell infinite.

**Thermal Boundary Conditions**

- **Slag Inlet** - This boundary was set to a constant temperature of 573.15 K, in an effort to match this boundary with the powder/air interface. This temperature matches literature values of the powder temperature at the slag/air interface. [11]

- **Insulated Boundaries** - The three symmetry plane boundaries were defined as insulated boundaries. Two of the three insulated boundaries can be found along the right boundary of the domain, one above the steel inlet and one below the steel inlet. The last boundary can be found along the lower boundary of the fluid domain. These boundaries were set to insulated because there was negligible heat flux across these boundaries in the real process. This is due to the temperature in these regions being constant and the regions of thermal gradients being sufficiently far from these boundaries.

- **Steel Inlet** - The steel inlet was set to a constant temperature, which was defined as \( T_{\text{liquidus}} + \)
Superheat. This is specific to each case.

- Slag and Steel Outlets - The slag and the steel outlet thermal boundaries were defined using user-defined functions called "backflowtemp_steel" and backflowtemp_slag". These user-defined functions specify a backflow temperature, for cases where flow reenters the domain from beyond that outlet. These user-defined functions can be found in Appendix A.

- Mold Hot Face - The Mold Hot Face was defined as a Coupled thermal boundary, which means that fluid region and the mold region share the same heat flux and temperature at this boundary. The mold domain is longer than the fluid domain to ensure that the fluid domain is always in contact with the mold. When portions of the mold hot face come out of contact with the fluid region as the mold moves up and down they behave as an adiabatic wall and then when they come back into contact with the fluid region they will share the temperature and heat flux profile of the fluid domain.

- Mold Top and Bottom Faces - The Mold Top and Bottom Faces were both specified as insulated boundaries. Simulations were run using a convective boundary along the Mold Top boundary, and it was found that there was negligible differences in the solutions. Therefore, it was determined that the Top and Bottom boundaries can both be considered insulated.

- Mold Cold Face - The Mold Cold Face was set as a convective boundary condition with a freestream temperature of $283.15^\circ K$ and a heat transfer coefficient of $h = 10,452 \text{ W/mK}$. More details about this boundary condition will be discussed in Section 2.3.6.

- Temperature Adjustments - In order to ensure that regions in the caster that should stay liquid do not drop below the liquidus temperature an "adjust" function called "fix_steel_temp", found in Appendix A, is applied to two regions in the fluid domain. The first region is the region near the steel inlet, which is defined as the region from the bottom of the domain up to 94 mm from the bottom of the domain and 5 mm to the left of the right side of the fluid domain. The second region is in the meniscus region defined as along the slag/steel interface that is 3 mm or more to the right of the mold hot face and 100 mm or more above the bottom of the domain. This condition prevents solidification of the surface from occurring, which prevents large hooks from forming. More information on the steel viscosity can be found in Section 2.2.3 of this report.
2.2.3 Material Properties

Three materials used in this model were, copper, steel, and slag. The material properties relevant to this model for copper and the properties for the steel and the slag that remain constant at all temperatures are shown below in Table 2.2. Other material properties were temperature dependent and are presented below.
Table 2.2 Copper, Steel, and Slag Material Properties [4]

<table>
<thead>
<tr>
<th>Property</th>
<th>Copper</th>
<th>Steel</th>
<th>Slag</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density ( \frac{kg}{m^3} )</td>
<td>8900</td>
<td>7000</td>
<td>2500</td>
</tr>
<tr>
<td>Conductivity ( \frac{W}{mK} )</td>
<td>380</td>
<td>30</td>
<td>-</td>
</tr>
<tr>
<td>( C_p \frac{J}{kgK} )</td>
<td>385</td>
<td>700</td>
<td>-</td>
</tr>
</tbody>
</table>

Steel Viscosity

The viscosity of steel is a complex property. The molten steel has a viscosity of \( 6.3 \times 10^{-3}[Pas] \), but once the steel is solidified its viscosity increases dramatically to approximately \( 1 \times 10^9 Pas \). The viscosity of the delta-ferrite phase can be determined using the Zhu Power Law [14], shown in Equations 2.23 and 2.24. This constitutive model can be related back to the viscosity of the steel using the relationship shown in Equation 2.25. The effects of varying strain rate and varying carbon content on the stress-strain relationship are shown in Figures 2.5 and 2.6 respectively. It can be seen that the effect of varying carbon content is relatively small in comparison to varying the strain rate. Therefore, changing the carbon content of this model will not significantly change the steel viscosity relationship. A realistic strain rate for solidifying steel in the shell of a continuous casting mold, is around \( 0.0001(1/s) \) [15] and the current model uses low carbon contents of steel, such as 0.001%. The resulting viscosity of the steel under these conditions at \( 1800^\circ K \) is \( 1.4 \times 10^9 Pa - s \). Therefore, it can be concluded that the steel viscosity should change by 13 orders of magnitude within the model.

\[
\dot{\varepsilon}(1/s) = 0.1F_\delta^n
\]  

\[
F_\delta = \frac{\bar{\sigma}(MPa)}{f_c(T(K)-300)^{-5.52} (1 + 1000\varepsilon)^m}
\]  

\[
f_c = 13678(pctC)^{-0.0556}
\]

\[
n = (1.617E - 4T(K) - 0.06166)^{-1}
\]

\[
m = -9.4196E - 5T(K) + 0.349501
\]

\[
\mu = \frac{\tau_{xy}}{\dot{\varepsilon}_{xy}} = \frac{2}{3} f_c \left( \frac{T(K)}{300} \right)^{-5.52} \frac{1}{\dot{\varepsilon}} \left( 10\dot{\varepsilon} \right)^{\frac{1}{n}}
\]  

where:

\( \dot{\varepsilon} \): Von-Mises Inelastic strain rate \( \frac{1}{s} \)

\( \sigma \): Von-Mises Stress \( [MPa] \)
It was found that it is computationally difficult for the model to converge when the viscosity differs by more than 8 orders of magnitude within the domain. At this time the model is only capable of converging when the viscosity of the solidified steel is truncated to $1 \times 10^5 \text{Pa} - \text{s}$. Therefore, in order to ensure that the steel shell behaves the same way it would in a real caster, an adjust user-defined function was applied to the solidified shell region. This function, called “fix_shell_vel”, can be found in Appendix A. This function forces the x-velocity in the steel shell region to 0 m/s and the y-velocity in the steel shell region to the casting speed. In doing so the model behaves the same as if the viscosity of the steel shell were set to its true value. Equation 2.26 shows that if the shear stress on the steel shell remains constant the change in velocity must be negligible as the viscosity becomes very large. Therefore, in order to correct for the fact that the steel shell viscosity that can be modeled is artificially low, fixing the velocity in the steel shell region causes the same effect.
\[ \mu \frac{\partial v}{\partial x} = \tau_{xy} \quad \mu \frac{\partial u}{\partial y} = \tau_{yx} \] 

(2.26)

where:

\( v \): The velocity in the y-direction [\( \frac{m}{s} \)]

\( u \): The velocity in the x-direction [\( \frac{m}{s} \)]

\( \tau_{xy} \): Stress [MPa]

\( \tau_{yx} \): Stress [MPa]

---

Figure 2.6 Stress-Strain Relationships for Steel at 1800° K and 0.0001[s] for Various Carbon Contents

Slag Viscosity

Slag properties are both dependent on temperature and whether the slag is melting or solidifying. Slag begins as a solid mold powder in the upper part of the mold. As the powder is heated the powder sinters and then forms liquid slag. The liquid slag then flows near the mold wall and down in between the steel shell and the mold hot face, where it acts as a lubricant preventing the steel shell from sticking to the mold. As the liquid slag solidifies near the mold wall the viscosity increases. Therefore, the slag temperature-viscosity and temperature-conductivity relationships can be described using two curves, a melting curve and a solidification curve. The solidification curve is applied in the region that is 3 mm or less from the
mold hot face and extends the full length of the domain. While the melting curves apply to the remainder of the domain.

Many models have been considered to describe this viscosity-temperature relationship. One common model for the liquid slag is the Riboud model shown in Equation 2.27. [16] The Riboud model was developed through experimental studies of 30 slags. However, the Riboud model does not account for the abrupt increase in the viscosity of the slag at the break temperature, $T_{br}$. Therefore, a power law is enacted to capture this phenomenon. [17] The power law, shown in Equation 2.28, requires that the viscosity at 1300 °C be known and that the parameter $n$ be determined to fit the viscosity to data. For the base case the viscosity at 1300 °C was set to 0.55 Pas, which came from supplier information published by Shin et al. [18] The value for $n$ was found by fitting the power law to the Riboud equation for the base case slag. The value of $n$ was found to be 1.8 for the base case. The slag viscosity profile used for the base case is shown in Figure 2.7. [4]

\[
\mu = AT e^{\exp \left( \frac{B}{T} \right)} \quad (2.27)
\]

Where,

\[
\ln A = -19.81 + 1.73(X_{CaO} + X_{MnO} + X_{MgO} + X_{FeO} + X_{B_2O_3}) + 5.82X_{CaF_2} + 7.02(X_{Na_2O} + X_{K_2O} + X_{Li_2O}) - 35.76X_{Al_2O_3}
\]

\[
\ln B = 31,140 - 23896(X_{CaO} + X_{MnO} + X_{MgO} + X_{FeO} + X_{B_2O_3}) - 46356X_{CaF_2} - 39519(X_{Na_2O} + X_{K_2O} + X_{Li_2O}) + 68833X_{Al_2O_3}
\]

where:

$T$: Temperature [°K]

$\mu$: Dynamic viscosity [Pas]

$X_A$: Weight percent of component A [%]

\[
\mu = \mu_o \left( \frac{T_o - T_{fsol}}{T - T_{fsol}} \right)^n \quad (2.28)
\]

where:

$\mu$: Dynamic viscosity [Pas]

$\mu_o$: Reference viscosity of slag at $T_o$ [Pas]

$T_o$: Reference Temperature, which in this case is 1573 [K]

$T_{fsol}$: Temperature chosen to fit the power law to experimental viscosity data [K]

$n$: Parameter used to fit the power law to experimental viscosity data [-]
Figure 2.7 Slag Viscosity Profile Used in the Base Case [4]

Slag Conductivity

The conductivity of the slag behaves similarly to the viscosity in that it has a different curve for whether the mold powder is melting into liquid slag, or if the liquid slag is solidifying into a solid slag rim. The conductivity of the solid mold powder is relatively low because the mold powder contains air. [19] Once the mold powder begins to melt the conductivity increases slowly to its maximum conductivity. The maximum conductivity of the slag is dependent on its composition. Generally accepted maximum values for slag conductivity for crystalline and glassy slags are 1 $W/mK$ and 3 $W/mK$ respectively. [20] The increase in conductivity seen in the glassy slag is due to the increase in radiation caused by the translucency of the slag. [20] The slag used in the base case is characterized as a glassy slag and therefore its maximum conductivity is 3 $W/mK$. It has been found that the conductivity of liquid slag as it cools back down to the solidification temperature remains constant due to the balance of the decrease of phonon conductivity, with the decrease in radiation that comes with decreasing temperature. [21] As the slag solidifies, its conductivity decreases back to 1 $W/mK$ in between the break temperature and the glass transition temperature. In this region the slag solidifies and therefore the radiation term becomes negligible. Lastly, the conductivity drops down to 0.5 $W/mK$, which was used in order to match the conductivity of experimental measurements. [22]. The conductivity curve that was applied in the base case is shown in Figure 2.8. Further research on the conductivity of various slags can be found in the Heat Flux Parametric Study portion of this report.
Slag Specific Heat

The specific heat of the slag is also a temperature dependent property. However, the curve is the same for both melting mold powders and solidifying molten slag. Measurements taken by Mills [23] have shown that the specific heat has a sharp increase at the break temperature. The full temperature - specific heat curve used in the base case is shown in Figure 2.9.

![Slag Conductivity Profile Used in the Base Case](image1)

Figure 2.8 Slag Conductivity Profile Used in the Base Case [4]

![Slag Specific Heat Profile Used in the Base Case](image2)

Figure 2.9 Slag Specific Heat Profile Used in the Base Case [4]
2.2.4 Mold Geometry Simplification

In reality the mold is a complex shape, which includes water channels used to cool the mold. Therefore, in order to model a 2-D vertical slice through the mold as a simple rectangle, several steps were required in order to determine the proper dimensions of the 2-D simplification and the thermal boundary condition on the mold’s cold face. In order to determine these parameters for the mold data from an extractor experiment performed by Zhang and Wang et al. [25] a procedure to model the mold developed elsewhere [5] [24] was applied to simplify the real 3D geometry. This involved creating a 2-D model of a horizontal slice of the mold. In Zhang’s experiment, the mold was called the ”extractor” and was used to simulate mold oscillation in a molten steel bath. A diagram of the extractor and a diagram of a 2-D horizontal slice of this extractor is shown in Figure 2.10. Details on Zhang’s experiment can be found elsewhere. [25] [26]

From these diagrams a model was made in FLUENT to model the temperature profile in a 2-D slice of the mold. A symmetry assumption was made and therefore only half of the horizontal slice was modeled. Additionally, the two extractor faces were approximated as insulated. The water channel was given a convective boundary condition. The free stream temperature and convection coefficient of the water in the water channel were set to the same values reported by Wang [27], 283 K and 9200 W m$^2$K. Lastly, the boundary condition on the extractor hot face was set to the average heat flux profile observed along the extractor hot face by Wang. [25] From this model the temperature profile of the horizontal slice was calculated. This temperature profile is also shown in Figure 2.11.

![Figure 2.10 Diagram of a 2-D Horizontal Slide of Zhang and Wang’s Extractor (Left) and a Diagram of the Extractor (Right) [27]](image-url)
In the region between the water channel and the extractor hot face a nearly linear temperature profile exists. Therefore, in this region a 1-D conduction heat transfer calculation was performed using Equation 2.29 to determine the thickness of the linear region, where \( d_{mold} \) is the equivalent mold thickness. From this calculation it was determined that the equivalent results to the 2D extractor cross section could be obtained with a simple rectangular region with a thickness of 12.33 mm thick, and a linearly-varying temperature. The next parameter that is required in order to simplify mold geometry to a 2-D rectangle is the convective heat transfer coefficient that is applied to the mold cold face. This parameter was determined using a thermal circuit between the temperature of the extractor hot face and the free stream temperature of the water channel. The equation used to describe this thermal circuit can be found in Equation 2.30, where \( h_c \) is the equivalent convective heat transfer coefficient. The calculated convective heat transfer coefficient is \( h_c = 10,452 \text{ W/mK} \). This information, the thickness of 12.33mm and the convective heat transfer coefficient of \( h_c = 10,452 \text{ W/mK} \), was used to construct the 2D vertical cross section of the mold (extractor) for the current thermal-flow model. Thus, the simple 2D vertical slice in the current thermal-flow model should have the same accuracy as a full 3D model of the mold or extractor.

![Figure 2.11 Model of a 2-D Horizontal Slice of the Extractor from Zhang and Wang's Experiment](image)

\[
d_{mold} = \frac{k_{copper}}{q} (T_h - T_c)
\] (2.29)
where:

$k_{copper}$: Thermal conductivity of the mold [W/mK]

$q$: Heat flux along the extractor hot face [MW/m²]

$T_h$: Temperature of the extractor hot face [K]

$T_c$: Temperature at the cold side of the linear region [K]

\[ h_c = \left( \frac{T_h - T_{freestream}}{q} - \frac{th}{k_{copper}} \right)^{-1} \]  \hspace{1cm} (2.30)

where:

$T_h$: Temperature of the extractor hot face [K]

$T_{freestream}$: Temperature of the freestream flow [K]

$th$: is the distance between $T_h$ and $T_{freestream}$ [m]

### 2.2.5 Slag Outlet Boundary Condition Validation

The slag outlet pressure boundary condition was set to 4500 Pa, which is near the ferrostatic pressure of the steel, at a depth of 105mm below the steel/slag interface. This boundary condition was chosen by Yan and was found by calculating the ferrostatic pressure at the slag exit location, and then altering the value to ensure that the results were not sensitive to this value. [5] The slag outlet pressure boundary condition is set close to the ferrostatic pressure, as opposed to the static pressure due to the weight of the slag because the slag gap is so thin it acts as a lubrication layer. Therefore, the laws of lubrication theory apply.

The simplified Navier Stokes Equations for the slag gap are shown in Equations 2.31 and 2.32. It can be seen in Equation 2.31 that there is a negligible change in pressure across the slag gap. Since the pressure in the steel is equal to the ferrostatic pressure, the pressure boundary condition at the slag/steel interface will also be equal to the ferrostatic pressure. Therefore, since there is no significant change in pressure across the slag gap, the pressure in the slag is also equal to the ferrostatic pressure.

\[ 0 = -\frac{\partial p}{\partial x} \hspace{1cm} (2.31) \]

\[ 0 = -\frac{\partial p}{\partial y} + \mu \frac{\partial^2 v}{\partial x^2} \hspace{1cm} (2.32) \]

Alternate models were created to validate that the pressure outlet boundary condition at the slag outlet was valid. The pressure profile of the slag gap found in the current main model, when the mold is at a neutral position, is shown in Figure 2.12. In order to validate that the pressure calculated at the slag exit of
the domain of the main model of the meniscus region is valid, two thinner, but longer, models were created to model the slag gap for the entirety of the mold. The first model includes only slag and the copper mold. The energy equation was solved, but solidification and melting was not included. Lastly, the turbulence model was turned off, so the equations simplify to laminar. The boundary conditions for the first alternate model are shown in Figure 2.13 and the resulting pressure profile in the slag gap is shown in Figure 2.14. All user defined functions used in the first alternate model can be found in Appendix B.

![Figure 2.12 The Pressure Profile in the Slag Gap for the Main Model when the Mold is at a Neutral Position](image)

In the first alternate model the right boundary condition of the domain was set to the casting speed. This constant velocity caused the right side of the domain to act like a wall. Therefore, even though the bottom boundary condition was set to the ferrostatic pressure of the steel, for the majority of the domain the pressure in the slag gap was influenced more by the weight of the slag than by the outlet pressure boundary condition.

For the second alternate model, both the slag and the steel were included in the model and the VOF model was utilized to handle the interaction of the two fluids. Additionally, the energy equation was solved in this model, but the Solidification and Melting model was not included. Additionally, the turbulence model was turned off, so the momentum equations simplify to laminar, for the second alternate model. The copper mold was also included, and was allowed to oscillate for two cycles. The momentum and thermal boundary conditions of the second alternate model are shown in Figures 2.15. The user defined functions
used in this model can be found in Appendix C. The resulting pressure profile found in the slag gap using the second alternate model is shown in Figure 2.16

![Figure 2.13 The Momentum and Thermal Boundary Conditions for The First Alternate Model](image)

Figure 2.13 The Momentum and Thermal Boundary Conditions for The First Alternate Model

![Figure 2.14 The Pressure Profile found in the Slag Gap in the First Alternate Model](image)

Figure 2.14 The Pressure Profile found in the Slag Gap in the First Alternate Model
Figure 2.15 The Momentum and Thermal Boundary Conditions for The Second Alternate Model

Figure 2.16 The Pressure Profile found in the Slag Gap in the Second Alternate Model Over One Oscillation Cycle

The second alternate model shows that the pressure in the slag gap agrees well with the theoretical ferrostatic pressure profile in the liquid steel pool. In this model, the steel and slag contact each other and
therefore, the pressure in the slag was influenced by the steel, as the slag layer was much thinner than the steel layer. The resulting pressure profile found in the main model, shown in Figure 2.12, is a combination of the two pressure profiles found in the alternate models. This is logical because the first alternate model’s right boundary condition keeps the top of the steel shell rigid, so that it does not transmit the ferrostatic pressure, and the second model allows lubrication theory to completely govern the pressure in the gap. In a real caster the solidifying shell will for a time and distance below the meniscus support the weight of the molten steel and therefore, the pressure in the slag gap will be influenced only by the weight of the slag. However, as the ferrostatic pressure of the steel increases as the pressure profile progresses down the mold the steel shell can no longer support the weight of the steel, so it simply transmits the pressure onto the slag in the gap. The pressure in the gap then increases towards the ferrostatic weight of the steel. This explains the difference of the pressure in the slag gap from the ferrostatic pressure seen near the meniscus in the main model.

2.2.6 Computational Details

Prior to running a full simulation of the continuous casting process using the model described above, several steps were required to initialize the model. These steps are listed below.

- Bikerman Initialization - In the first modeling step the energy equation and the solidification and melting models were turned off. The user-defined function called "interface”, which can be found in Appendix A, was applied to the model in order to initialize the shape of the interface between the steel and the slag using the Bikerman shape [28], which is defined by Equations 2.33 and 2.34. A transient fluid flow only simulation was then run for 2000 iterations using a time step of $1 \times 10^{-5}$.

Once the interface between the slag and steel was smoothed this step was considered complete.

$$x = x_o - \sqrt{2b^2 - y_b^2} + \frac{b}{\sqrt{2}} \ln \frac{b\sqrt{2} + \sqrt{2b^2 - y_b^2}}{y_b}$$ (2.33)

where:

$x$: Horizontal distance from the wall where the phases meet [$m$]

$y_b$: Vertical distance below the far field meniscus, which is located at a $y$-coordinate of 105 [$mm$] above the bottom of the domain

$$x_o = b - \frac{b}{\sqrt{2}} \ln(\sqrt{2} + 1) \quad \text{and} \quad b^2 = \frac{2\gamma_{Fe(l)} - sl}{g(\rho_{Fe} - \rho_{sl})}$$ (2.34)

where:

$\gamma_{Fe(l)} - sl$: Surface tension between the molten steel and the liquid slag [$\frac{N}{m}$]
\( \rho_{Fe} \): Density of the steel \( \frac{kg}{m^3} \)

\( \rho_{sl} \): Density of the slag \( \frac{kg}{m^3} \)

- Thermal Only Steady State Simulation - The second modeling step was a thermal only simulation. The purpose of this step was to initialize the temperature field and create an initial steel shell. In this simulation the Energy and Solidification and Melting models were turned on. However, in order to prevent convective effects from altering the initial temperature field and the steel shell, the flow equation was turned off and all velocities in the fluid domain were set to zero using the patch option. Additionally, the turbulence model was turned off, so the momentum equations simplify to laminar. An ”adjust” user-defined function called ”fix_temp_initial” was used to fix the temperature in the fluid region and to initialize the steel shell shape. This function can be found in Appendix A. This equation uses results found by Zhang and Wang et al. [25], which describe the relationship between the distance down the mold and the shell thickness, to define the initial steel shell shape. This relationship is shown in Equation 2.35, where \( s[mm] \) is the shell thickness and \( t_s[min] \) is the time after the shell is formed.

\[
s = 13.85\left(\frac{mm}{\sqrt{min}}\right) \times \sqrt{t_s[min]} \]

\[
s = 1.79\left(\frac{mm}{\sqrt{s}}\right) \times \sqrt{t_s[s]} \]  

(2.35)

The goal of this step was to find a steady state solution to the temperature field, therefore this step was done as a steady state simulation. In order to reach a converged solution the under relaxation factor of the energy equation was systematically decreased throughout the simulation. To begin the relaxation factor was set to the default of 1. The simulation was then run until the residual no longer changed. Then the under relaxation factor was decreased to 0.99. This small shift in the under relaxation factor changes the residual dramatically. This simulation was then run out until the residual no longer changed. Then the relaxation factor was dropped to 0.9 and from here on the same procedure was followed, but the under relaxation factor was decreased by 0.1 each time until the solution converged. This solution method was deemed acceptable as this simulation step’s sole purpose is to produce an adequate initial guess for the temperature profile in the domain. Once the solution has converged the resulting temperature profile and steel shell shape provided a good initial thermal profile to begin the next simulation step.

Convergence is met when the global residuals all drop below the values specified in Table 2.3.
Each global residual is defined as the average of all the absolute values of the residuals for that variable in the entire domain, normalized to equal one for the first iteration.

- Coupled Thermal and Fluid Flow Simulation - Once the thermal profile was initialized the velocity profile was reintroduced. The first step to do this was to remove the "fix_temp_initial" function from the model and replace it with the "fix_steel_temp" function. Additionally, the under-relaxation factor for the energy equation was set back to 1. This function adjusts the temperature at each time step to ensure that the region near the steel inlet and the interface between the slag and the steel remains liquid and therefore the appropriate amount of superheat is provided to each of these regions. Additionally, the user-defined function "fix_shell_vel" was included in the model, which sets the y-velocity of the steel shell to the casting speed. Both of these functions can be found in Appendix A.

The velocity was reintroduced by changing the simulation back to a transient simulation, turning the flow equation back on, turning the turbulence equation back on, and then setting the turbulence parameters within the domain, $k$ and $\omega$, to $1 \times 10^{-5} \frac{J}{kg}$ and $1 \times 10^{-5} \frac{1}{s}$, respectively, as an initial guess value using the patch feature. The transient simulation was then run using a time step of $1 \times 10^{-5} s$ until the velocity profile was reintroduced. This simply means that steel can visibly be seen moving from the steel mass flow inlet to the steel outlet.

Due to the fact that this model has been solved previously by Yan [5], the velocity profile was reintroduced to the model using a different method. [5] The velocity and pressure profiles from an already working version of this model created by Yan were exported from the working model and then imported into the current model. The transient simulation was then run out to adjust the profile to match the current model.

- Coupled Thermal and Fluid Flow Simulation with Mold Oscillation - Once the thermal and fluid flow profiles were initialized in the model the next step was to add mold oscillation. Up until this point the mold walls all remained stationary. At this step the user-defined functions "Mesh_vel" and "Mold_oscillation" were applied to the mesh and the coupled boundary between the mold and fluid domains respectively, which once again can be found in Appendix A. Then the transient simulation was continued using a fixed time step of $1 \times 10^{-5} s$. During each time step the simulation was allowed to iterate up to 20 times, but the solution converged to the global residuals, which is the residual that the average residual for the entire domain is required to meet before moving to the next time step, specified in Table 2.3 during each time step typically within 5 iterations. The under-relaxation factors were all left as the default FLUENT value for the final simulation shown in Table 2.4. [6] The model and was run out until a pseudo steady state solution was achieved in the model.
this model were then used as the set of initial conditions for the start of the base case, which will be discussed in Chapter 3.

Within Fluent several choices must be made to determine how Fluent will solve the model. The choices made for the solution method for each equation in the model are listed below:

- Pressure-Velocity Coupling - The model used a pressure-based solver to solve for the pressure-velocity coupling. This essentially means that the model is able to use the continuity and Navier-Stokes equations to solve for the pressure field and velocity fields. This model is able to use the pressure-based solver because the fluids are incompressible and the model does not contain any

<table>
<thead>
<tr>
<th>Equation</th>
<th>Residual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuity</td>
<td>$1.5 \times 10^{-4}$</td>
</tr>
<tr>
<td>X-Velocity</td>
<td>$6.0 \times 10^{-4}$</td>
</tr>
<tr>
<td>Y-Velocity</td>
<td>$6.0 \times 10^{-4}$</td>
</tr>
<tr>
<td>Energy</td>
<td>$1.0 \times 10^{-6}$</td>
</tr>
<tr>
<td>Turbulent Kinetic Energy</td>
<td>$1.0 \times 10^{-3}$</td>
</tr>
<tr>
<td>Turbulent Dissipation Rate</td>
<td>$1.0 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

Table 2.3 Global Residual Values Chosen for Each Equation Solved in the FLUENT Model

Table 2.4 Under-Relaxation Factors Chosen for Each Equation Solved in the FLUENT Model

<table>
<thead>
<tr>
<th>Equation</th>
<th>Under-Relxation Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>0.3</td>
</tr>
<tr>
<td>Momentum</td>
<td>1.0</td>
</tr>
<tr>
<td>Body Forces</td>
<td>1.0</td>
</tr>
<tr>
<td>Momentum</td>
<td>0.7</td>
</tr>
<tr>
<td>Turbulent Kinetic Energy</td>
<td>0.8</td>
</tr>
<tr>
<td>Specific Dissipation Rate</td>
<td>0.8</td>
</tr>
<tr>
<td>Turbulent Viscosity</td>
<td>0.8</td>
</tr>
<tr>
<td>Liquid Fraction Update</td>
<td>0.9</td>
</tr>
<tr>
<td>Energy</td>
<td>1.0</td>
</tr>
</tbody>
</table>

high velocity flows. Within the pressure-based method there are multiple solution methods that are available. This model utilizes the Semi Implicit Method for Pressure Linked Equations - Consistent (SIMPLEC). This method is a part of the SIMPLE family. SIMPLE is the default solver in FLUENT to solve pressure-based models. The SIMPLEC method varies from the SIMPLE method in that it has the ability to reduce convergence times when the pressure-velocity coupling is found to be the source of slow convergence. When there is no pressure-velocity coupling convergence issues the two methods tend to converge in similar time. [6] In this model any convergence challenges encountered have been due to the continuity or momentum equations and therefore it was found that the model may benefit from the SIMPLEC method.

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• Gradient - The solution method used for the gradient is the Least Squares Cell-Based Method, which assumes that the solution varies linearly between cell centers. This method is the default method in FLUENT for the gradient due to its good accuracy and its relatively low compilation time. [6]

• Pressure - To solve for the pressure this model used the PRESTO! method, or the Pressure Staggering Option. This method solves for the pressure at each cell face using a staggered discretization, which improves the accuracy of the solution.

• Momentum - The Second Order Upwind approach was used to solve the momentum equations. This is due to the high Reynold’s numbers found in the regions of the fluid domain.

• Volume of Fluid Method - The interface between the slag and the steel was solved using the geometry reconstruct method, which uses a piece-wise linear approach to first calculate the interface between the two fluids. The volume fraction is calculated based on the fluxes found during the previous time step. [6]

• Turbulence Equations - The turbulence equations were solved using a First Order Upwind approach, which is again due to the high Reynold’s numbers found in some regions of the fluid domain.

• Energy - The Energy equation was solved using a First Order Upwind approach. This method was chosen due to the Peclet number ranging from 2.5 to 71.5 in various regions of the domain. The thermal Peclet number is defined by Equation 2.36. [29]

\[ Pe = \frac{lu}{\alpha} \]  

where:
- \( l \): Length scale of the fluid flow [\( m \)]
- \( u \): Velocity in a Given Cell [\( \frac{m}{s} \)]
- \( \alpha \): Thermal Diffusivity [\( \frac{W}{mK} \)]

• transient Formulation - The transient solution was solved using a First Order Implicit Method. This method was chosen to be implicit to increase accuracy of the solution and first order as opposed to second order to reduce computational time. [6]

2.3 Conclusions

This model solves the continuity, momentum, and energy equations using ANSYS FLUENT. This model includes steel, slag, and copper. The material properties of all components were summarized in this chapter. The interaction between the slag and the steel was calculated using the Volume of Fluid method. Additionally, this model includes a solidification and melting model and the \( k - \omega - SST \) turbulence
model. Various submodels have been created to validate certain boundary conditions and their results were described in this chapter. Additionally, all boundary conditions have been defined. Lastly, a discussion on the computational method used to initialize the model was included in this section. This chapter outlined all the necessary information to build the current model. Chapter 3 will discuss validation of the model.

2.4 Chapter 2 References


CHAPTER 3
MODEL VALIDATION

Prior to using the model described above to complete studies on various parameters of interest, this model was run using casting conditions from an experiment performed by Zhang and Wang et al. [1] to validate the model. Additionally, this base case serves as a point of reference for all of the parametric studies. This case uses all the material properties and computational properties described in Chapter 2. The casting conditions from this case are shown below in Table 3.1 and the mold position and mold velocity for the base case are shown in Figure 3.1.

Table 3.1 Casting Conditions for the Base Case

<table>
<thead>
<tr>
<th>Condition</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>1.67</td>
<td>Hz</td>
</tr>
<tr>
<td>Stroke</td>
<td>10</td>
<td>mm</td>
</tr>
<tr>
<td>Modification Ratio</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Casting Speed</td>
<td>0.6</td>
<td>m/min</td>
</tr>
<tr>
<td>NST</td>
<td>0.263</td>
<td>s</td>
</tr>
<tr>
<td>Steel Solidus Temperature</td>
<td>1795</td>
<td>K</td>
</tr>
<tr>
<td>Steel Liquidus Temperature</td>
<td>1800</td>
<td>K</td>
</tr>
</tbody>
</table>

![Figure 3.1 The Mold Position and Mold Velocity for the Base Case](image_url)

In Figure 3.1 the maximum upward velocity of the mold is labeled Maximum Velocity and the maxi-
mum downward velocity is labeled Minimum Velocity. At many points throughout this report and in many figures found in this report the terms maximum velocity or max velocity and minimum velocity or min velocity are used to describe these times on the mold velocity curve. To further clarify what the maximum and minimum velocity looks like in the slag gap these two velocities are shown in Figure 3.2.

![Diagram showing the mold, solid slag, liquid slag, solidified shell, casting speed, the maximum velocity profile in the slag gap, and the minimum velocity in the slag gap.](image)

Figure 3.2 A Diagram Showing the Mold, Solid Slag, Liquid Slag, Solidified Shell, Casting Speed, The Maximum Velocity Profile in the Slag Gap, and The Minimum Velocity in the Slag Gap

3.1 Temperature and Velocity Results

The model was run for 10 cycles and the first three oscillation marks were left out of the data analysis in order to ensure that the model was adjusted to the casting conditions. The bulk fluid flow patterns are shown in Figure 3.3. In this temperature contour plot it can be seen that the fluid enters the domain at the steel mass flow inlet, on the right side of the domain, which represents a turbulent eddy near the top of the mold close to the meniscus that persists for approximately 10 seconds. The bulk fluid motion then induces two smaller fluid flow recirculation zones, one above the bulk flow and one below the bulk flow. The yellow region in the steel near the mold wall in this, and all temperature contours to come, represents the top of the solidified shell. As the shell moves down the mold it grows, cools, and is then in the temperature range of 1500 - 1795 °K, and therefore appears as a combination of yellow and green at the domain exit.
Figure 3.3 A Broad View Temperature Contour of the FLUENT Model Using Base Case Conditions
Temperature contour plots showing the meniscus region for the mold upstroke and the mold downstroke are shown in Figures 3.4 and 3.11 respectively. During the upstroke it can be seen that the molten steel was pulled near the mold wall due to the pressure caused by the upward mold motion. Throughout the downstroke the pressure caused by the slag rim pushes the molten steel away from the mold. There was no hook formed in this case, as the superheat in the meniscus region was relatively high.

Figure 3.4 The Temperature Contour in Meniscus Region for the Base Case When the Mold is at a) the End of NST b) Half Way Between the END of NST and the Maximum Velocity b) the Maximum Velocity d) Half Way Between the Maximum Velocity and the Start of NST

3.2 Sensitivity Study

The turbulent fluid flow pattern shown in the base case is one of many possible fluid flow patterns that can exist during a short period of time in the meniscus region. Therefore, to verify that changing the fluid flow pattern in the meniscus region will not significantly change the oscillation mark profiles that are created by the model two additional cases were studied which utilize different mass inlet conditions. The first case, Sensitivity Case 1 (SC1), utilized the same mass flow rate user-defined function used in the base
case, called "steel_mass_inlet" in Appendix A, but the direction of flow at the mass inlet boundary was directed downwards at a 45 degree angle, with respect to the normal to the boundary, in the negative x and y direction. The fluid flow pattern created by this boundary condition is shown in Figure 3.5. The second case, Sensitivity Case 2 (SC2), split the steel inlet boundary into two halves and directed 10% of the flow through the top half of the boundary and the remaining 90% of the flow through the bottom half of the boundary. The flow through both the top and the bottom of the boundary was directed downwards at a 45 degree angle as well. The fluid flow patterns created during this simulation varied greatly throughout the simulation. The fluid flow patterns at three selected times during the simulation are shown in Figures 3.6 through 3.8.

Figure 3.5 Temperature Contour Plot and Velocity Profile Found in the Base Case with An Angled Mass Flow Inlet at Time 14.119 Seconds
Figure 3.6 Temperature Contour Plot and Velocity Profile Found in the Base Case with An Angled and Stepped Mass Flow Inlet at Time 11.524 Seconds
Figure 3.7 Temperature Contour Plot and Velocity Profile Found in the Base Case with An Angled Mass Flow Inlet 12.524 Seconds
The shell profiles found for cases SC1 and SC2 are plotted along with the base case in Figure 3.9 and the average oscillation mark profiles are compared in Figure 3.10. The oscillation mark pitch, depth, width, surface roughness, and standard deviation, the average heat flux, and the average mold friction are compared for the base case, case SC1, and case SC2 in Table 3.2. It can be seen that the oscillation mark profiles agree very well with one another and that the differences found in the data are not significant enough to attribute the differences to anything but the general fluctuations found in the model due to the fact that turbulence is present. The average mold friction values did change substantially, which is likely due to the fact that during these simulations the molten steel level rose in the meniscus region, which led to more resistance to the downward motion of the mold.
Figure 3.9 Comparison of the Shell Profiles Found for Cases SC1 and SC2 to the Shell Profile Found for the Base Case

Figure 3.10 Comparison of the Average Oscillation Mark Profile Found for Cases SC1 and SC2 to the Average Oscillation Mark Profile Found for the Base Case
The formation of oscillation marks is dominated by the oscillation of the mold and the solidification of the steel shell. Due to the low velocities found near the solidification front the fluid flow patterns found in the remainder of the mold and the turbulence in the meniscus region do not significantly impact the shape and depth of the oscillation marks. The turbulent nature of the flow allows for the oscillation mark shapes to vary slightly from cycle to cycle, but it does not dramatically change these features. Therefore, while the fluid flow pattern used in the base case only represents one of many turbulent fluid flow patterns it is a representative fluid flow pattern for conducting parametric studies of the meniscus region.

Additionally, it can be concluded that the oscillation mark shape is not sensitive to the constants chosen for the turbulence model. The maximum error found in the oscillation mark shape from these studies was found to be 6.1%. This error can be attributed to both error from the turbulent fluid flow pattern and numerical error. These results also suggest that choice of domain, which is missing most of the liquid pool in the mold, is likely not important to the oscillation mark formation at the meniscus.

### 3.3 Oscillation Mark Depth Results

The resulting steel shell profile of the base case is shown in Figure 3.12 along with a steel shell profile that was found experimentally by Zhang and Wang et al. [1] The results show that in both the FLUENT model and the experiment the slag thickness varied between 1.4-1.8 mm. In Zhang and Wang’s experiment only the two oscillation marks closest to the meniscus can be considered for comparison. During the start-up of the experiment the very deep mark seen in the region 35-50 mm below the far field meniscus was formed. This was considered to be a transverse depression associated with colder steel at the startup of the experiment, and therefore can’t be considered an oscillation mark forming under the pseudo-steady state conditions of the current model. [1] The oscillation marks found by Zhang and Wang runge in depth from 0.2-0.4 mm and the oscillation marks calculated by the FLUENT model runge in depth from 0.3-0.6 mm. The average oscillation mark profile calculated from the seven oscillation found using the FLUENT

---

Table 3.2 Oscillation Mark Statistics for the Sensitivity Study

<table>
<thead>
<tr>
<th></th>
<th>BC</th>
<th>SC1</th>
<th>SC2</th>
<th>Percent Difference</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BC - SC1 [%]</td>
<td>BC - SC2 [%]</td>
<td>Units</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Theoretical Pitch</td>
<td>5.99</td>
<td>5.99</td>
<td>5.99</td>
<td>[-]</td>
<td>[-]</td>
</tr>
<tr>
<td>Calculated Pitch</td>
<td>6.05</td>
<td>6.25</td>
<td>6.21</td>
<td>3.3</td>
<td>2.6</td>
</tr>
<tr>
<td>Average OM Width</td>
<td>5.855</td>
<td>5.920</td>
<td>5.771</td>
<td>1.1</td>
<td>1.4</td>
</tr>
<tr>
<td>Average OM Depth</td>
<td>0.313</td>
<td>0.294</td>
<td>0.329</td>
<td>6.1</td>
<td>5.1</td>
</tr>
<tr>
<td>Surface Roughness, Ra</td>
<td>178.6</td>
<td>174.3</td>
<td>185.0</td>
<td>2.4</td>
<td>3.6</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.137</td>
<td>0.111</td>
<td>0.113</td>
<td>18.9</td>
<td>17.5</td>
</tr>
<tr>
<td>Average Heat Flux</td>
<td>1.291</td>
<td>1.387</td>
<td>1.382</td>
<td>7.4</td>
<td>7.0</td>
</tr>
<tr>
<td>Average Mold Friction</td>
<td>0.970</td>
<td>1.537</td>
<td>0.787</td>
<td>58.5</td>
<td>18.9</td>
</tr>
</tbody>
</table>
model is shown in Figure 3.13.

Figure 3.11 Temperature Contours in Meniscus Region for the Base Case When the Mold is at a) the Start of NST b) Half Way Between the Start of NST and the Minimum Velocity b) the Minimum Velocity d) Half Way Between the Minimum Velocity and the End of NST

The average oscillation mark profile was found to be 0.313 mm deep and 5.855 mm wide and corresponds with a surface roughness of 178 µm. The surface roughness was found using the Ra method shown in Equation 3.1. This method was used to calculate the surface roughness as it was found to be the most internationally accepted method. [2] The average pitch of the oscillation marks was calculated to be 6.05 mm using Equation 3.2, which agrees with the theoretical value of 5.988 mm within a reasonable expected variation of 1%. These results show that the model is capable of producing realistic oscillation marks. However, since Zhang and Wang were only able to collect data on 2 oscillation marks there was not enough data to say whether the deeper oscillation marks calculated with the FLUENT model is significant. Additionally, this figure shows that the deepest point of the oscillation mark occurs at the end of NST. Therefore, the first half of the oscillation mark was created during the downstroke and the second
half of the oscillation mark was formed during the upstroke, which suggests that the upward motion of the molten steel is a more stable process than the change in fluid flow caused by the downstroke.

\[
Ra = \frac{1}{L} \int_0^L |Z(x)| \, dx
\]  

(3.1)

where:

\(L\): Length of the steel shell \([m]\)

\(Z(x)\): Distance of the steel shell surface profile from the average slag gap \([m]\)

\[
\text{pitch theoretical} = \frac{v_c}{f}
\]  

(3.2)

where:

\(v_c\): Casting speed \([\frac{m}{s}]\)

\(f\): Frequency \([Hz]\)

Data collected from plant experiments performed by Shin et al. [4] showed that oscillation mark depths in a real caster can vary from 0.2-0.8 mm, and that at the casting conditions used by Zhang and Wang the predicted oscillation mark depths range from 0.5-0.6 mm. [4] Therefore, it can be concluded that the model accurately predicts oscillation mark profiles and that the shallower oscillation marks found by Zhang and Wang may be due to differences between a real caster and the experimental set-up or due to the fact that not enough oscillation marks were not collected to conclude anything further about the oscillation mark depth.

3.4 Shell Thickness Results

The steel shell thickness of the base case found using the FLUENT model is shown in Figure 3.14, where the far field meniscus is located at the y-coordinate 105 mm above the bottom of the domain. The growth of the steel shell can be described as a square root time relationship, shown in Equation 3.3, where the parameter \(K\) is dependent on particular casting conditions and time equals zero is defined as starting at 5 mm below the far field meniscus.

\[
s = K \sqrt{t}
\]  

(3.3)

where:

\(s\): Shell thickness \([mm]\) = \(x - x_o\)

\(x_o\): The slag gap thickness \([mm]\)
\( K \): Solidification factor \[ \frac{m m}{\sqrt{\sigma}} \text{ or } \frac{m m}{\sqrt{m m}} \]

\( t_s \): Solidification time \([s \text{ or } min]\)

Figure 3.12 a) Steel Shell Profile Found by Zhang and Wang [1] b) Steel Shell Profile Calculated in FLUENT During the Validation Study Using Wang’s Casting Conditions
Zhang and Wang et al. calculated the K value of the shell formed during the experiment to be 1.79 $mm/\sqrt{s}$. [1] The value of K was found from the results of the FLUENT model to be 1.33 $mm/\sqrt{s}$. The differences in the two values may be influenced by differences in the way the solidified shell was defined in the two scenarios. The solidified shell was defined in Figure 3.3 as the liquidus line, but in the plant experiment the shell is measured after the extractor has been removed from the molten steel bath. Therefore, steel that was in the "mushy region" while the extractor was still in the steel bath likely remained on the extractor and solidified completely as the extractor was drawn out of the molten steel bath. This caused the shell to appear thicker in the experiment. The K values calculated in the FLUENT and the experimental results of Zhang and Wang et al. [1] are both low relative to K values found for shell growth that considers the steel shell down to mold exit, which have been been measured experimentally to be approximately 3 $mm/\sqrt{s}$ [3]. The lower values found in the meniscus region are likely due to the high superheat found in the experimental set-up, which was also applied to the FLUENT model. Additionally, near the meniscus when an oscillation mark is present it is observed that the shell is thinner than the shell in the same region where an oscillation mark is not present. This is due to the increase in thermal resistance that is created by additional slag being present in the oscillation mark, which has been reported in many previous experimental studies. [3] Furthermore, the shell thickness variations caused by the oscillation marks become less sever with distance down the mold, which again is expected. [3]
3.5 Heat Flux Results

Heat flux profiles of the base case were calculated by Zhang and Wang et al. using a 2D inverse heat conduction approach, which uses temperature data collected by thermocouples embedded in the mold to determine the heat flux at the mold hot face. The heat flux profiles calculated by Zhang and Wang only extend 8 mm below the far field meniscus. The average heat flux in the region below the far field meniscus calculated by Zhang and Wang et al. was 1.1 MW/m². The heat flux profile found for the base case is shown in Figure 3.15. In this figure and in all figures in the future that reference the ”max” and ”min” velocity these terms represent the maximum upward velocity of the mold and the minimum downward velocity of the mold. In this figure it can be seen that the high heat flux in the meniscus region also moves upward during the upstroke, and extends the furthest up the mold at the start of NST. Then as the molten steel is pushed away from the mold wall between the start of NST and the end of NST the heat flux in the region above the far field meniscus decreases.

The heat flux profiles found using the FLUENT model are in the Eulerian frame of reference, while the experimental results were found using the Lagrangian frame of reference, which makes comparing these observations to those found by Zhang and Wang et al. difficult. [1] The average heat flux calculated with the FLUENT model was 1.29 MW/m², which compares with the experimental measurements within 17.3%. The discrepancy in the average heat flux values might be attributed in part to differences in slag
properties. The slag modeled in the FLUENT model was based on the slag information provided by Shin et al. [4], which is a glassy slag. The slag reported by Zhang and Wang et al. [1] was found to be more crystalline than the slag reported by Shin. More information on the difference between glassy and crystalline slags can be found in the Section 4.3 of this report, but the important difference between these two slags is that the slag modeled in FLUENT has a higher thermal conductivity in the liquid slag than the slag used by Zhang and Wang et al. Therefore, the heat flux should be larger for the FLUENT model.

Figure 3.15 The Heat Flux Profile Along the Mold Hot Face for the Base Case at Various Mold Positions

3.6 Mold Friction and Slag Gap Pressure Results

Beyond the validation of the model there are additional parameters of interest that can be studied with the base case of this model. One of these is the mold friction. The mold friction profile calculated for the base case along the mold hot face is shown in Figure 3.16. Positive mold friction is defined as the friction force that points in the positive y-direction along the mold hot face. Therefore, positive mold friction is defined as the force that pushes up on the liquid slag and the slag rim, while the negative mold friction pulls down on the liquid slag and the slag rim. The maximum friction pushing the mold upward was found at the end of NST at the far field meniscus level. This is likely due to the friction caused by the increased resistance of the gap material in the meniscus region pushing upwards at the end of NST. The average mold friction calculated for the base case was 0.970 kN/m. This value was found by averaging the mold fric-
tion over the mold hot face and then averaging this value over time. The friction value is very small in comparison to values based on the entire mold found in plant experiments [5] because there is good liquid slag lubrication in the top portion of the mold.

Figure 3.16 The Mold Friction Profile for the Base Case at Various Mold Positions Throughout the Oscillation Cycle

The pressure was studied within the slag gap, 0.65 mm from the mold hot face, for the base case and is plotted in Figure 3.17 at various mold positions. The pressure in the slag gap increases substantially at the end of NST 5 mm below the far field meniscus. This is due to the position of the slag rim at the end of NST. At the end of NST the slag rim has moved down towards the far field meniscus, which moves the slag out of this region and into the slag gap between the mold and the shell (on the left) and into the top surface slag layer (on the right). This causes the pressure in the region right below the far field meniscus increases dramatically. Additionally, the pressure was studied over time at three positions. The first position selected was near the steel shell tip, at the coordinate (1, 97), which is 1 mm from the mold hot face and 97 mm above the bottom of the domain. The second location selected was above the meniscus, at the coordinate (5, 107), which is 5 mm from the mold hot face and 107 mm from the bottom of the domain. The last location that was selected was in the slag gap, at the coordinate (1, 92), which is 1 mm away from the mold hot face and 92 mm above the bottom of the domain. The selected locations are shown in Figure 3.18. The pressure plotted over time for all three locations is shown in Figure 3.19. It was found that the
slag pressure is at a maximum near the steel shell tip and in the slag gap at the end of NST. This is logical because this is when slag is being infiltrated into the slag gap. The pressure above the meniscus was found to be negligible in comparison to the pressure found in the slag gap. These results all agree well with the mold friction results. The maximum mold friction should correspond to the greatest pressure in the slag gap.

![Graph showing pressure in the slag gap for various mold positions.](image)

Figure 3.17 The Pressure in the Slag Gap for the Base Case at Various Mold Positions Throughout the Oscillation Cycle 0.65 mm from the Mold Hot Face

![Graph showing points selected for studying pressure over time.](image)

Figure 3.18 The Points Selected to Study the Pressure Over Time near the Steel Shell Tip, Above the Meniscus and, in the Slag Gap
3.7 Slag Velocity and Consumption Results

The time-variation velocity profile of the slag across the slag gap was found for the base case 30 mm below the far field meniscus and is shown in Figure 3.20. The maximum upward and minimum downward slag velocities are found at the points half way between the end of NST and the start of NST, when the mold is at a maximum and minimum velocity. In this figure the regions where the velocities were found to be flat correspond to solidified slag, which moves up and down with the mold. The velocity in the slag gap contributes to the slag consumption. The slag consumption is split into two kinds of consumption. The lubrication slag consumption is the slag that lubricates the steel shell and occurs due to the slag being pulled into the gap and traveling down in between the mold and the steel shell. The average lubrication slag consumption is calculated using Equation 3.4, where $q_{lub}$ is the lubrication slag consumption, $v_{slag}$ is the slag velocity, $d_{gap}$ is the slag gap, and $\rho_{slag}$ is the density of the slag. The average lubrication slag consumption was found to be 3.709 g/m$^2$/s. The lubrication slag consumption is plotted over time in Figure 3.21, where positive slag consumption means slag is moving down into the slag gap between the steel shell and the mold wall. The consumption was found to increase during NST as the mold moves down and the velocity in the gap becomes negative. The second kind of slag is oscillation mark slag consumption, which is due
to slag being entrapped in oscillation marks and traveling down within the oscillation marks. This kind of slag consumption does not contribute to lubrication in the gap. The average oscillation mark consumption can be found by integrating the average oscillation mark profile to find the value $A_{OM}$ and then Equation 3.5 can be used to calculate the value of the oscillation mark consumption. The average oscillation mark consumption found for the base case was 4.177 g/m * s, which then resulted in a total slag consumption of 7.886 g/m * s, according to Equation 3.6. The total consumption value was found to be higher than the consumption predicted by Shin et al. [4] for the base case casting conditions. This is due to the slag gap in Shin’s cases being much thinner, approximately 3 times thinner, than the slag gap calculated using the current model. [4] Slag consumption can also be communicated as the consumption per cycle with units of $q/(m*cycle)$ or the consumption per unit area with units of $kg/m^2$, which are shown in Equations 3.7 and 3.8 respectively.

The lubrication slag consumption was found to increase over time. This is because the slag gap grows thicker over time. As the base case was run out for 15 cycles it was found the slag gap thickness will increase over time, which is shown in Figure 3.22. This was likely due to the fact that the shell was still adjusting to a pseudo-steady state solution. Even 15 cycles is less than 10 seconds of time in an actual caster. Over a ten second time period the shell is likely to continue to adjust, which will lead to changes in the slag gap thickness and the steel shell growth.

\[
q_{lub} = v_{slag} d_{gap} \rho_{slag} \tag{3.4}
\]

\[
q_{OM} = A_{OM} \rho_{slag} f \tag{3.5}
\]

\[
q_{tot} = q_{OM} + q_{lub} \tag{3.6}
\]

\[
q_{tot} = (q_{OM} + q_{lub}) \frac{1}{f} \tag{3.7}
\]

\[
q_{tot} = (q_{OM} + q_{lub}) \left( \frac{1kg}{1000g} \right) \left( \frac{1}{v_c} \right) \tag{3.8}
\]
Figure 3.20 The Slag Velocity Profile in the Slag Gap, 30 mm Below the Far Field Meniscus, the Base Case at Various Mold Positions Throughout the Oscillation Cycle

Figure 3.21 The Lubrication Slag Consumption Found for the Base Case Plotted Over Time
3.8 Model Verification

Several simulations were made in order to verify that the model is accurately solving the equations in the model. The meniscus shape at the slag/steel interface can be solved for analytically using the Bikerman Equation. Additionally, the fact that the model achieves a pseudo-steady state under the base case conditions, which show that the model is returning to the same state after each cycle further verifies this model. During each cycle the model calculates the same set of mathematical equations, with the exception of the variations that occur due to the turbulent fluid flow. Therefore, any differences found in the oscillation mark shape, heat flux, and mold friction profiles can be attributed to either variations caused by turbulence or numerical error.

3.8.1 Bikerman Verification

The Bikerman Equation shown in Chapter 2 is the analytical solution to the shape formed in the meniscus region due to the difference in density between the two fluids and the interfacial surface tension between them. The slag/steel interface, which can be defined as the steel volume fraction, $\alpha_p$, of 0.5, is compared to the Bikerman Equation in Figure 3.23. These two profiles agree within 0.27% in the meniscus region.

Figure 3.22 All Oscillation Marks Calculated by FLUENT in the Validation Study Superimposed with the Average Shell Oscillation Mark Profile
3.8.2 Cyclic Nature Verification

This model solves the same equations during each cycle. Therefore, the results of each cycle should be the same as all subsequent cycles, and any error can be attributed to numerical error and differences caused by the turbulent fluid flow present in the model. The cyclic nature of the oscillation mark profile and fluid flow patterns are shown in Section 3.4. The average difference in the oscillation mark depth from one oscillation mark to the subsequent oscillation mark was found to be 28.1 %, which corresponds with the standard deviation of the oscillation mark depth given in Table 3.2. Additionally, the heat flux profile and the mold friction profile for the base case are plotted over two cycles, which are shown in Figures 3.24 and 3.25. The two cycles that are compared in these figures are the fourth and fifth oscillation marks reported in Figure 3.12. From cycle to cycle the heat flux profiles agreed with one another with an average error of 2.9 %, and the mold friction profiles agreed with one another with an average error of 11.0 %. The cyclic nature created by the mold oscillation can be seen to cause the oscillation mark profile, the heat transfer, the mold friction, and the fluid flow patterns to reach a pseudo-steady state. The variations seen in the oscillation mark profile, from cycle to cycle, can be attributed to the turbulent fluid flow present in the model causing variations in the equations solved during each cycle. These variations are similar to the variations seen in cases SC1 and SC2 shown in the sensitivity study, found in Section 3.2. This suggests that the model is numerically reasonable and that the equations are being solved accurately.
3.9 Mesh Refinement Study

A mesh refinement study was performed, which compares the mesh that was chosen for the base case with a refined mesh. The mesh chosen for the base case and all subsequent parametric studies contains 87,862 elements. The elements in this mesh ranged in size from 50 \( \mu m \) by 50 \( \mu m \), in the meniscus region and the steel shell region, to 1 mm by 1 mm elements in the steel bulk fluid flow region. This mesh was compared with a mesh where all elements were reduced in size. The refined mesh contained 327,924 elements. The refined mesh contained elements that ranged in size from 15 \( \mu m \) by 15 \( \mu m \), in the meniscus and steel shell region, to 24 \( \mu m \) by 24 \( \mu m \) in the steel bulk fluid flow region.

The quality of the two meshes are characterized by the mesh orthogonality, skewness, and aspect ratio. [6] For the mesh used in the base case the orthogonality, skewness, and aspect ratio were found to be 0.975, 0.025, and 1.254, respectively, while those values for the refined mesh were found to be 0.99, 0.0058, and 2.217. Therefore, the refined mesh was slightly higher quality in terms of orthogonality and skewness, and the base case mesh was found to be slightly higher quality in terms of the aspect ratio. The quality of the mesh was found to have a very important effect on the results.

The results of the refined mesh were compared with results of the current model prior to mold oscillation being introduced to the model. The slag/steel interface is compared in the meniscus region for the two versions of the model in Figure 3.26, and these profiles were found to have an average percent difference of 2.53% in the meniscus region. The interface profiles agreed very closely with one another in the meniscus region. The differences between the interface shapes further away from the mold might be attributed to differences in fluid flow, as discussed in the sensitivity section. The velocity in the slag gap for both versions of the model are shown in Figure 3.27 and it was found that these profiles agree very well in shape. The velocity does differ between the two versions of this model, but the differences are negligible due to the fact that the mold is not oscillating. Lastly, the heat flux profile was found along the mold hot face for both models, which are shown in Figure 3.28. The average difference in the profiles was found to be 5.43%.

The refined model was found to require a 600% increase in computation time. Therefore, considering that the results from this refined mesh were very similar (and no better than) those from the base case mesh, the parametric studies in the next section were performed with the base case mesh, as the extra computation time was not found to provide a benefit.
Figure 3.24 Comparison of the Heat Flux Profile Found Along the Mold Hot Face for 2 Cycles

Figure 3.25 Comparison of the Mold Friction Profile Found Along the Mold Hot Face for 2 Cycles
Figure 3.26 The Slag/Steel Interface Found for the Base Case and the Base Case with a Refined Mesh

Figure 3.27 The Velocity in the Slag Gap Found for the Base Case and the Base Case with a Refined Mesh
Figure 3.28 The Heat Flux Profile Along the Mold Hot Face Found for the Base Case and the Base Case with a Refined Mesh

3.10 Chapter 3 References


CHAPTER 4
PARAMETRIC STUDIES

Many parameters in the model may influence the shape of oscillation marks. Therefore, the validated model was altered to accommodate for different oscillation conditions, casting speeds, slag properties, molten steel levels, and temperature dependent surface tension relationships. The results of these studies are summarized in this chapter.

4.1 Oscillation Conditions Study - Frequency, Stroke, and Modification Ratio

The casting conditions parametric study aims to determine how the frequency, stroke, and modification ratio of the oscillation impact the shape of oscillation marks and mechanism used to create them. Therefore, this study is split into three separate sections.

4.1.1 Frequency Study

In the frequency study all geometry, boundary conditions, user-defined functions, and material properties specified for the base case remain constant throughout all simulations. The only parameter that was altered was the frequency of the mold oscillation. This study provides additional information that has not yet been observed in plant trials. [18] The frequencies that were considered in this study are shown below in Table 4.1.

<table>
<thead>
<tr>
<th>Case</th>
<th>Frequency [Hz]</th>
<th>Theoretical Pitch [mm]</th>
<th>NST [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC</td>
<td>1.670</td>
<td>5.98</td>
<td>0.263</td>
</tr>
<tr>
<td>F1</td>
<td>1.760</td>
<td>5.68</td>
<td>0.251</td>
</tr>
<tr>
<td>F2</td>
<td>2.093</td>
<td>4.78</td>
<td>0.216</td>
</tr>
<tr>
<td>F3</td>
<td>2.427</td>
<td>4.12</td>
<td>0.189</td>
</tr>
</tbody>
</table>

The oscillation marks found in this study were all created by the same mechanism as that found in the base case. During NST the downward motion of the slag rim caused increased pressure in the gap, which in turn caused the molten steel to be pushed away from the mold wall. This led to the formation of the root of the oscillation mark. Then the molten steel was drawn near the mold by the suction created by the up-stroke of the mold. As the shell traveled downwards during this time the remainder of the oscillation mark was formed. This process is shown for all three frequency cases below in Figures 4.1 through 4.3. The shell profile of all cases in the frequency study are shown superimposed in Figure 4.4. Additionally, the individual shell profiles found for cases F1, F2, and F3 are shown in Figures 4.5 through 4.6. From these profiles the theoretical pitch, calculated pitch, average OM width, average OM depth, standard deviation in the oscillation mark profile, the surface roughness, and slag consumption have been calculated and are
During this study 12 oscillation marks were calculated, and the last 10 of these 12 were used to calculate statistics. The first 2 oscillation marks created are neglected to ensure that the solution has adjusted to the new casting conditions prior to collecting data for statistical analysis. This same method was also used for all other parametric studies presented in this report. The shape of the last 10 oscillation marks calculated for all cases along with the average profile found for each case are summarized in Figures 4.8 through 4.10. The data summarized in Table 4.2 shows that the theoretical pitch and calculated pitches agree well with one another.
An additional parameter that was investigated in this study is the standard deviation of the oscillation mark profile depth. The average standard deviation for each case is also summarized in Table 4.2. The average standard deviation tends to increase with increasing frequency. This new finding suggests that more small level variations are occurring near the meniscus, owing to the higher frequency oscillation, which in turn make the oscillation mark formation more variable. Some additional insights on the shapes of oscillation marks can be found by plotting the standard deviations for all cases against the width of the oscillation mark, shown in Figure 4.12, and from plotting the average profile plus and minus one standard deviation of the profile shown in Figure 4.13. From these figures it can be seen that the standard deviation is greater at the forefront of the oscillation mark for all cases. This means that there is more variation in the formation of the lower half of the oscillation marks, which are formed during NST than in PST. The theoretical and calculated pitch for all cases agree within 3.5%. The small variation is expected, due to the fluid flow in the meniscus region, and causes similar variations in oscillation marks observed in commercial practice.
Figure 4.3 The Temperature Contour in the Meniscus Region for Case F3 When the Mold is at a) the End of NST b) the Maximum Velocity b) the Start of NST d) the Minimum Velocity

Table 4.2 Summary of Data Collected from the Frequency Parametric Study

<table>
<thead>
<tr>
<th></th>
<th>Base Case</th>
<th>Case F1</th>
<th>Case F2</th>
<th>Case F3</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>1.670</td>
<td>1.760</td>
<td>2.093</td>
<td>2.427</td>
<td>Hz</td>
</tr>
<tr>
<td>Theoretical Pitch</td>
<td>5.99</td>
<td>5.68</td>
<td>4.78</td>
<td>4.12</td>
<td>mm</td>
</tr>
<tr>
<td>Calculated Pitch</td>
<td>6.05</td>
<td>5.60</td>
<td>4.94</td>
<td>4.21</td>
<td>mm</td>
</tr>
<tr>
<td>Average OM Width</td>
<td>5.855</td>
<td>5.489</td>
<td>4.662</td>
<td>4.087</td>
<td>mm</td>
</tr>
<tr>
<td>Average OM Depth</td>
<td>0.313</td>
<td>0.356</td>
<td>0.237</td>
<td>0.105</td>
<td>mm</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.137</td>
<td>0.073</td>
<td>0.085</td>
<td>0.096</td>
<td>mm</td>
</tr>
<tr>
<td>Surface Roughness, Ra</td>
<td>178.6</td>
<td>157.1</td>
<td>131.9</td>
<td>128.8</td>
<td>μm</td>
</tr>
<tr>
<td>Average Heat Flux</td>
<td>1.291</td>
<td>1.452</td>
<td>1.471</td>
<td>1.500</td>
<td>MW/m²</td>
</tr>
<tr>
<td>Average Mold Friction in the Meniscus Region</td>
<td>0.970</td>
<td>1.299</td>
<td>2.314</td>
<td>3.023</td>
<td>kN/m</td>
</tr>
<tr>
<td>Average Lubrication Slag Consumption</td>
<td>3.709</td>
<td>3.523</td>
<td>6.157</td>
<td>8.711</td>
<td>g/ms</td>
</tr>
<tr>
<td>Average OM Slag Consumption</td>
<td>4.177</td>
<td>3.500</td>
<td>2.220</td>
<td>1.602</td>
<td>g/ms</td>
</tr>
<tr>
<td>Average Total Slag Consumption ($Q_s$)</td>
<td>7.886</td>
<td>7.023</td>
<td>8.377</td>
<td>10.313</td>
<td>g/ms</td>
</tr>
<tr>
<td>Average Total Slag Consumption ($Q_c$)</td>
<td>4.722</td>
<td>3.990</td>
<td>4.002</td>
<td>4.249</td>
<td>g/ms</td>
</tr>
<tr>
<td>Average Total Slag Consumption ($Q$)</td>
<td>0.789</td>
<td>0.702</td>
<td>0.838</td>
<td>1.031</td>
<td>kg/m²</td>
</tr>
</tbody>
</table>
Figure 4.4 The Shell Profile Calculated for all Cases in the Frequency Study

Figure 4.5 The Shell Profile Calculated for Case F1
Figure 4.6 The Shell Profile Calculated for Case F2

Figure 4.7 The Shell Profile Calculated for Case F3
Figure 4.8 10 Oscillation Marks Calculated for Case F1 and the Average of all 10 Profiles

Figure 4.9 10 Oscillation Marks Calculated for Case F2 and the Average of all 10 Profiles
Figure 4.10 10 Oscillation Marks Calculated for Case F3 and the Average of all 10 Profiles

Figure 4.11 The Average Shell Profile Calculated for all Cases in the Frequency Study
Figure 4.12 The Standard Deviation of Oscillation Mark Depth for Each Case in the Frequency Study Along the Width of the Oscillation Mark

Figure 4.13 The Average Oscillation Mark Profile and Error Bars Representing +/- 1 Standard Deviation for Each Case in the Frequency Study
As expected, the average oscillation mark depth and the surface roughness were both found to decrease increasing frequency. This study serves partially as further validation that the model behaves as expected because results from plant experiments have shown that as frequency increases oscillation mark depth decreases. [1] This trend is consistent with the data collected in this study.

A new parameter that has not been studied before is the oscillation mark width. The oscillation mark width was also found to decrease with increasing frequency. Therefore, since the depth and width of the oscillation marks decreases it can be concluded that as frequency is increased the oscillation marks become less severe.

The heat flux profiles along the mold hot face are plotted for all cases in the frequency study in Figure 4.14. This study confirms that the high heat flux extends the furthest up the mold when the molten steel has been drawn up to its highest point, which is at the start of NST. Additionally, it can be seen that the heat flux profiles do not vary substantially as the frequency increases. In particular, the location of the sharp transition, that indicates the closest proximity of the liquid steel to the mold during the oscillation cycle, is almost independent of frequency. The heat flux profiles for Cases F1 through F3 at various mold positions are shown in Figures 4.15 through 4.17. The average heat fluxes were also calculated for the region 50 mm to 100 mm below the far field meniscus and these values are included in Table 4.2. There is a clear and consistent trend that shows that higher frequency tends to produce slightly higher heat flux in the meniscus region, which is likely due to the decrease in oscillation mark depth. As the depth of oscillation marks decreases the amount of slag contained in the oscillation marks decreases, which increases the heat flux. The individual heat flux profiles and the average heat flux calculations confirm that the frequency is not a direct influencing factor on heat flux, but that its influence on oscillation mark depth leads to changes in the heat flux in the meniscus region.

The mold friction profiles simulated along the mold hot face are shown for all cases in Figure 4.18. At difference times during the oscillation cycle this study shows that the mold friction is at a maximum at the end of NST. This is logical because this is when the slag rim is pushing down on the meniscus the most. The individual mold friction plots for Cases F1 through F3 are shown in Figures 4.19 through 4.21. The maximum mold friction was found to greatly increase with increasing frequency. This is logical because as the frequency increases the mold travels the same distance in a shorter period of time, which also means that the slag rim travels downwards more quickly during the down stroke. This provides the liquid slag less time to move out of the region between the slag rim and the meniscus. Therefore, there is more resistance to the downward movement of the slag rim, which leads to increased mold friction.
Figure 4.14 The Heat Flux Profile Along the Mold Hot Face Calculated for all Cases in the Frequency Study When the Mold is at a) the END of NST b) the Maximum Velocity c) the Start of NST d) the Minimum Velocity
Figure 4.15 The Heat Flux Profile for Case F1 at Various Mold Positions Throughout the Oscillation Cycle

Figure 4.16 The Heat Flux Profile for Case F2 at Various Mold Positions Throughout the Oscillation Cycle
The oscillation mark consumption was found to decrease with increasing frequency. This is logical because the area of the oscillation marks decrease both with respects to their depth and width as the frequency increases, so the consumption within the marks decreases. However, the lubrication slag consumption was found to increase with increasing frequency. This is due to the increase in velocity in the slag gap that occurs with higher frequency. The velocity in the slag gap can be seen for Cases F1 through F3 in Figures 4.22 through 4.24. The average lubrication slag consumption for the base case is slightly higher than the average lubrication slag consumption for case F1, which is contrary to the trend found in the frequency study. However, while the slag velocity in the gap is lower for the base case than for case F1 the slag gap found in the base case was larger, which caused the lubrication slag consumption to be higher. The trend found for the oscillation mark consumption agrees with the trend found by Shin et al. [1] Lastly, this study suggest that the trends found in the lubrication slag consumption impact the total slag consumption more than the trends seen in the oscillation mark consumption.

4.1.2 Stroke Study

In the stroke parametric study the stroke of the mold oscillation was altered from that used in the base case, which was 10 mm, in order to determine how the stroke may impact oscillation marks. The strokes considered in this study are shown below in Table 4.3.
Figure 4.18 The Mold Friction Profile Along the Mold Hot Face Calculated for all Cases in the Frequency Study When the Mold is at a) the END of NST b) the Maximum Velocity c) the Start of NST d) the Minimum Velocity
Figure 4.19 The Mold Friction Profile for Case F1 at Various Mold Positions Throughout the Oscillation Cycle

Figure 4.20 The Mold Friction Profile for Case F2 at Various Mold Positions Throughout the Oscillation Cycle
Figure 4.21 The Mold Friction Profile for Case F3 at Various Mold Positions Throughout the Oscillation Cycle

Figure 4.22 The Slag Velocity Profile in the Slag Gap, 30 mm Below the Far Field Meniscus, for Case F1 at Various Mold Positions Throughout the Oscillation Cycle
Figure 4.23 The Slag Velocity Profile in the Slag Gap, 30 mm Below the Far Field Meniscus, for Case F2 at Various Mold Positions Throughout the Oscillation Cycle

Figure 4.24 The Slag Velocity Profile in the Slag Gap, 30 mm Below the Far Field Meniscus, for Case F3 at Various Mold Positions Throughout the Oscillation Cycle
Table 4.3 Case Information for the Stroke Parametric Study

<table>
<thead>
<tr>
<th>Case</th>
<th>Stroke [mm]</th>
<th>Theoretical Pitch [mm]</th>
<th>NST [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST1</td>
<td>6.00</td>
<td>5.99</td>
<td>0.238</td>
</tr>
<tr>
<td>BC</td>
<td>10.00</td>
<td>5.99</td>
<td>0.263</td>
</tr>
<tr>
<td>ST2</td>
<td>14.00</td>
<td>5.99</td>
<td>0.273</td>
</tr>
</tbody>
</table>

The temperature contour plots with velocities for the stroke study are shown in Figures 4.25 through 4.26, which show that the mechanism for oscillation mark formation is the same as the mechanism seen in both the base case and the frequency study. However, it can been seen in case ST2 that a larger hook is formed than that which is seen in the base case. In the high stroke scenario the molten steel is pushed further away from the mold wall, which lowers the temperature in the region where the steel shell is solidifying, which leads to increased solidification of the steel shell, which is also known as a hook. Lastly, it is important to note that slag inclusions were also observed in case ST2.

Figure 4.25 The Temperature Contour in Meniscus Region for Case ST1 When the Mold is at a) the End of NST b) the Maximum Velocity b) the Start of NST d) the Minimum Velocity
Figure 4.26 The Temperature Contour in Meniscus Region for Case ST2 When the Mold is at a) the End of NST b) the Maximum Velocity b) the Start of NST d) the Minimum Velocity

Figure 4.27 The Shell Profile Calculated for all Cases in the Stroke Study
Figure 4.28 The Shell Profile Calculated for Case ST1 (Stroke = 6mm)

Figure 4.29 The Shell Profile Calculated for Case ST2 (Stroke = 14 mm)
The resulting shell profile from this study for all cases is shown in Figure 4.27 and the individual shell profiles are shown for cases ST1 and ST2 in Figures 4.28 and 4.29 respectively. The slag gap was found to remain approximately constant in the 14 mm case and it was found to increase quickly in the 6 mm case. The slag gap for the base case increased slowly over time. Therefore, these results suggest that increasing the stroke will cause the slag gap to be more stable.

A summary of results from the stroke study are shown in Table 4.4 and the average oscillation marks are plotted in Figures 4.30 and 4.31. The calculated pitch for all each case agreed with its theoretical pitch within 3.67%. The average oscillation mark depth was found to increase greatly, with increasing stroke, which is in agreement with results found by Shin et al. [1]. The increase in depth was found to be very significant, as the depth increased by more than 50% when the stroke was increased from 6 to 14 mm. Additionally, the standard deviation was found to increase with increasing stroke, so the oscillation marks were found to be more variable at higher strokes. The average profiles are compared for all cases in Figure 4.32. Additionally, the standard deviation is plotted along the width of the mark in Figure 4.33 and the averages are plotted with error bars signifying the standard deviation along the width of the oscillation mark in Figure 4.34. The oscillation marks once again exhibit more variation during the downstroke, which is likely due to the increased instability of the fluid flow at the meniscus caused by the larger movement.

Table 4.4 Summary of Data Collected from the Stroke Parametric Study

<table>
<thead>
<tr>
<th></th>
<th>Case ST1</th>
<th>Base Case</th>
<th>Case ST2</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stroke</td>
<td>6.00</td>
<td>10.00</td>
<td>14.00</td>
<td>mm</td>
</tr>
<tr>
<td>Theoretical Pitch</td>
<td>5.99</td>
<td>5.99</td>
<td>5.99</td>
<td>mm</td>
</tr>
<tr>
<td>Calculated Pitch</td>
<td>6.10</td>
<td>6.05</td>
<td>6.21</td>
<td>mm</td>
</tr>
<tr>
<td>Average OM Width</td>
<td>5.776</td>
<td>5.855</td>
<td>5.855</td>
<td>mm</td>
</tr>
<tr>
<td>Average OM Depth</td>
<td>0.250</td>
<td>0.313</td>
<td>0.550</td>
<td>mm</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.126</td>
<td>0.137</td>
<td>0.201</td>
<td>mm</td>
</tr>
<tr>
<td>Surface Roughness, Ra</td>
<td>145.7</td>
<td>178.6</td>
<td>275.4</td>
<td>µm</td>
</tr>
<tr>
<td>Average Heat Flux</td>
<td>1.260</td>
<td>1.291</td>
<td>1.235</td>
<td>MW/m²</td>
</tr>
<tr>
<td>Average Mold Friction in the Meniscus Region</td>
<td>0.435</td>
<td>0.970</td>
<td>1.011</td>
<td>kN/m²</td>
</tr>
<tr>
<td>Average Lubrication Slag Consumption</td>
<td>11.306</td>
<td>3.709</td>
<td>6.746</td>
<td>g/m²</td>
</tr>
<tr>
<td>Average Oscillation Mark Slag Consumption</td>
<td>1.190</td>
<td>4.177</td>
<td>4.887</td>
<td>g/m²</td>
</tr>
<tr>
<td>Average Total Slag Consumption (Q_s)</td>
<td>12.496</td>
<td>7.886</td>
<td>11.633</td>
<td>g/m² cycle</td>
</tr>
<tr>
<td>Average Total Slag Consumption (Q_c)</td>
<td>7.483</td>
<td>4.722</td>
<td>6.966</td>
<td>g/m² cycle</td>
</tr>
<tr>
<td>Average Total Slag Consumption (Q)</td>
<td>1.249</td>
<td>0.789</td>
<td>1.163</td>
<td>kg/m²</td>
</tr>
</tbody>
</table>
Figure 4.30 10 Oscillation Marks Calculated for Case ST1 and the Average of all 10 Profiles

Figure 4.31 10 Oscillation Marks Calculated for Case ST2 and the Average of all 10 Profiles
Figure 4.32 The Average Shell Profile Calculated for all Cases in the Stroke Study

Figure 4.33 The Standard Deviation of Oscillation Mark Depth for Each Case in the Stroke Study Along the Width of the Oscillation Mark
Figure 4.34 The Average Oscillation Mark Profile and Error Bars Representing +/- 1 Standard Deviation for Each Case in the Stroke Study

The heat flux profiles along the mold hot face are plotted for all cases, at various mold positions throughout the cycle, in Figure 4.35. No significant variations in heat flux were observed. There was also no significance variation in the average heat flux values shown in Table 4.4. The heat flux profiles along the mold hot face are shown for cases ST1 and ST2 individually in Figures 4.36 and 4.37. The high heat flux once again extends the furthest up the mold at the start of NST, which is once again when the molten steel has been drawn nearest to the mold wall. During NST, the slag rim pushes the meniscus down below the shell tip, which lowers the heat flux peak down the mold. It is significant to note that this slag rim pressure does not induce overflow during this time. The maximum heat flux occurs higher above the far field meniscus for the 14 mm stroke case than for the 6 mm stroke case, which is due to the molten steel being drawn further up the mold wall in the higher stroke case.

The mold friction is plotted for all 3 cases in the stroke study at various mold positions throughout the oscillation cycle in Figure 4.38, and the individual mold friction plots are shown in Figures 4.39 and 4.40. The maximum mold friction once again occurs at the end of NST. It was found that increasing the stroke will increase the mold friction. It was also found that with the higher the stroke the period of time where the mold friction is significant is longer and the region in which the mold friction is significant is broader,
Figure 4.35 The Heat Flux Profile Along the Mold Hot Face Calculated for all Cases in the Stroke Study When the Mold is at a) the END of NST b) the Maximum Velocity c) the Start of NST d) the Minimum Velocity
Figure 4.36 The Heat Flux Profile for Case ST1 at Various Mold Positions Throughout the Oscillation Cycle

Figure 4.37 The Heat Flux Profile for Case ST2 at Various Mold Positions Throughout the Oscillation Cycle
Figure 4.38 The Mold Friction Profile Along the Mold Hot Face Calculated for all Cases in the Stroke Study When the Mold is at a) the END of NST b) the Maximum Velocity c) the Start of NST d) the Minimum Velocity
Figure 4.39 The Mold Friction Profile for Case ST1 at Various Mold Positions Throughout the Oscillation Cycle

Figure 4.40 The Mold Friction Profile for Case ST2 at Various Mold Positions Throughout the Oscillation Cycle
which can be contributed to the increased momentum of the slag rim caused by the increased stroke. Since these cases have a higher stroke and the same frequency the slag rim reaches a higher velocity during the upstroke and the downstroke, which leads to higher mold friction.

The slag velocity profile across the interfacial gap for cases ST1 and ST2 are shown in Figures 4.41 and 4.42 respectively. The lubrication slag consumption was found to increase for the decreasing stroke, but this is an artifact of the slag gap thickening in the low stroke case, as opposed to an artifact of the velocity in the slag gap. However, as the oscillation mark depths increases with increasing stroke the oscillation mark consumption was naturally found to increase with increasing stroke accordingly. Similar to the frequency study the lubrication slag consumption was found to be the dominant factor in the trend of total slag consumption, and the slag consumption was found to be higher for the low stroke case.

Figure 4.41 The Slag Velocity Profile in the Slag Gap, 30 mm Below the Far Field Meniscus, for Case ST1 at Various Mold Positions Throughout the Oscillation Cycle

4.1.3 Modification Ratio Study

Traditional methods of continuous casting set mold oscillation to a sinusoidal function. However, studies have suggested that there may be certain benefits to altering the oscillation pattern to a non-sinusoidal oscillation. [2] During non-sinusoidal oscillation the negative strip portion of the cycle is shortened, so that the mold moves down and back up very quickly relative to slow movement during the rest of the cycle. The equation used to describe this movement of the mold/fluid boundary and the movement of the mold.
mesh was altered in case MR1 to the function shown in Equation 4.1, where $\alpha_m$ is the modification ratio and $a$ is the amplitude of the cycle, which is half of the stroke. $\alpha_m$ is defined by Equation 4.2, where $A_o$ is the time difference between peaks in the mold position curve. The modification ratios considered in this study are shown in Table 4.5 and the resulting mold position curve and mold velocity curve are shown in Figures 4.43 and 4.44.

$$v_m = 2\pi a f \left[1 - ccos(2\pi ft)\cos[2\pi ft - csin(2\pi ft)] \right]$$  \hspace{1cm} (4.1)$$

where,

$$c = 4\pi \alpha_m / \left(8 - \pi^2 \alpha_m^2 \right)$$

$$\alpha_m = 4A_o f$$  \hspace{1cm} (4.2)$$

where:

$v_m$: Velocity of the mold [m/s]
$a$: Half stroke [m]
$f$: Frequency of oscillation [Hz]
$t$: Time [s]

$A_0$: Difference in time of the peak found in the mold position curve form that of the mold position curve with $\alpha_m = 0$ [s]

<table>
<thead>
<tr>
<th>Case</th>
<th>$\alpha_m$ [%]</th>
<th>Theoretical Pitch [mm]</th>
<th>NST [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC</td>
<td>0</td>
<td>5.99</td>
<td>0.263</td>
</tr>
<tr>
<td>MR1</td>
<td>24</td>
<td>5.99</td>
<td>0.252</td>
</tr>
</tbody>
</table>

The mechanism that creates oscillation marks in the non-sinusoidal case was found to be the same as the mechanism found for all other studies thus far. The process of the molten steel being pulled closer to the mold hot face during the upstroke and then being pushed down and away by the slag rim during the downstroke is shown in Figure 4.45. The resulting oscillation marks formed in the base case and case MR1 are shown in Figure 4.46 and the individual shell profile for case MR1 is shown in Figure 4.47.

The individual and average oscillation mark profiles for the non-sinusoidal case are shown in Figure 4.48 and a summary of the results for the modification ratio study are shown in Table 4.6. The calculated pitch for the non-sinusoidal case was found to agree with the theoretical pitch within 1%. The average oscillation mark depth calculated for the non-sinusoidal case was found to be significantly shallower,
by approximately 33%, than the average oscillation mark calculated for the sinusoidal case. The oscillation shapes of both the sinusoidal and non-sinusoidal cases are compared in Figure 4.49, which once again illustrates the shallower depth found in the non-sinusoidal case. Additionally, it was found that there is slightly less variability in the oscillation marks for the non-sinusoidal case, which is exhibited in the average standard deviation calculation, and in plots summarizing the standard deviation information shown in Figures 4.50 and 4.51. The greatest variations in the oscillation mark depth were found in the region between the minimum velocity and the maximum velocity, as the mold quickly changes direction, as opposed to during negative strip time, which was observed in the base case.

The heat flux profiles along the mold hot face for both the non-sinusoidal and sinusoidal cases are shown in Figure 4.52. The heat flux was found to be 11% higher in the region 40 - 100 mm below the far field meniscus for the non-sinusoidal case. However, the slag gap thickness proves to be relatively the same between the two cases. This shows that when the slag gap is not playing a dominant role in the heat transfer across the gap the oscillation marks are able to impact the heat flux. Since the oscillation marks are shallower in the non-sinusoidal case there is less slag built up in the marks and therefore the heat flux

![Figure 4.44 The Mold Velocity Curve for the Base Case and for Case MR1](image)

The heat flux profiles along the mold hot face for both the non-sinusoidal and sinusoidal cases are shown in Figure 4.52. The heat flux was found to be 11% higher in the region 40 - 100 mm below the far field meniscus for the non-sinusoidal case. However, the slag gap thickness proves to be relatively the same between the two cases. This shows that when the slag gap is not playing a dominant role in the heat transfer across the gap the oscillation marks are able to impact the heat flux. Since the oscillation marks are shallower in the non-sinusoidal case there is less slag built up in the marks and therefore the heat flux
Figure 4.45 The Temperature Contour in Meniscus Region for Case MR1 When the Mold is at a) the End of NST b) the Maximum Velocity b) the Start of NST d) the Minimum Velocity

Table 4.6 Summary of Data Collected from the Modification Ratio Parametric Study

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Base Case</th>
<th>Case NS1</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_m$</td>
<td>0</td>
<td>24</td>
<td>%</td>
</tr>
<tr>
<td>Theoretical Pitch</td>
<td>5.99</td>
<td>5.99</td>
<td>mm</td>
</tr>
<tr>
<td>Calculated Pitch</td>
<td>6.05</td>
<td>5.95</td>
<td>mm</td>
</tr>
<tr>
<td>Average OM Width</td>
<td>5.855</td>
<td>5.726</td>
<td>mm</td>
</tr>
<tr>
<td>Average OM Depth</td>
<td>0.313</td>
<td>0.235</td>
<td>mm</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.137</td>
<td>0.103</td>
<td>mm</td>
</tr>
<tr>
<td>Surface Roughness, Ra</td>
<td>178.6</td>
<td>125.4</td>
<td>$\mu$m</td>
</tr>
<tr>
<td>Average Heat Flux</td>
<td>1.291</td>
<td>1.426</td>
<td>$\frac{MW}{m^2}$</td>
</tr>
<tr>
<td>Average Mold Friction in the Meniscus Region</td>
<td>0.970</td>
<td>1.162</td>
<td>$\frac{kN}{m}$</td>
</tr>
<tr>
<td>Average Lubrication Slag Consumption</td>
<td>3.709</td>
<td>2.813</td>
<td>$\frac{g}{m^s}$</td>
</tr>
<tr>
<td>Average Oscillation Mark Slag Consumption</td>
<td>4.177</td>
<td>2.303</td>
<td>$\frac{g}{m^s}$</td>
</tr>
<tr>
<td>Average Total Slag Consumption ($Q_s$)</td>
<td>7.886</td>
<td>5.116</td>
<td>$\frac{g}{m^2}$</td>
</tr>
<tr>
<td>Average Total Slag Consumption ($Q_c$)</td>
<td>4.722</td>
<td>3.063</td>
<td>$\frac{g}{m^2}$</td>
</tr>
<tr>
<td>Average Total Slag Consumption (Q)</td>
<td>0.789</td>
<td>0.512</td>
<td>$\frac{kg}{m^2}$</td>
</tr>
</tbody>
</table>
Figure 4.46 The Shell Profile Calculated for all Cases in the Modification Ratio Study

Figure 4.47 The Shell Profile Calculated for Case MR1 ($\alpha_m = 24\%$)
Figure 4.48 10 Oscillation Marks Calculated for Case MR1 and the Average of all 10 Profiles

Figure 4.49 The Average Shell Profile Calculated for all Cases in the Modification Ratio Study
Figure 4.50 The Standard Deviation of Oscillation Mark Depth for Each Case in the Modification Ratio Study Along the Width of the Oscillation Mark

Figure 4.51 The Average Oscillation Mark Profile and Error Bars Representing +/- 1 Standard Deviation for Each Case in the Modification Ratio Study
Figure 4.52 The Heat Flux Profile Along the Mold Hot Face Calculated for all Cases in the Modification Ratio Study When the Mold is at a) the END of NST b) the Maximum Velocity c) the Start of NST d) the Minimum Velocity
is higher. The heat flux profile along the mold hot face for the non-sinusoidal case is shown in Figure 4.53. Similar to the base case, the high heat flux extends the furthest up the mold wall at the start of NST for a non-sinusoidal case. Thus, the nature of the oscillation parameters does not affect the trend of the sharp change in heat flux (which corresponds to the meniscus location) with time.

![Figure 4.53 The Heat Flux Profile for Case MR1 at Various Mold Positions Throughout the Oscillation Cycle](image)

The average mold friction calculated for the non-sinusoidal case was found to be 20% higher than the base case. The mold friction profile calculated for the non-sinusoidal case is shown in Figure 4.54. This can be contributed to the increase in velocity seen during the NST for case MR1. The mold friction is plotted at various mold positions during the oscillation cycle for the non-sinusoidal case in Figure 4.55, which shows that the mold friction profile is similar to the base case at all times during the oscillation cycle.

The slag velocity profile across the interfacial gap is plotted at various times during the oscillation cycle for the non-sinusoidal case in Figure 4.56. The minimum slag velocity (i.e. the greatest downward velocity) is greater in magnitude than the maximum slag velocity in case MR1. However, the NST was designed to be much shorter for the non-sinusoidal case than the base case, which becomes dominant over the increased slag velocity in the gap. Therefore, the lubrication slag consumption is lower for the non-sinusoidal case. Additionally, as the oscillation marks are smaller for the non-sinusoidal case the oscillation mark consumption is also smaller for the non-sinusoidal case. Therefore, the total slag consumption is significantly less for the non-sinusoidal case, which is contrary to the findings of Shin et al. [1].
Figure 4.54 The Mold Friction Profile Along the Mold Hot Face Calculated for all Cases in the Modification Ratio Study When the Mold is at a) the END of NST b) the Maximum Velocity c) the Start of NST d) the Minimum Velocity
Figure 4.55 The Mold Friction Profile for Case MR1 at Various Mold Positions Throughout the Oscillation Cycle

Figure 4.56 The Slag Velocity Profile in the Slag Gap, 30 mm Below the Far Field Meniscus, for Case MR1 at Various Mold Positions Throughout the Oscillation Cycle
4.2 Casting Speed Study

In the casting speed parametric study the casting speed of the steel shell was altered from that used in the base case, which was 0.6 \( m/min \), in order to determine its effect on oscillation marks. The casting speeds considered in this study are shown below in Table 4.7.

<table>
<thead>
<tr>
<th>Case</th>
<th>Casting Speed ([\frac{m}{min}])</th>
<th>Theoretical Pitch ([mm])</th>
<th>NST ([s])</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC</td>
<td>0.6</td>
<td>5.99</td>
<td>0.263</td>
</tr>
<tr>
<td>CS1</td>
<td>1.0</td>
<td>10.00</td>
<td>0.238</td>
</tr>
<tr>
<td>CS2</td>
<td>1.5</td>
<td>14.97</td>
<td>0.205</td>
</tr>
</tbody>
</table>

The temperature contour and velocity plots for the casting speed study are shown in Figures 4.57 to 4.58, which show that the mechanism responsible for the formation of oscillation marks is the same in cases CS1 and CS2 as the mechanism seen in all other parametric studies thus far. The resulting shell profiles from all cases in the casting speed study are shown in Figure 4.59 and the individual shell profiles for cases CS1 and CS2 are shown in Figures 4.60 and 4.61. The slag gap thicknesses were observed to increase more quickly with a higher casting speed. Additionally, visually it can be seen that the oscillation marks change shape with different casting speeds. A summary of the results from the casting speed study are shown in Table 4.8 and the average oscillation marks are plotted in Figures 4.62 and 4.63. As the casting speed was increased, the oscillation marks became much wider and shallower. Specifically, increasing the casting speed from 0.6 \( m/min \) to 1.5\( m/min \) led to a 150% increase in the oscillation mark width and a 43% decrease in the oscillation mark depth. These results agree well with the results observed by several researchers.[1] [3] [4] The calculated pitch for all cases agreed with the theoretical pitch within 1%.

The shell surface profile in a given pitch for the 1.0 \( m/min \) case contained a slight depression between each pair of oscillation marks. Secondary marks were observed by Yan. [5] The oscillation mark begins to form in the same way seen thus far. The slag rim begins to move down and push the molten steel away from the mold wall causing a depression to form, which is the primary oscillation mark. However, the steel shell is moving down more quickly in this case than the base case and therefore after the minimum downward velocity of the mold occurs the shell’s downward movement and shell solidification prevents the oscillation mark from penetrating any deeper into the steel strand. This causes a slight decrease in the slag gap, but the continued downward movement of the mold once away pushes the molten steel away from the mold wall. The steel is solidifying and therefore is maintaining its shape as it travels down and the shell forms. It is not until the mold has reached its maximum mold velocity that the molten steel
Figure 4.57 The Temperature Contour in Meniscus Region for Case CS1 When the Mold is at a) the End of NST b) the Maximum Velocity b) the Start of NST d) the Minimum Velocity
Figure 4.58 The Temperature Contour in Meniscus Region for Case CS2 When the Mold is at a) the End of NST b) the Maximum Velocity b) the Start of NST d) the Minimum Velocity
Figure 4.59 The Shell Profile Calculated for all Cases in the Casting Speed Study

Figure 4.60 The Shell Profile Calculated for Case CS1 (Casting Speed = 1.0 \( \frac{m}{min} \))
Figure 4.61 The Shell Profile Calculated for Case CS2 (Casting Speed = 1.5 \( \frac{m}{min} \)) has enough momentum to overcome the solidifying shell. At this point the upper portion of the oscillation mark is formed. This same phenomena is observed in the high casting speed case, but the even faster downward movement of the steel shell prevents any changes in the oscillation mark depth until the molten steel has reached its maximum upward velocity.

Naturally, the standard deviation was found to significantly decrease with increasing casting speed, so the oscillation marks were found to be far less variable at higher casting speeds. The average profiles are compared for all cases in Figure 4.64. Additionally, the standard deviation is plotted along the width of the mark in Figure 4.65 and the averages are plotted with error bars signifying the standard deviation along the width of the oscillation mark in Figure 4.66. The oscillation marks once again exhibit more variation during the downstroke.

The Heat Flux profiles along the mold hot face for all cases are plotted at various mold positions throughout the cycle in Figure 4.67. The average heat flux values were also calculated and shown in Table 4.8. The average heat flux was found to be relatively similar at all three casting speeds, and does not show the increase with casting speed that is expected. The heat flux profiles along the mold hot face are shown for cases CS1 and CS2 individually in Figures 4.68 and 4.69. The high heat flux extends the furthest up the mold once again at the start of NST. The increase in the average heat flux seen in case CS1 can
be attributed to the decrease in the depth of oscillation marks. However, the heat flux decreases again in case CS2. The slag gap was found to increase with time in all cases, but the slag gap was found to increase more quickly with higher casting speed, which leads to increased thermal resistance in the slag gap and this is likely why the heat flux was found to decrease for case CS2.

Table 4.8 Summary of Data Collected from the Casting Speed Parametric Study

<table>
<thead>
<tr>
<th></th>
<th>Base Case</th>
<th>Case CS1</th>
<th>Case CS2</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Casting Speed</td>
<td>0.60</td>
<td>1.00</td>
<td>1.50</td>
<td>mm/s</td>
</tr>
<tr>
<td>Theoretical Pitch</td>
<td>5.99</td>
<td>10.00</td>
<td>14.97</td>
<td>mm</td>
</tr>
<tr>
<td>Calculated Pitch</td>
<td>6.05</td>
<td>10.10</td>
<td>15.10</td>
<td>mm</td>
</tr>
<tr>
<td>Average OM Width</td>
<td>5.855</td>
<td>9.921</td>
<td>14.928</td>
<td>mm</td>
</tr>
<tr>
<td>Average OM Depth</td>
<td>0.313</td>
<td>0.274</td>
<td>0.178</td>
<td>mm</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.137</td>
<td>0.083</td>
<td>0.056</td>
<td>mm</td>
</tr>
<tr>
<td>Surface Roughness, Ra</td>
<td>178.6</td>
<td>106.4</td>
<td>73.6</td>
<td>µm</td>
</tr>
<tr>
<td>Average Heat Flux</td>
<td>1.291</td>
<td>1.360</td>
<td>1.290</td>
<td>MW/m²</td>
</tr>
<tr>
<td>Average Mold Friction</td>
<td>0.970</td>
<td>2.229</td>
<td>3.792</td>
<td>kN/m²</td>
</tr>
<tr>
<td>Average Lubrication Slag Consumption</td>
<td>3.709</td>
<td>3.825</td>
<td>4.724</td>
<td>g/m³</td>
</tr>
<tr>
<td>Average Oscillation Mark Slag Consumption</td>
<td>4.177</td>
<td>5.507</td>
<td>4.491</td>
<td>g/m³</td>
</tr>
<tr>
<td>Average Total Slag Consumption (Q_s)</td>
<td>7.886</td>
<td>9.332</td>
<td>9.215</td>
<td>g/m³</td>
</tr>
<tr>
<td>Average Total Slag Consumption (Q_c)</td>
<td>4.722</td>
<td>5.588</td>
<td>5.518</td>
<td>g/m³</td>
</tr>
<tr>
<td>Average Total Slag Consumption (Q)</td>
<td>0.789</td>
<td>0.559</td>
<td>0.369</td>
<td>kg/m²</td>
</tr>
</tbody>
</table>

Figure 4.62 10 Oscillation Marks Calculated for Case CS1 and the Average of all 10 Profiles
Figure 4.63 10 Oscillation Marks Calculated for Case CS2 and the Average of all 10 Profiles

Figure 4.64 The Average Shell Profile Calculated for all Cases in the Casting Speed Study
Figure 4.65 The Standard Deviation of Oscillation Mark Depth for Each Case in the Casting Speed Study Along the Width of the Oscillation Mark

Figure 4.66 The Average Oscillation Mark Profile and Error Bars Representing +/- 1 Standard Deviation for Each Case in the Casting Speed Study
Figure 4.67 The Heat Flux Profile Along the Mold Hot Face Calculated for all Cases in the Casting Speed Study When the Mold is at a) the END of NST b) the Maximum Velocity c) the Start of NST d) the Minimum Velocity
Figure 4.68 The Heat Flux Profile for Case CS1 at Various Mold Positions Throughout the Oscillation Cycle

Figure 4.69 The Heat Flux Profile for Case CS2 at Various Mold Positions Throughout the Oscillation Cycle
The mold friction is plotted for all cases in the casting speed study, at various mold positions throughout the oscillation cycle, in Figure 4.70. The maximum mold friction once again occurs at the end of NST. It was found that increasing the casting speed will increase the mold friction. This is due to the fact the shell is solidifying during the negative strip time in the meniscus region causing increased resistance to movement of the slag rim, liquid slag in the gap, and the molten steel. The individual mold friction plots are shown in Figures 4.71 and 4.72.

Figure 4.70 The Mold Friction Profile Along the Mold Hot Face Calculated for all Cases in the Casting Speed Study When the Mold is at a) the END of NST b) the Maximum Velocity c) the Start of NST d) the Minimum Velocity

The slag velocity profile across the gap for cases CS1 and CS2 are shown in Figures 4.73 and 4.74. The lubrication slag consumption was found to increase for increasing casting speed, but this is an artifact of the slag gap thickening more in the higher casting speed seen in Figure 4.59, as opposed to an artifact of the velocity in the slag gap. The oscillation mark consumption was found to increase in case CS1 but then
Figure 4.71 The Mold Friction Profile for Case CS1 at Various Mold Positions Throughout the Oscillation Cycle

Figure 4.72 The Mold Friction Profile for Case CS2 at Various Mold Positions Throughout the Oscillation Cycle
Figure 4.73 The Slag Velocity Profile in the Slag Gap, 30 mm Below the Far Field Meniscus, for Case CS1 at Various Mold Positions Throughout the Oscillation Cycle

Figure 4.74 The Slag Velocity Profile in the Slag Gap, 30 mm Below the Far Field Meniscus, for Case CS1 at Various Mold Positions Throughout the Oscillation Cycle
decrease again for CS2. This shows that the increase in pitch is dominant in case CS1 and the decrease in oscillation mark depth is dominant in case CS2. The overall area slag consumption was found to decrease with increasing casting speed. The increase in casting speed from 0.6 \text{ m/min} to 1.0 \text{ m/min} led to a 29\% decrease in the area which agrees very closely with the results found by Shin et al., which predicted a 32\% decrease in the area slag consumption for the same increase in casting speed. [6]

4.3 Slag Lubrication Study

Slag properties can greatly influence both the heat flux in the meniscus region and how effectively the slag lubricates the steel shell. The slag viscosity is the main factor influencing how the slag performs as a lubricant. For this study a slag that was used in an experiment performed by Meng [7], which exhibits lower viscosity in the liquid region, was used to study how the slag’s viscosity affects the oscillation mark formation mechanism, oscillation mark shape, and other variables. Additionally, due to the lower viscosity of the slag this study serves as a means to determine if sticker defects are likely to occur with a standard commercial slag, whose liquid viscosity is on the lower end of slags generally used in commercial casters. Sticker defects are described in Chapter One of this report. However, to review, a sticker defect occurs when the steel shell comes into contact with the mold wall. As the mold moves into NST the steel shell can then separate from the mold wall, which can lead to a breakout. [8] It is logical to assume that a sticker defect is more likely to occur in a caster containing lower viscosity because the steel shell can more easily move through the slag and come into contact with the mold wall. However, sticker defects are less likely to occur in ultra-low carbon steel, which is the steel being modeled in this study. The following sections provide background on how the viscosity and conductivity curves were determined for the slag used in this study, as well as for two additional slags which will be discussed in other sections of this report.

4.3.1 Slag Viscosity Profiles

The viscosity of mold powder melting into liquid slag and the viscosity of liquid slag solidifying into a solid slag layer are described by two different temperature-viscosity curves. The viscosity curve for the mold powder as it melts into liquid slag is more dependent on the structure of the powder than it is on the slag composition. [9] Additionally, this curve is only applied in the upper region of the domain that does not greatly impact the oscillation marks. Therefore, this curve, referred to in the Material Properties section of the report as the ”melting curve”, remains constant throughout all parametric studies. This relationship has been used by multiple researchers, and has been found to be effective [5] [10] [11] [12]

The temperature-viscosity curve used for the solidifying slag is very dependent on the composition of the slag. Slag viscosity is often described by its viscosity at 1300 °C and its break temperature. The break temperature is when the viscosity-temperature curve deviates from linear, and represents the start of crys-
tallization. Another important temperature is the temperature at which the viscosity essentially becomes extremely large and behaves as a rigid solid. For crystalline slags, this temperature corresponds to the end of crystallization, and for glassy slags, this temperature corresponds to the glass transition temperature. Measurements performed by Meng on three slags, slag S1, S2, and K1 [7] have been used to compose viscosity curves for the lubrication study and for future studies. The chemical compositions of all three slags are shown in Table 4.9. The resulting viscosity curves for these three slags found by Meng are shown in Figure 4.75. The break temperatures observed from this data and those calculated using Equation 4.3, which is an equation found by Mill’s, [9] are shown in Table 4.10. It can be seen that Meng’s observations exhibit the same trend as that suggested by Mill’s and their values agree as well. The experimental measurements for the glassy slag, S2, predicts a break temperature that is lower than the results calculated using Mill’s equation by 116 °K. The break temperature of a crystalline slag is generally much lower and more easily determined due to the fact that as the crystals begin to form in a crystalline slag solidification takes place quite rapidly. Whereas, with a glassy slag the solidification process is slower and less predictable, and therefore it is reasonable to assume that Meng and Mill’s values will not match as well for a glassy slag as they do for a more crystalline slag. The agreement in the trend does show that it is likely that Meng’s results are good. Additionally, as Meng predicted a lower break temperature than Mill’s, Meng’s break temperature exhibits a more extreme case, which is beneficial to the goals of this study. Therefore the temperature-viscosity curves found using Meng’s data was be used in this study.

Table 4.9 The Chemical Compositions of Slags S1, S2, and K1 Used for the Slag Lubrication and Low Heat Flux Parametric Studies [wt pct]

<table>
<thead>
<tr>
<th>Component</th>
<th>S1</th>
<th>S2</th>
<th>K1</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>33.30</td>
<td>37.39</td>
<td>29.93</td>
</tr>
<tr>
<td>CaO</td>
<td>39.90</td>
<td>22.82</td>
<td>39.41</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>5.38</td>
<td>2.37</td>
<td>4.58</td>
</tr>
<tr>
<td>F</td>
<td>7.52</td>
<td>6.67</td>
<td>12.93</td>
</tr>
<tr>
<td>Na₂O</td>
<td>4.61</td>
<td>13.11</td>
<td>9.04</td>
</tr>
<tr>
<td>MgO</td>
<td>2.96</td>
<td>1.41</td>
<td>0.79</td>
</tr>
<tr>
<td>TiO₂</td>
<td>&lt; 1.0</td>
<td>&lt; 0.5</td>
<td>–</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>&lt; 1.5</td>
<td>&lt; 1.5</td>
<td>0.19</td>
</tr>
<tr>
<td>MnO</td>
<td>&lt; 1.0</td>
<td>&lt; 0.5</td>
<td>0.01</td>
</tr>
<tr>
<td>K₂O</td>
<td>&lt; 1.0</td>
<td>&lt; 0.5</td>
<td>0.80</td>
</tr>
<tr>
<td>Li₂O</td>
<td>–</td>
<td>&lt; 1.0</td>
<td>–</td>
</tr>
<tr>
<td>B₂O₃</td>
<td>–</td>
<td>1.38</td>
<td>–</td>
</tr>
<tr>
<td>C – Total</td>
<td>3.99</td>
<td>11.21</td>
<td>2.23</td>
</tr>
<tr>
<td>CO₂</td>
<td>3.12</td>
<td>3.68</td>
<td>2.62</td>
</tr>
<tr>
<td>C – Free</td>
<td>3.14</td>
<td>10.21</td>
<td>1.52</td>
</tr>
</tbody>
</table>
\[ T_{br}(^\circ C) = 1120 - 3.3\%SiO_2 - 8.43\%Al_2O_3 + 8.65\%CaO - 13.86\%MgO - 3.3\%Na_2O - 18.4\%FeO - 3.2\%MnO - 2.2\%K_2O - 6.6\%Li_2O - 6.47\%F \] (4.3)

Table 4.10 The Experimental and Calculated Break Temperatures for Slags S1, S2, and K1

<table>
<thead>
<tr>
<th>Slag</th>
<th>Meng’s Break Temperature [K] - Experimental</th>
<th>Mill’s Break Temperature [K] - Calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>1498</td>
<td>1473</td>
</tr>
<tr>
<td>S2</td>
<td>1213</td>
<td>1329</td>
</tr>
<tr>
<td>K1</td>
<td>1468</td>
<td>1470</td>
</tr>
</tbody>
</table>

Due to the computational restrictions described in the Material Properties section of this report the viscosity profiles for all slags must be truncated to \( 1 \times 10^5 Pa - s \). The FLUENT models are unable to converge when the true viscosity for slags at low temperatures are used. Therefore, the temperature-viscosity profiles shown in Figure 4.76 were entered into FLUENT by altering the user-defined function called "slag viscosity", which can be found in the Appendix A.

4.3.2 Slag Conductivity Profiles

The primary material property that influences the heat flux in the meniscus region is the slag thermal conductivity. The conductivity of a slag, like the viscosity, has a different curve for the melting of mold powder and the solidification of liquid slag. The "melting curve" is applied in the upper region of the do-
main, away from the meniscus region. The "solidifying curve" is applied to the slag gap, in the region 3 mm or less away from the mold hot face, and is very important to the heat flux in the meniscus region.

The conductivity of mold powders is once again dependent on the structure of each individual powder, but a generally accepted conductivity for powder by other researchers [11],[12] is 0.5 W/m²K, which was found experimentally by Taylor and Mills [13]. The conductivity begins to increase as the mold powder sinters at the sintering temperature. The sintering temperature was not found for the slags used and therefore the glass transition temperature [7] was used in place of the sintering temperature. This was deemed acceptable as these two temperatures are very similar and since the melting conductivity does not greatly influence the heat flux in the slag gap. Between the glass transition temperature and the liquidus temperature the conductivity increases to a value of 1 W/m²K. [11],[12] At temperatures above the liquidus temperature the conductivity continues to increase to account for radiation present in the liquid. The maximum conductivity chosen for this curve was the conductivity of liquid slag.

![Figure 4.76 The Solidifying Temperature-Viscosity Curves for Slags S1, S2, and K1 Provided to the Thermal-Flow Model](image)

The conductivity of liquid slag is constant at temperatures above the break temperature during solidification. The constant nature of the thermal conductivity was found in experiments performed by Hasegawa. [14] It was also found by Hasegawa that the conductivity of liquid slag is primarily influenced by the ratio of CaO to Al₂O₃. In order to create a parametric study where the heat flux is impacted solely by the glassy verses crystalline nature of the slag it was assumed that the ratio of CaO to Al₂O₃ was the same for all slags considered in the parametric studies. This is a realistic assumption considering the phenomena of
alumina pick-up. Slags will often absorb alumina inclusions from the steel during casting. Therefore, if it is assumed that each slag experiences a typical amount of alumina pick-up during casting, which would allow the ratio of $CaO$ to $Al_2O_3$ for each slag to be the same, so the constant conductivity for the liquid slag can be assumed to be the same for slags S1, S2, and K1 [10], which makes it easier to compare the results between slags. The assumptions made pertaining to alumina pickup and the new ratios of $CaO$ to $Al_2O_3$ are shown in Table 4.11. The ratio of $CaO$ to $Al_2O_3$ corresponds to a conductivity of 2 $W/m^2K$ according to the experimental results of Hasegawa. [14] This is the conductivity found without including the effects of radiation.

Table 4.11 Alumina Pick-Up Assumptions for Slags S1, S2, and K1

<table>
<thead>
<tr>
<th>Test</th>
<th>S1</th>
<th>S2</th>
<th>K1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Al_2O_3$ Pick Up [%]</td>
<td>6.77</td>
<td>4.50</td>
<td>7.35</td>
</tr>
<tr>
<td>New $Al_2O_3$ [mass %]</td>
<td>12.15</td>
<td>6.87</td>
<td>11.93</td>
</tr>
<tr>
<td>New $CaO$ [mass %]</td>
<td>36.98</td>
<td>20.88</td>
<td>36.23</td>
</tr>
<tr>
<td>New $SiO_2$ [mass %]</td>
<td>31.21</td>
<td>36.00</td>
<td>27.67</td>
</tr>
<tr>
<td>New Ratio of $CaO$ to $Al_2O_3$</td>
<td>3.04</td>
<td>3.04</td>
<td>3.04</td>
</tr>
</tbody>
</table>

The current FLUENT model does not include radiation. Therefore, in order to simulate the proper heat transfer across the slag gap it is important that the conductivity of the slag is artificially increased to account for the additional heat flux that is incurred by radiation. CON1D was used to determine the value that should be used for the liquid slag conductivity. CON1D is a software program that is capable of performing analytical calculations to determine the heat flux in the gap, the actual slag gap thickness, and many other parameters. [15] CON1D has the capability to calculate the radiation in the slag gap, in addition to the conduction, interfacial resistance, and other important phenomena. Therefore, the casting conditions, the steel composition, and slag composition of the base case were put into CON1D, with the slag conductivity set to 2 $W/m^2K$, and the emissivity of the slag set to 0.9, and the heat flux profile along the mold hot face was calculated. Then radiation effects were removed from the CON1D simulation (i.e. the emissivity was set to 0), and the conductivity was increased by trial and error until the heat flux profiles agreed within 0.1%. These results can be seen in Figure 4.77. The equivalent conductivity was found to be 4.5 $W/m^2K$. This value was found to be consistent with recent measurements by Long et al. [16]

As the slag cools below the break temperature the slag conductivity begins to decrease. The conductivity of the slag decreases down to 1 $W/m^2K$ in between the break temperature and glass-transition temperature. This decrease in conductivity is due to the loss of the radiation term as the slag solidifies and becomes more opaque. Below the glass-transition temperature the slag conductivity continues to decrease, but at a much slower rate. The conductivity drops to a value of 0.5 $W/m^2K$ at 300 K. [17] The liquidus,
break, and glass-transition temperatures for each slag are summarized in Table 4.10. The overall conductivity curves found for the three slags used in the parametric studies are shown in Figures 4.78 and 4.79. It can be seen in Figure 4.79 that the conductivity of K1 is relatively neutral, but it was still found to have a higher conductivity than the curve utilized in the base case.

![Figure 4.77 Heat Flux Profiles Used to Determine the Equivalent Conductivity to Include Radiation Effects](image)

Figure 4.77 Heat Flux Profiles Used to Determine the Equivalent Conductivity to Include Radiation Effects

![Figure 4.78 The Melting Temperature-Conductivity Curves for Slags S1, S2, and K1](image)

Figure 4.78 The Melting Temperature-Conductivity Curves for Slags S1, S2, and K1
4.3.3 Results of the Lubrication Study

The lubrication study uses all of the casting conditions from the base case, except that the slag material properties were changed to those found for slag K1. This is due to slag K1 having the lowest viscosity of those tested by Meng et al. [7] and a lower viscosity than the viscosity used in the base case. The theoretical pitch and NST for the lubrication case, L1, are shown in Table 4.12. It can be seen that these values are the same as the base case.

Table 4.12 Case Information for the Slag Lubrication Parametric Study

<table>
<thead>
<tr>
<th>Case</th>
<th>Theoretical Pitch [mm]</th>
<th>NST [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC</td>
<td>5.99</td>
<td>0.263</td>
</tr>
<tr>
<td>L1</td>
<td>5.99</td>
<td>0.263</td>
</tr>
</tbody>
</table>

The temperature contour plot for case L1 is shown in Figure 4.80. The low viscosity does not change the oscillation mark formation mechanism, but it does allow for generally a rougher shell finish. The oscillation marks were found to form in the same manner as seen thus far. Additionally, it can be noted that no sticker defects were observed during this study. The profile of the base case and case L1 are shown together in Figure 4.81. This study requires only one oscillation cycle to dramatically shift the slag gap thickness. This is partially due to the increased thermal conductivity of slag K1, as compared to the slag modeled in the base case. As the thermal conductivity increases the solid slag layer grows thicker, which increases the slag gap. Additionally, the lower viscosity of the slag allows for more infiltration of slag during the downstroke. The shell profile is shown for case L1 individually in Figure 4.82.
Figure 4.80 The Temperature Contour in Meniscus Region for Case L1 When the Mold is at a) the End of NST b) the Maximum Velocity b) the Start of NST d) the Minimum Velocity

Figure 4.81 The Shell Profile Calculated for all Cases in the Slag Lubrication Study
The average oscillation mark profile is plotted for the lubrication case in Figure 4.83 and the results of this study are summarized in Table 4.13. The calculated pitch agrees with the theoretical pitch for case L1 within 1.32%. The average oscillation mark depth increased by 33% for the lubrication case. This is likely due to the slag’s reduced ability to resist the downward momentum of the slag rim due to the decreased viscosity, in a situation where the steel does not provide much resistance to deformation. The average profile for the base case and case L1 are shown together in Figure 4.84. Additionally, the standard deviation of the marks are studied in Figures 4.85 and 4.86. The average standard deviation is larger for case L1, which again is likely due to the slag having less resistance to fluid motion and therefore, this causes the fluid flow to be more variable in the slag gap and the meniscus region. Case L1 does not exhibit a distinct location where the standard deviation is higher.

The heat flux profiles for the base case and case L1 are plotted together in Figure 4.88 and is shown individually for case L1 in Figure 4.87. The high heat flux once again extends the furthest up the mold wall at the start of NST. Additionally, it can be seen that the average heat flux is higher for case L1. This is due to the higher conductivity of the liquid slag for slag K1, as compared to the slag modeled in the base case.

Utilizing a lower viscosity slag does contribute to better lubrication. This is seen in Figures 4.90 and 4.89, which show that the mold friction is much lower for the low viscosity case. The lower viscosity slag
allows for the fluid to move more freely in the slag gap, which decreases the resistance experienced by the slag rim and therefore lowers the mold friction.

Table 4.13 Summary of Data Collected from the Lubrication Parametric Study

<table>
<thead>
<tr>
<th></th>
<th>Base Case</th>
<th>Case L1</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical Pitch</td>
<td>5.99</td>
<td>5.99</td>
<td>mm</td>
</tr>
<tr>
<td>Calculated Pitch</td>
<td>6.05</td>
<td>6.07</td>
<td>mm</td>
</tr>
<tr>
<td>Average OM Width</td>
<td>5.855</td>
<td>5.810</td>
<td>mm</td>
</tr>
<tr>
<td>Average OM Depth</td>
<td>0.313</td>
<td>0.407</td>
<td>mm</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.137</td>
<td>0.196</td>
<td>mm</td>
</tr>
<tr>
<td>Surface Roughness, Ra</td>
<td>178.6</td>
<td>214.3</td>
<td>µm</td>
</tr>
<tr>
<td>Average Heat Flux</td>
<td>1.291</td>
<td>1.359</td>
<td>MW/m²</td>
</tr>
<tr>
<td>Average Mold Friction</td>
<td>0.970</td>
<td>0.166</td>
<td>kN/m²</td>
</tr>
<tr>
<td>Average Lubrication Slag Consumption</td>
<td>3.709</td>
<td>13.583</td>
<td>g/ms</td>
</tr>
<tr>
<td>Average Oscillation Mark Slag Consumption</td>
<td>4.177</td>
<td>5.443</td>
<td>g/ms</td>
</tr>
<tr>
<td>Average Total Slag Consumption (Qₛ)</td>
<td>7.886</td>
<td>19.026</td>
<td>g/ms</td>
</tr>
<tr>
<td>Average Total Slag Consumption(Qₑ)</td>
<td>4.722</td>
<td>11.393</td>
<td>g/mcycle</td>
</tr>
<tr>
<td>Average Total Slag Consumption (Q)</td>
<td>0.789</td>
<td>1.903</td>
<td>kg/m²</td>
</tr>
</tbody>
</table>

Figure 4.83 10 Oscillation Marks Calculated for Case L1 and the Average of all 10 Profiles
Figure 4.84 The Average Shell Profile Calculated for all Cases in the Lubrication Study

Figure 4.85 The Standard Deviation of Oscillation Mark Depth for Each Case in the Lubrication Study Along the Width of the Oscillation Mark
Figure 4.86 The Average Oscillation Mark Profile and Error Bars Representing +/- 1 Standard Deviation for Each Case in the Lubrication Study

Figure 4.87 The Heat Flux Profile for Case L1 at Various Mold Positions Throughout the Oscillation Cycle
Figure 4.88 The Heat Flux Profile Along the Mold Hot Face Calculated for all Cases in the Lubrication Study When the Mold is at a) the END of NST b) the Maximum Velocity c) the Start of NST d) the Minimum Velocity
Figure 4.89 The Mold Friction Profile Along the Mold Hot Face Calculated for all Cases in the Lubrication Study When the Mold is at a) the END of NST b) the Maximum Velocity c) the Start of NST d) the Minimum Velocity
Lastly, as is to be expected lowering the viscosity of the slag has a significant impact on the slag consumption. The velocity of the slag in the slag gap is shown in Figure 4.91. The velocity in the slag gap for case L1 does not vary from the velocity found in the base case. Therefore, any changes in the lubrication slag consumption between the two cases is due to the slag gap thickness, as opposed to the slag velocity. The lubrication slag consumption was found to increase in case L1, which is logical due to the substantial increase in the slag gap thickness. Additionally, as the oscillation marks were found to be significantly deeper in case L1 the oscillation mark consumption also increased. Therefore, the total slag consumption increased for the lubrication case.

4.4 Low Heat Flux Study

The purpose of the low heat flux study is to determine how the low heat flux influences the depth and width of the formed oscillation marks, as well as other variables. The theoretical pitch, NST, casting speed, superheat, and type of slag used in the low heat flux case are shown and compared to the conditions of the base case in Table 4.14. All other casting conditions remain the same as the base case. The slag that is modeled in this study is slag S1, which was described in Section 4.3. This slag was chosen because the conductivity of the solidifying slag is lower than the conductivity of the slag in the base case. Additionally, the superheat and casting speed are lowered in this case in order to further contribute to the low heat flux.

<table>
<thead>
<tr>
<th>Case</th>
<th>Theoretical Pitch [mm]</th>
<th>NST [s]</th>
<th>Casting Speed [m/min]</th>
<th>Superheat [K]</th>
<th>Slag</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC</td>
<td>5.99</td>
<td>0.263</td>
<td>0.60</td>
<td>10</td>
<td>Base Case</td>
</tr>
<tr>
<td>HF1</td>
<td>4.99</td>
<td>0.269</td>
<td>0.50</td>
<td>3</td>
<td>Crystalline</td>
</tr>
</tbody>
</table>

The temperature contour plots for case HF1 are shown in Figure 4.92. While the oscillation mark formation mechanism appears to be similar it can be seen in a comparison of temperature contour of the low heat flux case to the base case, shown in Figure 4.93, that a slightly more significant hook is formed at the end of NST. Therefore, while the overflow occurs during PST, as opposed to during NST, which was proposed by Badri et al. [8], the heat flux is shown to influence the size of a hook.

The steel shell growth for the low heat flux case is shown in Figure 4.94. A similar trend is seen as was observed in the base case, but the K factor is lower, 1.27 mm/s\(^{1/2}\), as expected due to the decrease in heat flux, which slowed the solidification of the shell. Additionally, the oscillation marks were found to be shallower in this case and therefore, the change in shell thickness that was observed in the region of oscillation marks in the base case were less pronounced in the low heat flux case. These results agree well with the findings from plant experiments performed by Wolf. [18] Wolf found that using a crystalline
slag for depression-sensitive steel grades (such as ULC and peritectic) should improve surface uniformity, improve heat transfer uniformity, and thereby lessen the chance of cracks.

Figure 4.90 The Mold Friction Profile for Case L1 at Various Mold Positions Throughout the Oscillation Cycle

Figure 4.91 The Slag Velocity Profile in the Slag Gap, 30 mm Below the Far Field Meniscus, for Case L1 at Various Mold Positions Throughout the Oscillation Cycle
Figure 4.92 The Temperature Contour in Meniscus Region for Case HF1 When the Mold is at a) the End of NST b) the Maximum Velocity b) the Start of NST d) the Minimum Velocity
Figure 4.93 The Temperature Contour in Meniscus Region for a) the Base Case and b) Case HF1 at the End of NST
The shell profiles of the base case and case HF1 are shown together in Figure 4.95, and the shell profile is shown for case HF1 individually in Figure 4.96. It can be observed that the slag gap is thicker for the low heat flux case, which is expected for the crystalline slag, owing to its thicker solid layer, which requires more space for the liquid to be consumed. The result of the increased slag thickness is to lower heat flux. Interestingly, while more apparent hooks form, due to the lower superheat, and the increased time for meniscus freezing enabled by the lower casting speed, the oscillation marks actually decrease in depth. This is shown by the average oscillation mark profile overlapped with all oscillation marks found in case HF1 in Figure 4.97 and the average profile compared with the average profile of the base case shown in Figure 4.98. The oscillation mark depth and width are also summarized in Table 4.15. The decrease in oscillation mark depth is likely due to the increase in viscosity found in slag S1. The more crystalline the slag the higher the break temperature, and therefore the more quickly the viscosity increases with decreasing temperature. [9] This observation agrees well with the results of the lubrication study, where lower viscosity was found to increase the depth of oscillation marks. Therefore, logically the more viscous slag should lead to shallower oscillation marks.
Figure 4.95 The Shell Profile Calculated for all Cases in the Slag Lubrication Study

Figure 4.96 The Shell Profile Calculated for Case HF1
Figure 4.97 10 Oscillation Marks Calculated for Case HF1 and the Average of all 10 Profiles

Figure 4.98 The Average Shell Profile Calculated for all Cases in the Heat Flux Study
Table 4.15 Summary of Data Collected from the Low Heat Flux Parametric Study

<table>
<thead>
<tr>
<th></th>
<th>Base Case</th>
<th>Case HF1</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical Pitch</td>
<td>5.99</td>
<td>4.99</td>
<td>mm</td>
</tr>
<tr>
<td>Calculated Pitch</td>
<td>6.05</td>
<td>4.93</td>
<td>mm</td>
</tr>
<tr>
<td>Average OM Width</td>
<td>5.855</td>
<td>4.611</td>
<td>mm</td>
</tr>
<tr>
<td>Average OM Depth</td>
<td>0.313</td>
<td>0.164</td>
<td>mm</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.137</td>
<td>0.053</td>
<td>mm</td>
</tr>
<tr>
<td>Surface Roughness, Ra</td>
<td>178.6</td>
<td>87.8</td>
<td>µm</td>
</tr>
<tr>
<td>Average Heat Flux</td>
<td>1.291</td>
<td>1.079</td>
<td>MW/m$^2$</td>
</tr>
<tr>
<td>Average Mold Friction</td>
<td>0.970</td>
<td>3.253</td>
<td>kN/m</td>
</tr>
<tr>
<td>Average Lubrication Slag Consump.</td>
<td>3.709</td>
<td>9.677</td>
<td>g/ms</td>
</tr>
<tr>
<td>Average Oscillation Mark Slag Consump.</td>
<td>4.177</td>
<td>1.289</td>
<td>g/ms</td>
</tr>
<tr>
<td>Average Total Slag Consumption ($Q_s$)</td>
<td>7.886</td>
<td>10.966</td>
<td>g/ms</td>
</tr>
<tr>
<td>Average Total Slag Consumption ($Q_c$)</td>
<td>0.789</td>
<td>6.566</td>
<td>g/mcycle</td>
</tr>
<tr>
<td>Average Total Slag Consumption ($Q$)</td>
<td>7.886</td>
<td>1.097</td>
<td>kg/m$^2$</td>
</tr>
</tbody>
</table>

The standard deviation of the marks are studied in Figures 4.99 and 4.100. The average standard deviation is smaller for case HF1, which is likely due to the increased viscosity of the slag. This agrees with the findings of case L1. This is logical because as the viscosity of the slag increases the fluid motion in of the slag in the gap is less variable, which leads to more predictable oscillation marks.

The heat flux profiles for the base case and case HF1 are plotted together in Figure 4.101 and the shell profile for case HF1 is shown in Figure 4.102. The location of the sharp rise in high heat flux once again extends the furthest up the mold wall at the start of NST. Additionally, it can be seen that the average heat flux is approximately 20% lower for case HF1, which is as expected. This is due to the increased slag gap thickness and the decreased conductivity of the solidifying slag, which is more important than the shallower OMs.

Utilizing a higher viscosity, which is found in the crystalline slag, increases the average mold friction, as expected. This is seen in Figures 4.103 and 4.104, which show that the mold friction is higher for case HF1. The low heat flux case, which is also a high viscosity case, shows that when the viscosity of the slag is increased, the mold friction becomes significant beyond just the end of NST. Therefore, mold friction is observed to be significant due to more than just the increased pressure in the slag gap during the end of NST. The increased viscosity causes increased friction along the length of the mold and it also causes substantial negative mold friction at the end of upstroke, which is not observed in other cases.

Lastly, as is to be expected, changing the slag composition can have a significant impact on the slag consumption. The velocity of the slag in the slag gap is shown in Figure 4.105. The velocity in the slag gap for case HF1 behaves differently than the slag velocity for other cases, which is once again due to the
increased viscosity. The increased viscosity of the solidifying slag causes the slag to resist the changes in

![Figure 4.99 The Standard Deviation of Oscillation Mark Depth for Each Case in the Heat Flux Study Along the Width of the Oscillation Mark](image)

![Figure 4.100 The Average Oscillation Mark Profile and Error Bars Representing +/- 1 Standard Deviation for Each Case in the Heat Flux Study](image)
Figure 4.101 The Heat Flux Profile Along the Mold Hot Face Calculated for all Cases in the Heat Flux Study When the Mold is at a) the END of NST b) the Maximum Velocity c) the Start of NST d) the Minimum Velocity
Figure 4.102 The Heat Flux Profile for Case HF1 at Various Mold Positions Throughout the Oscillation Cycle

Figure 4.103 The Mold Friction Profile for Case HF1 at Various Mold Positions Throughout the Oscillation Cycle
Figure 4.104 The Mold Friction Profile Along the Mold Hot Face Calculated for all Cases in the Heat Flux Study When the Mold is at a) the END of NST b) the Maximum Velocity c) the Start of NST d) the Minimum Velocity
the direction of fluid flow more than in other cases. Therefore, the slag velocity in the gap at the start of NST is still slightly positive near the steel shell and the slag velocity at the end of NST is slightly below the casting speed near the steel shell. The increased slag gap thickness leads to a substantial increase in the lubrication slag consumption for case HF1. Additionally, the decrease in the oscillation mark width and depth leads to a decrease in the oscillation mark consumption. The lubrication effect is the dominant effect in this case and therefore, the total slag consumption increases. These results agree with the results found by Shin et al. [1]

4.5 Level Fluctuations Study

In continuous casting, level rises and level drops in the molten steel level are common. These fluctuations are responsible for many of the surface defects in continuous casting, due to their effect on initial solidification at the meniscus. This section investigates this phenomenon by considering a case, LF1, where the molten steel level rises by 10 mm and the drops back down to the nominal meniscus level and a case, LF2, where the molten steel level drops by 5 mm and then rises back to the nominal far field meniscus.

In both cases the level rise and level drop of the steel level was controlled by altering the “steel _inlet _mass” user defined function found in Appendix A. In order to alter the level of the molten steel the desired level change can be converted into an equivalent mass flow rate change using Equation 4.4, where $\Delta_{massflow}$ is the rate of change of the rate of change in the mass flow rate. The change in mass flow rate is

\[
\Delta_{massflow} = \text{desired level change}
\]
shown for the cases LF1 and LF2 in Figure 4.106.

\[
\Delta_{\text{massflow}} = \frac{1}{N_{\text{timesteps}}} \frac{\Delta_{\text{level}} W_{\text{domain}} \rho_{\text{steel}} 2f}{N_{\text{cycles}}}
\]

(4.4)

where:

\(\Delta_{\text{massflow}}\): Slope of change in mass flow rate curve \(\left[ \frac{\text{kg}}{\text{mass step}} \right]\)

\(N_{\text{timesteps}}\): Number of timesteps during the level rise or level drop [-]

\(\Delta_{\text{level}}\): Change in the level \([\text{m}]\)

\(W_{\text{domain}}\): Width of the domain \([\text{m}]\)

\(\rho_{\text{steel}}\): Density of the steel \(\left[ \frac{\text{kg}}{\text{m}^3} \right]\)

\(f\): Frequency of the oscillation cycle \([\text{Hz}]\)

\(N_{\text{cycles}}\): Number of cycles that the oscillation takes place over [-]

Level fluctuations have been considered by Thomas and Jenkins. [19] In theory as the level of molten steel in the caster rises, the slag rim will cause increased pressure in the molten steel at a higher level, which should cause oscillation marks to be formed at a larger pitch during a level rise. Correspondingly, during a level drop the opposite should take place so as the level drops the pitch between oscillation marks.
should decrease. The relationship between the rate of level change and the pitch between the oscillation marks has been proposed to follow the following Equation 4.5, where $V_L$ is velocity representing the rate of level increase [$m/s$]. [19]

$$V_L = (P - P_{avg})f$$  \hspace{1cm} (4.5)

where:

$P$: Pitch during a level change [$m$]

$P_{avg}$: Theoretical average pitch for the given casting conditions [$m$]

$f$: Frequency of the oscillation [$Hz$]

The theoretical pitch and NST for shown for all cases in the level fluctuations study are shown in Table 4.16. These values are the same for all cases as the casting conditions remain the same as those used in the base case.

As mentioned previously, the theory behind the pitch of oscillation marks increasing with increasing level requires that the oscillation mark is formed in the molten steel above the nominal far field meniscus.

Table 4.16 Case Information for the Level Fluctuations Parametric Study

<table>
<thead>
<tr>
<th>Case</th>
<th>Theoretical Pitch [$mm$]</th>
<th>NST [$s$]</th>
<th>Level Change</th>
<th>Theoretical $V_L$ [$mm/s$]</th>
<th>Theoretical Pitch [$mm$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC</td>
<td>5.99</td>
<td>0.263</td>
<td>No Level Change</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>LF1</td>
<td>5.99</td>
<td>0.263</td>
<td>Rise then Fall</td>
<td>5.56</td>
<td>9.30</td>
</tr>
<tr>
<td>LF2</td>
<td>5.99</td>
<td>0.263</td>
<td>Fall then Rise</td>
<td>-1.50</td>
<td>4.48</td>
</tr>
</tbody>
</table>

The shell profile extracted from the level rise case, along with the observed level in the meniscus region and at the far field meniscus are plotted in Figure 4.107. In this section when an oscillation mark is referred to as a number, it is referring to the oscillation mark counting right to left in this figure. Additionally, on this plot the theoretical level rise is shown. This level is calculated using the equation developed by Thomas and Jenkins based on the observed pitches of each oscillation mark and the average theoretical pitch calculated using the casting conditions of the base case. [19] It can be seen that the actual level change, observed both in the meniscus region and in the far field region, and the level change predicted by Thomas and Jenkins [19] vary significantly. Additionally, the average oscillation mark profile calculated during the level rise case is shown along with the base case in Figure 4.108 and is shown with all oscillation marks overlapped in Figure 4.109. From these figures it can be seen that the average oscillation mark profile found in the level rise case does not vary significantly from the average oscillation mark profile calculated in the base case.
Figure 4.107 The Shell Profile, Observed Level Rise, and the Level Rise Predicted by Thomas and Jenkins [19] for Case LF1

Figure 4.108 The Average Oscillation Mark Profiles Found for the Base Case and Case LF1
Figure 4.109 The Average Oscillation Mark Profile for Case LF1 Overlapped on All Oscillation Mark Profiles for Case LF1

Therefore, this requires that the steel solidifies at a higher level up the mold wall. Temperature contour plots for an oscillation cycle during the level rise and an oscillation cycle during the level drop are shown in Figures 4.110 and 4.111, respectively. During the level rise and the level fall it is observed that the oscillation marks and shell solidification both occur near the nominal far field meniscus level, which causes the oscillation mark shape and pitch to remain consistent with that found in the base case. This is logical because in order for an oscillation mark to maintain its shape the steel shell must solidify quickly after the mark is made and the temperature contour plots show that the molten steel does not solidify when the steel level is found higher up the mold wall where the slag rim is thick at the increased level. The molten steel is unlikely to solidify at the elevated levels due to the increased thermal resistance created by the slag rim. The solidified slag rim, which is shown in the dark blue region of the temperature contours, has a lower thermal conductivity than the liquid slag found in the slag gap. Therefore, as the level rises the molten steel is pushed further away from the mold wall and the slag rim increases the resistance to heat transfer, therefore the heat flux is not adequate to cause solidification of the steel shell. The current level rise case is a relatively fast level rise and fall. Therefore, if the level rise were to be more gradual the slag rim may melt as the level rises, which may cause more solidification to occur during the level rise and therefore the pitch change predicted by Jenkin’s may occur under a slower level rise.
Figure 4.110 The Temperature Contour Plot of One Oscillation Cycle During the Level Rise Occurring During the Ninth Oscillation Mark (Counting Right to Left) of Case LF1
Figure 4.111 The Temperature Contour Plot of One Oscillation Cycle During the Level Fall Occurring During the Ninth Oscillation Mark (Counting Right to Left) of Case LF1
The heat flux profiles found at several steel levels at the start of NST, which has been found to be where the maximum heat flux occurs, are shown in Figure 4.112, and further support this theory. It was found that as the level rises the heat flux in the meniscus region increases within the region 5 mm above the meniscus due to the molten steel being higher up the mold, but as the level increases more than 5 mm the heat flux profile is not found to shift, which is due to the slag rim preventing further increases in heat flux. However, as the level then begins to drop it can be seen that the heat flux initially increases in the region 5 mm to 10 mm above the nominal meniscus and then decreases as the level begins to return to the nominal meniscus level. This is due to changes in the slag rim, which can be seen in the broad view temperature contour plots shown in Figures 4.114 and 4.115, which show the entire level rise and drop cycle. It is observed that as the level reaches its peak the slag rim begins to melt and change shape. Then as the level drops the slag rim has moved away from the meniscus region which allows for greater heat transfer in the region above the nominal meniscus level. However, this is coupled with the fact that the molten steel level is dropping and therefore as the level falls two phenomena occur. The first phenomena being that the molten steel is dropping and moves further down the mold wall and away from the mold wall. The movement in the slag rim coupled with the falling meniscus level allows for increased slag to enter into the gap, which leads to the increase in the slag gap shown in the shell profile. Therefore, the heat flux in the region +/- 5 mm from the nominal meniscus level decreases during the level drop that follows the level rise over the slag rim.

Figure 4.112 The Heat Flux Profile Along the Mold Hot Face Found at Various Meniscus Levels for Case LF1 at the Start of NST
The effects of the change in the slag rim shape and slag gap thickness are further observed in the mold friction, which is shown in Figure 4.113. The mold friction found along the mold hot face is plotted for various meniscus levels at the end of NST, which is where the peak mold friction has been observed in previous studies. It was found that during the level change the mold friction decreases. This is likely due to the slag being pushed out of the gap during the level rise, which leads to less resistance of the slag rim during the downstroke. Additionally, as the steel level begins to drop back down the slag rim has moved up and this initially further decreases this resistance and therefore decreases the mold friction. However, as the slag begins to infiltrate the gap the resistance once again increases and the mold friction begins to increase slowly.

![Figure 4.113 The Mold Friction Found Along the Mold Hot Face at Various Meniscus Levels for Case LF1 at the End of NST](image)

The level drop case behaves very differently from the level rise case. The shell profile is shown for the level drop case, along with the level change curve for both the meniscus region and the far field meniscus and the theoretical level predicted by Jenkins equation in Figure 4.116. The shell profile was found to be significantly more variable and therefore it is best to describe what is happening in each region of this curve. The first five oscillation marks shown in this figure (counting right to left) are calculated using the base case conditions, without any changes to the steel mass flow inlet. Therefore, these oscillation marks...
Figure 4.114 Broad View Temperature Contour Plots of the Level Rise in Case LF1

All Dimensions are in mm
Figure 4.115 Broad View Temperature Contour Plots of the Level Fall in Case LF1

All Dimensions are in mm
appear to be very regular in comparison to what has been seen in studies thus far. The sixth and seventh oscillation marks that are formed are again formed under normal conditions, but their shape appears to be different as the slag gap increases and then decreases during these marks. The level drop occurs during the eighth through the tenth mark. During this time the steel level begins to drop, which leads to less force pushing steel near the mold wall, so the slag gap remains thick and the oscillation marks are less pronounced. The creation of mark nine is shown in Figure 4.117. As can be seen in this image the molten steel does not overflow as dramatically during PST as seen in other cases, as the molten steel is not available since the level has dropped. During oscillation marks eleven through thirteen the level rises back to its nominal value, which leads to the overflow during PST to return to its normal amount. This is shown in Figure 4.118, which shows the creation of oscillation mark twelve. During this cycle, due to the low steel level, a small hook is formed. As the molten steel returns to its nominal meniscus level the overflow is large enough to overflow the hook, which creates a deep oscillation mark and traps some of the slag in the steel shell. The theoretical level fluctuations predicted by Thomas and Jenkin’s equation [19] do not agree well with the levels observed in this study. There is a level drop and a level rise predicted by Jenkins in the region 16 to 34 mm below the far field meniscus, but this level change is not as severe as the actual fluctuation observed, and it occurs over a shorter period of time.

![Figure 4.116 The Shell Profile, Observed Level Rise, and the Level Rise Predicted by Thomas and Jenkins [19] for Case LF2](image)

Figure 4.116 The Shell Profile, Observed Level Rise, and the Level Rise Predicted by Thomas and Jenkins [19] for Case LF2
Figure 4.117 The Temperature Contour Plot of One Oscillation Cycle During the Level Drop Occurring During the Ninth Oscillation Mark (Counting Right to Left) of Case LF2
Figure 4.118 The Temperature Contour Plot of One Oscillation Cycle During the Level Rise Occuring During the Twelth Oscillation Mark (Counting Right to Left) of Case LF2
There is a lot of variation seen in these oscillation marks due to the drastic changes in fluid flow pattern and meniscus shape that is created due to the level drop. This is in part due to geometry of the current model. The mass inlet is position just 5 mm below the far field meniscus in the current model. Therefore, in order to keep from the level drop going below this level a level drop of 5 mm was used for this study. However, this still puts the final far field level very close to the mass inlet. Additionally, due to time restrictions this drop occurred over 3 cycles, which is a relatively fast level drop and then was set to rise over the same time period. Additionally, in order for this minor drop to occur the mass flow was not simply allowed to decrease in magnitude, but actually changed direction. These elements caused for changes in the fluid flow patterns in the domain, which are shown in the broad view temperature contours plots of the entire cycle shown in Figures 4.120 and 4.121. This behavior models an event that can occur in a real caster due to turbulent behavior, but it does prevent from accurately observing the trends found by Thomas and Jenkins. [19] Therefore, it can be concluded that changes in the pitch are observed during a level drop scenario and that Thomas and Jenkin’s equation is able to predict this trend. However, further studies should be performed in order to determine whether or not the equation accurately predicts scenarios including only level drop behavior, as this study included additional elements that may cause deviations from true caster behavior.

The heat flux and mold friction were also considered in this study. The heat flux profile along the mold hot face is plotted for various meniscus levels at the start of NST in Figure 4.119.
Figure 4.120 Broad View Temperature Contour Plots of the Level Drop of Case LF2

All Dimensions are in mm
Figure 4.121 Broad View Temperature Contour Plots of the Level Rise of Case LF2

All Dimensions are in mm
In this figure it can be seen that as the level falls the heat flux begins to decrease, which is due to the molten steel not being pulled as far up the mold wall during the upstroke. During the level drop slag is again allowed to move into the gap and this causes an increase in slag gap thickness, so even during the subsequent level rise the heat flux continues to drop. The mold friction is shown in Figure 4.122. The mold friction is found to increase during the entire level change. This is due to the increased slag gap thickness found during the level change.

![Mold Friction Graph](image)

Figure 4.122 The Mold Friction Found Along the Mold Hot Face at Various Meniscus Levels for Case LF2 at the End of NST

### 4.6 Marangoni Effect Study

The Marangoni Effect can cause changes in the direction of fluid flow. This effect is caused by changes in the surface tension between two fluids. [20] The Marangoni Effect is often seen in welding, as a change in the direction of fluid flow within the weld pool. This can lead to different shapes of weld pools, either wide and shallow or deep and narrow depending on how the fluid flow pattern changes. [21] The change in fluid flow pattern is only observed if the change in the surface tension is significant in comparison to other forces present, such as pressure, body, viscous, and inertial forces. The main factors that impact changes in surface tension are sulfur concentration and temperature gradients. [21] Both of which are present in continuous casting.

The surface tension between the slag and the molten steel can be defined by the Girfalco-Good Equa-
tion 2.11 [22]. This equation requires the interfacial surface tension of both fluids relative to an inert gas. Additionally, the constant $\phi$ must be calculated using Equation 2.12 [23], both of which are shown in Chapter Two.

The surface tension between the slag and an inert gas, $\gamma_{\text{slag-gas}}$, can be calculated using a weighted average approach. In this kind of approach the weight percent of each component in the known chemical composition of the slag is multiplied by the surface tension, relative to an inert gas, of that particular slag component. This procedure is completed for all components present in the slag and the results are summed to determine one surface tension for the slag relative to an inert gas. [9] All surface tensions are dependent on temperature and therefore, the surface tension - temperature relationships for each slag component are shown below in Table 4.17.

Table 4.17 Surface Tension - Temperature Relationships of Various Slag Components [24]

<table>
<thead>
<tr>
<th>Component</th>
<th>Surface Tension - Temperature [K] Relationships</th>
</tr>
</thead>
<tbody>
<tr>
<td>$CaO$</td>
<td>791 - 0.0935$T$</td>
</tr>
<tr>
<td>$SiO_2$</td>
<td>243.2 + 0.031$T$</td>
</tr>
<tr>
<td>$Al_2O_3$</td>
<td>1024 - 0.177$T$</td>
</tr>
<tr>
<td>$MgO$</td>
<td>1770 - 0.636$T$</td>
</tr>
<tr>
<td>$Na_2O/Li_2O$</td>
<td>438 - 0.116$T$</td>
</tr>
<tr>
<td>$CaF_2$</td>
<td>1604.4 - 0.72$T$</td>
</tr>
</tbody>
</table>

The surface tension of the steel relative to an inert gas, $\gamma_{\text{steel-gas}}$, is dependent on the temperature of the steel and the sulfur content of the steel. Research has been done in the welding industry to determine how temperature and sulfur content impact surface tension. [21] The relationships found are summarized in Figures 4.123 and 4.124. It can been seen that the surface tension of iron decreases with increasing sulfur content, while the change in surface tension due to a change in temperature increases with increasing sulfur content. Therefore, the higher the sulfur content the more sensitive the surface tension is to changes in temperature. For a given sulfur content an equation of the form shown in Equation 4.6, where $C_1$ is the surface tension of the steel, containing a specified amount of sulfur, at 1873 °K, $C_2$ is the surface tension gradient of the steel, containing a specified amount of sulfur, at 1873 °K, and $T_o$ is 1873 °K, can be used to described how the surface tension of steel, relative to an inert gas, changes with temperature.

$$\gamma = C_1 + C_2(T - T_o)$$

All steels contain some amount of sulfur, which remains constant in the bulk of the molten steel. However, as the molten steel solidifies sulfur is rejected along the solidification front. [25] Therefore, at the solidification front the sulfur content of the steel increases. The increase in sulfur content will decrease
Figure 4.123 Effect of Sulfur Content on the Surface Tension of Iron at 1873 K [21]

Figure 4.124 Effect of Sulfur Content on the Surface Tension Gradient of Steel [21]
the surface tension of the steel in this region and will increase the steel’s surface tension gradient, therefore changing the surface tension of the steel. These variabilities in the steel’s surface tension, relative to an inert gas, also alter the overall surface tension between the slag and the steel. Therefore, in this parametric study an effort was made to quantify these changes in surface tension in order to determine whether or not the Marangoni Effect plays a significant role in the meniscus region of the caster.

In order to determine the surface tension at any given location in the domain and at any given time within the simulation, the sulfur content at each location must be quantified. Therefore, the concentration field equation shown in Equation 4.7 taken from Yuan’s microsegregation model [25] was used to estimate the concentration field near the solidified steel shell. In this equation \( C(r) \) is the sulfur concentration at a radius \( r \) away from the shell tip. Typical values for all of these variables required in Equations 4.7 and 4.8 were taken from Yuan’s research. [25]

The sulfur concentration that is impactful in this study is the increase in sulfur concentration due to macrosegregation, or the segregation of sulfur along the whole solidification front rather than the segregation from one single dendrite tip. However, to truly model the segregation behavior in the meniscus region a microsegregation and macrosegregation model must be combined. This is out of the scope of this project, and therefore Yuan’s microsegregation model is used, but the value of \( r_d \) is modified in attempts to replicate the true solidification front.

\[
C(r) = C_o + \left( \frac{r_d}{r} \right) (C^* - C_o)
\]

where:
- \( C_o \): Sulfur concentration in the bulk of the molten steel [-]
- \( r_d \): Radial distance away from a dendrite tip [m]
- \( C^* \): A constant defined by Equation 4.8

\[
\frac{v_{sli}t_d}{2D_s} = \frac{(C^* - C_o)}{C^*(1 - k)}
\]

where:
- \( v_{sli} \): Velocity of the solidification front [m/s]
- \( D_s \): Diffusion coefficient of sulfur in the steel [-]
- \( k \): Distribution coefficient of the steel [-]

The sulfur concentration profile was calculated using several approximations of \( r_d \), as shown in Figure 4.125. Using the calculated sulfur concentration profile, other known surface tension relationships, and
a temperature profile of the meniscus region extracted from the base case the slag/steel surface tension profile was calculated and plotted in Figure 4.126. In Figure 4.125 the red line signifies the bulk sulfur concentration. Therefore, at any position less than the position at the intersection of the concentration profile with the red line, the concentration is equal to the bulk concentration. Additionally, in Figure 4.126 at any position less than the position at the intersection of the concentration profile with the red line, the surface tension is equal to that of the surface tension at the bulk concentration. It can be seen in Figure 4.126 that the changes in surface tension are small until the approximation for $r_d$ becomes relatively large, around 100 to 1000 times the radius of a dendrite tip, which are not realistic for the actual distance the solidification front extends beyond the shell tip. [26] However, due to the numerical accuracy of the model any impact on the surface tension due to a solidification front located less than 100 times that of a dendrite tip can not been captured in the model. Therefore, it was determined that using the approximation of $100r_d$ would both appear in the current model and would provide a worse case scenario as the surface tension variations are likely larger than anything seen in a real caster.

![Figure 4.125 Sulfur Concentration Profile for Various Approximations of the Solidification Front](image)

In addition to studying the impact of changing the position of the solidification front, it is also important to determine the best bulk sulfur content to apply to the case used in the parametric study. The goal is to model the worst case scenario to determine if the Marangoni effect plays any role in the meniscus region. Therefore, the steel/slag surface tension was calculated along the interface for various realistic values of bulk sulfur content. This is shown in Figure 4.127. The results show that the larger the bulk sulfur content the larger the change in surface tension.
For this parametric study the same model used as in base case with the exception of the surface tension coefficient. In the base case a constant surface tension of 1.3 N/m was applied to the interface of the slag and the steel, while in the parametric study the surface tension was set to a user-defined-function called "sfct", which can be found in the Appendix E. This function causes the surface tension to behave as seen in the relationship in Figure 4.126. Two choices had to be made to determine how this relationship
would behave, the bulk sulfur content and the equivalent distance of the macrosegregation. Realistically speaking the macrosegregation will not extend up to 100 or 1000 times that of the microsegregation model. However, the resolution on the mesh for this model will not register the impact of choosing a distance for the macrosegregation to occur over that is less than 50 µm. Therefore, the macrosegregation distance was chosen to be 100\( r_d \), which is 100 times that of the microsegregation. Additionally, as the most severe changes in surface tension were seen for a large bulk sulfur content the study was first performed with a bulk sulfur content of 0.1 %. However, the results of this study caused unrealistic movement in the meniscus. The reason behind this was determined to be that coupling the unrealistic distance for the macrosegregation with the high bulk sulfur content caused the changes in surface tension to be unrealistic, which in turn led to unrealistic behavior in the meniscus region. Therefore, to accommodate for the model being incapable of modeling the appropriate macrosegregation distance, a bulk sulfur content of 0.01 % was used, which resulted in realistic behavior in the meniscus region.

The shell profile for the base case and the case including the appropriate surface tension are shown in Figure 4.128. There is no significant impact on the oscillation marks and slag gap thickness. Additionally, the temperature contour plot for the case that attempts to include the appropriate surface tension is shown in Figure 4.129. If the Marangoni effect were to be observed in the caster a continuous counter clockwise flow would develop in the very corner of the meniscus region. From this study this behavior was not seen. Therefore, no further investigation was performed using this addition to the model.

![Figure 4.128 The Steel Shell Profile Calculated for the Base Case and the Case Including a Variable Surface Tension](image-url)
4.7 Chapter 4 References


5.1 Trends Observed in All Parametric Studies

From the cases that were run, general trends have been observed in the oscillation mark depth, oscillation mark width, average heat flux, average mold friction, and the total slag consumption. These trends do not include the level fluctuations study or the Marangoni effect study, as the casting conditions of these studies did not vary from the base case casting conditions. The first trend that was observed is summarized in Figure 5.1. It was found that as NST increases so does oscillation mark depth. This makes sense because with the oscillation mark mechanism that was observed in these studies, oscillation marks begin to form at the start of NST and reach their deepest point at the end of NST. Therefore, as the NST increases the slag rim is pushing the molten steel away from the mold wall for a longer period of time, which allows the oscillation mark to penetrate deeper into the steel shell. Case HF1 was found to diverge from this trend, which is due to the high viscosity of the slag modeled in this case. It was found that slag viscosity has a significant influence on oscillation mark depth and therefore, this case is expected to deviate from the trend observed with the other slag. Additionally, it was found that the oscillation mark depth increases with increasing lead, which is shown in Figure 5.2. The lead can be defined by Equation 5.1, where Lead is in $mm$.

![Figure 5.1 Oscillation Mark Depth as a Function of Negative Strip Time for all Cases](image)
Figure 5.2 Oscillation Mark Depth as a Function of Lead for all Cases

\[
\text{Lead} = st \times \sin(\pi f) - v_c \times t_n
\]  

(5.1)

where:

\(-st\): Stroke \([\text{mm}]\)

\(-f\): Frequency \([\text{Hz}]\)

\(-v_c\): Casting Speed \([\frac{\text{mm}}{\text{s}}]\)

\(-t_n\): Negative Strip Time \([\text{s}]\)

The width of oscillation marks were found to depend more on the casting speed of the shell than on the negative strip time, or any other oscillation parameter. The oscillation mark width is plotted as a function of casting speed in Figure 5.3. It was observed that the width of oscillation marks increases with increasing casting speed. As an oscillation mark is being formed in the steel shell the steel shell is simultaneously moving downwards at the casting speed. This leads to the oscillation mark being formed over a larger vertical region and therefore increase the oscillation mark width. An additional way to summarize this finding would be to say that the pitch is directly related to the pitch. Fluctuations in the oscillation mark width are also observed in the frequency study, but not as severe as the changes in frequency were smaller than the changes in casting speed.
The average heat flux along the mold hot face calculated in the region 50 − 100 mm below the far field meniscus was found to decrease with increasing NST. This result is shown in Figure 5.4. As the NST increases this means PST decreases. Therefore, the time period where the molten steel is drawn near the mold hot face, which increases the heat flux along the mold hot face, is decreased. This logically leads to a lower average heat flux. Additionally, as NST increases the depth of oscillation marks were found to increase, which means that more slag will be built up between the steel shell and the mold wall increasing the thermal resistance between the steel shell and the mold wall. Therefore, the heat flux will also decrease due to increased oscillation mark depth. Once again the low heat flux trial, case HF1, should not be considered in determining this trend, as the slag that was modeled in this case contributes to the heat flux profile more than the negative strip time.

The average mold friction along the mold hot face is shown to decrease with increasing NST in Figure 5.5. As the NST increases the amount of time that the slag rim has to move from its highest position down to its lowest position during the downstroke also increases. This leads to a lower velocity of the slag rim, which means that the slag rims momentum is lower. Since the slag rims momentum is lower there is less resistance to the slag rim decreasing back to a zero velocity at the mold's lowest position. Therefore, since the momentum is lower the mold friction also decreases. The lubrication study and the heat flux study were found to be outliers from this trend, which is again due to the change in the slag properties. Ad-
Additionally, case ST1 was found to diverge from this trend. This signifies that the decrease in the velocity of the slag found by decreasing the stroke is a dominant effect over the effect of negative strip time.

Figure 5.4 Average Heat Flux as a Function of Negative Strip Time for all Cases

Figure 5.5 Mold Friction as a Function of Negative Strip Time for all Cases
The total slag consumption was found to increase with increasing NST, which is shown in Figure 5.6. There are two components to slag consumption, oscillation mark consumption and lubrication consumption. It was found that as NST increases the depth of oscillation marks also increases. Therefore, the oscillation mark consumption also increases. Additionally, it was observed that the slag gap thickness increases with increasing NST, which means the lubrication slag consumption is likely to increase. Therefore, the total slag consumption increases with increasing NST. The equation developed by Shin et al. to describe the total slag consumption shown in Equation 5.2 is also included on this plot. [1] This equation contains many variables and therefore the frequency was chosen to remain constant, at 1.67 Hz, and the casting speed was then altered to fit various values of NST. The trend found from the studies included in this report agree well with Shin’s equation.

\[ q_{tot} = \left(2.5e - 2\rho_{slag} k^{1.43} \left(\frac{2\Delta \gamma}{\Delta \rho g}\right)^{0.556} \rho_n^{0.389} v_c^{-1.49} + 0.507 e^{3.59\nu} \right) f \]  

(5.2)

where:

- \( \rho_{slag} \): Density of slag, set to 2600 [kg/m³] for this study
- \( k \): Empirical constant dependent on slag properties, set to 14.6 for this study [-]
- \( \Delta \gamma \): Difference between the surface tension of the steel and the slag, set to 1.3 [N/m] for this study
- \( \Delta \rho \): The difference between the steel density and the slag density, set to 3400 [kg/m³] for this study
\( g \): The gravitational constant \( \left[ \frac{m}{s^2} \right] \)

\( t_n \): Negative strip time \([s]\)

\( v_c \): Casting speed \( \left[ \frac{m}{s} \right] \)

\( t_p \): Positive strip time \([s]\)

\( f \): Frequency, set to 1.67 \([Hz]\) for this study

5.2 Practical Implications

In all cases included in this study with the exception of the level fluctuations and Marangoni studies, oscillation marks were formed in the same manner. During the downstroke of the oscillation, it was found that the slag rim increases pressure beneath it, which pushes the molten steel to be pushed away from the mold wall, this creates the bottom half of the oscillation mark and creates the deepest part of the oscillation mark. Then during the upstroke, molten steel was found to be drawn near the mold wall due to suction created by the upwards movement of the mold. This upward movement of the molten steel was found to create the upper half of the oscillation mark.

Hooks were not found in most studies, due to the high superheat, 10 \(^{\circ}K\), that was applied in the meniscus region of the domain. However, hooks were observed in three simulations. Case ST2, showed that the hooks can occur at high strokes. The increased stroke caused the magnitude of the maximum and minimum mold velocities to increase and therefore increased the momentum of the slag rim. The increased momentum of the slag rim caused the molten steel to be pushed further away from the mold wall during the downstroke. This led to the temperatures near the top of the solidified steel shell to decrease, which led to the formation of a hook. Additionally, hooks were observed in the Case HF1. In this study the heat flux in the meniscus region was decreased and therefore the shell was able to solidify more during the downstroke of the mold and this created a hook. In addition a hook was observed in Case LF2, due to the decreased level in the molten steel, which led to a region with locally lower heat flux.

The peak heat flux was found to occur at the start of NST, in most cases that did not involve hook formation. This is logical as during the upstroke it was found that the molten steel was drawn near the mold wall. At the start of NST the molten steel is at its highest point, which leads to increased heat flux in the region above the far field meniscus. This is contrary to the peak heat flux found in experimental results presented by Badri. [2] However, it is logical for two reasons. The first reason is due to the difference between the Eulerian reference frame used to analyze data in the FLUENT MODEL and the Lagrangian reference frame used to analyze data in the experimental set-up. In the experiment the heat flux is calculated using temperature measurements taken from thermocouples that are embedded in the mold wall. Therefore, during the downstroke of the mold the thermocouples move down with the mold and this places the
thermocouples below the molten steel level at the start of NST. This logically will increase the temperature of the thermocouples more than the suction of molten steel near the mold wall found during upstroke. The second reason the heat flux peaks do not agree may be attributed to when the overflow occurs. It was found by Jonayat et al. [3] that with the casting conditions used by Badri, the overflow of molten steel being drawn near the mold wall may occur at different points in the oscillation cycle. This change was found to occur primarily due to the presence of hooks. If a hook is severe enough it is logical that the molten steel may overflow at the end of NST, as the steel in the meniscus region would not be pushed away in the same was seen in this report, which may further explain the difference in the times that peak heat flux occur.

It was found that mold friction reaches a maximum at the end of NST. This is due to the slag rim facing the greatest amount of resistance to downward motion at the end of NST. This increase in resistance causes an upward force on the slag rim, which causes increased mold friction. The predicted mold friction values are much smaller than friction measured in the entire mold, which shows that friction in the meniscus region is very small, as expected due to the thick liquid slag layer. [4]

The oscillation mark depth and width were calculated in each case and it was found that oscillation mark depth will decrease with increasing frequency, increasing modification ratio, increasing casting speed, and increasing slag viscosity, while oscillation mark depth was found to increase with increasing stroke. The oscillation mark width was found to vary in the same way as the pitch. Therefore, the width was found to increase with increasing casting speed and with decreasing frequency. The ratio of oscillation mark width to pitch for each case is reported in Table 5.1. The average ratio of oscillation mark width to pitch was 97.23% with a standard deviation of 1.96%. The only case found to lie significantly outside of one standard deviation from the average is case HF1. In this case the viscosity of the slag was much higher than in other cases and therefore, the oscillation marks were found to not only be shallower than the base case, but also to be thinner.

In case MR1, which includes non-sinusoidal oscillation with a modification ratio of 24 %, it was observed that small lips formed in the upper half of the oscillation mark. It was observed that the first lip occurs during the time after the end of NST while the mold is still moving down, which is larger for the non-sinusoidal case than for the base case. The second lip was observed as the mold velocity started to decrease in velocity from the maximum mold velocity. Non-sinusoidal oscillation also caused shallower oscillation marks, but higher mold friction, both of which are due to the shorter NST found in a non-sinusoidal oscillation.
Table 5.1 Ratio of Oscillation Mark Width to Pitch for All Cases

<table>
<thead>
<tr>
<th>Case</th>
<th>Oscillation Mark to Pitch Ratio [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC</td>
<td>97.78</td>
</tr>
<tr>
<td>F1</td>
<td>96.61</td>
</tr>
<tr>
<td>F2</td>
<td>97.58</td>
</tr>
<tr>
<td>F3</td>
<td>99.19</td>
</tr>
<tr>
<td>ST1</td>
<td>96.46</td>
</tr>
<tr>
<td>ST2</td>
<td>97.78</td>
</tr>
<tr>
<td>MR1</td>
<td>95.62</td>
</tr>
<tr>
<td>CS1</td>
<td>99.41</td>
</tr>
<tr>
<td>CS2</td>
<td>99.72</td>
</tr>
<tr>
<td>L1</td>
<td>97.03</td>
</tr>
<tr>
<td>HF1</td>
<td>92.40</td>
</tr>
</tbody>
</table>

In the casting speed study it was found that two oscillation mark peaks were formed in the oscillation marks at the 1 m/min casting speed case, and were faintly seen in the high casting speed case. When the casting speed is increase the time period prior to NST and following NST, when the mold is still moving down but is moving down less quickly than the casting speed, increases when all oscillation parameters remain constant. During the time period following NST when the mold is still moving down it was found that the solidified steel shell moved slightly below the far field meniscus, which prevents the lower portion of the oscillation mark from continuing to increase in depth. Then the solidified shell prevents the molten steel from overflowing at the start of the upstroke and it does not overflow and create the second half of the oscillation mark until the mold reaches its maximum upwards velocity because until it reaches the maximum velocity the molten steel does not have enough momentum to overcome the solidified steel shell.

The pitch of the oscillation marks formed in the level rise case, LF1, did not vary as was predicted by Jenkins et al. [5] during the level fluctuations. It was found that changes in the pitch are not likely to be found during a stable level rise with no hooks because as the level rises, the increased thermal resistance of the slag rim causes the heat flux between the molten steel at the elevated meniscus level and the mold to decrease, which means the steel will not solidify. Therefore, the slag rim is able to push the molten steel away from the mold wall and the oscillation marks form at the same pitch as in the base case. It was found that changes in pitch can occur in a level drop case, but the current model causes some additional turbu-
lence in the meniscus region, which encourages hook formation, and slag capture into the solidifying shell. Further recommendations on this issue can be found in the Future Work section of this report. However, from this study it was found that level drops followed by rises can be detrimental to steel surface quality due to the slight hooks and slag inclusions that were observed in case LF2. These same defects were not observed in cast LF1, which modeled a stable level rise with no hooks followed by a stable level drop.

The Marangoni effect was investigated with the current model. It was found that the surface tension between the slag and the steel is dependent both on the temperature of the interface and sulfur content of the interface, which can change in the solidification region due to segregation. It was found that the Marangoni effect does not significantly affect the flow under the current casting conditions. However, once again limitations of the current model were identified and further investigation of this phenomenon is recommended in the Future Work section of this report.

The overall trends that were observed from all studies are that the oscillation mark depth and the total slag consumption were found to increase with increasing negative strip time, while the average heat flux and average mold friction were found to decrease with increasing negative strip time. The oscillation mark width was found to comprise about 97% of the pitch, which thus determines their shape. Lastly, for every case considered in this study the calculated pitch agreed well with the theoretical pitch.

5.3 Conclusion

A thermo-fluid model has been created in ANSYS FLUENT to study oscillation mark formation in the continuous steel casting process of steel. This model includes transient, 2D, fluid flow of molten steel and liquid slag in the meniscus region, heat transfer in the mold, interfacial gap, slag, and steel, low-Reynolds turbulence, solidification and melting of the steel shell, and the volume of fluid method to determine the interface between molten steel and liquid slag, including temperature-dependent surface tension and meniscus formation. This model also features temperature-dependent properties of the slag and steel phases, with different properties for melting and solidification of slag. Most importantly, this model includes the mold wall and a moving mesh to include mold oscillation. The governing equations, boundary conditions, material properties, and computational details of this model have are presented in Chapter 2 of this report.

The results of this model have been validated using several different experimental and plant results. [6] [1] It was found that the slag gap thickness agreed well with the experimental results of measurements on a mold-simulator by Zhang and Wang et al. [6] Additionally, it was found that when taking experimental error into account the shell growth found in the experimental set-up agreed well with the results found using the base case model. [6] The simulated slag-layer thickness and oscillation mark depths agreed well with the plant measurements. Also, it was found that in the meniscus region the formation of oscillation
marks including their pitch, depth, width, and general shape all agree well with plant measurements. [4] It was also found that the average heat flux predicted in the mold simulator (base case conditions) agreed well with the average heat flux calculated from the experimental data, and that any minor discrepancies found here are likely attributed to differences in the slag properties present in the experimental set-up and those supplied to the base case model. Simulated slag consumption agreed well with plant measurements.

Using this model, several different parametric studies have been performed to investigate the impact of altering oscillation frequency, stroke, and modification ratio, casting speed, slag properties, molten steel levels, and the surface tension between the slag and the steel. The oscillation mark formation mechanism, transient temperature contours and velocity profiles, oscillation mark depth, oscillation mark width, heat flux profiles along the mold hot face, the mold friction along the mold hot face, and slag consumption have been investigated in these studies. Results on each of these investigations are presented in Chapter 4 and the practical implications of each study are summarized in Chapter 5.2. This model can be used for many additional studies and some of these are outlined in the Future Work section of this chapter.

5.4 Future Work

While many factors have been considered in this study this model can still be improved and many further studies can be done utilizing this model. One aspect of this model that can be improved is the user-defined function used to describe the viscosity of the steel. As noted in the model background section of this report, the correct viscosity of the steel shell is not currently being used due to convergence issues. If the viscosity were to be modeled properly there are many studies that could be done using this model. Two future studies in particular that would be made possible if the steel shell’s viscosity were to behave as in a true steel shell are a high heat flux study and a steel grade study. In the lubrication study section of this report the material properties of three slags were discussed, slag S2 was described as a glassy slag. Glassy slags have been found to have higher thermal conductivity than crystalline slags, which in combination with high casting speed and high superheat in the meniscus region can lead to high heat flux profiles along the mold hot face. At this time the steel shell does not form properly under these conditions due to the low viscosity of the steel shell. Additionally, currently the only steel that has been successfully modeled using this model is an ultra low carbon steel. With a high carbon content steel the mushy region becomes larger. The viscosity that is currently being modeled in the mushy region prevents the steel shell from maintaining its shape as it solidifies. Therefore, if the steel shell viscosity were increased to behave as it would in reality a steel grade study could be performed with this model.

Many of the studies summarized in this report can be expanded into future studies. The level fluctuations study can be expanded to further study how level fluctuations can change the pitch of the oscillation-
tion marks. It is recommended that a new version of this model be created such that the steel inlet does not conflict with level drops. Additionally, the impact of different rates of level drops could also impact the results of the level fluctuations study. Another kind of level fluctuation that could be studied with the current model is to study the impact of surface waves on the shape of oscillation marks. The slag study could also be expanded to study the effect of increasing alumina pick-up. It was shown in the lubrication study that slag properties change with the amount of alumina pick-up that occurs in the caster. Therefore, by studying different levels of alumina pick-up, the shape and depth of oscillation marks may be linked to the amount of alumina that is present in the steel prior to casting. Lastly, one more study that could be expanded on is the Marangoni study. The casting conditions of the base case do not show the Marangoni effect to be significant. However, the current model could be refined even more in order to properly capture the effects of macrosegregation in the solidification of the steel shell. Additionally, the variable surface tension could be included in cases that use other casting conditions to see if this effect is dependent on the casting conditions.

5.5 Chapter 5 References


APPENDIX A
BASE CASE USER DEFINED FUNCTIONS

This appendix includes the user defined functions used in the current model under base case conditions.

```c
#include <stdio.h>
#include "udf.h"
#include <math.h>

#define supheat 10.0 /* Must change in the GUI for "steel_inlet" */
#define fixzone 5.0e-3 /* steel temp fix zone width */
#define Tliq 1800.0 /* Steel Liquidus Temperature */
#define Tsol 1795.0 /* Steel Solidus Temperature */
#define StartTime 4.654 /* The physical time when the mold starts to oscillate */
#define PullVel -0.01 /* pull velocity in y direction */
#define str 0.01 /* stroke */
#define fq 1.67 /* oscillation frequency */

/*==================================================================*/
/* MOLD OSCILLATION PROFILE UDF */
/*==================================================================*/

/* For sliding mesh in cell zone condition */
DEFINE_TRANSIENT_PROFILE(Mesh_vel,time)
{
    real mold_vel=0.0;
    real pi = 3.1415926;
    mold_vel=str*pi*q*sin(q*2.0*pi*(time-StartTime));
    return mold_vel;
    /* The sine curve allows the oscillation to begin at the neutral position */
    /* The curve is also shifted by the starttime, to ensure that the oscillation begins at the neutral position for each trial */
}

/*==================================================================*/
/* For BC of the mold hot face on the fuid side */
DEFINE_PROFILE(Mold_oscillation,t,w)
{
    face,t,f;
    real pi = 3.1415926;

    begin_f_loop(f,t)
    {
        PROFILE(f,t,w)=(str*pi*q)*sin(q*2.000*pi*(CURRENT_TIME-StartTime));
    }
    end_f_loop(f,t)
}

/*==================================================================*/
/* INITIAL INTERFACE POSITION FIX - BASED ON BIKERMAN EQUATION */
/*==================================================================*/

/*==================================================================*/
/* Initial Profile using Bikerman`s Equation */
DEFINE_INIT(interface, mixture_domain)
{
    real gamma = 1.3; /* Surface Tension between Steel and Slag */
    real g = 9.81; /* Gravity */
    real theta_steel = 7000.0;
    */

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real rho slag = 2500.0;
real rhod = rho steel - rho slag; /* Density difference between Steel and slag */
real b = sqrt((2.0*gamma)/(g*rhod));
real xo = b - (b/sqrt(2.0))*log(sqrt(2.0)+1.0);

/* Dimension variables: Should be changed based on Case */
real gap = 1.3e-3; /* slag gap thickness */
real shell tip = 100.0e-3; /* Y value of Shell Tip */
/* Height of Interface from shell tip used in this particular model which is set to be a bit smaller than b (b=7.7e-3) */
real h = 6.0e-3;
real fr = shell tip + b; /* Y value of the Interface at infinite x */

/* Shift Value has to be calculated based on the height of free surface over shell 
the following calculation should result in 
xsh = 3.53124e-4 m, for y = 6e-3 m */
real xsh = xo - sqrt(2.0*b*b-b*h) + h;
real shift = gap - xsh;

real xBK; /* x defined in Bikerman equation */
real yBK; /* y defined in Bikerman equation */
real x; /* x shifted to suit this particular model */
real xc[ND]; /* xc = Centroid Location Vector */

/* Message(“xsh= %g\n”, xsh); 
*/

/* get the fluid zone cell thread (can be found in cell zone condition panel) */
mix_thread = Lookup_Thread(mixture_domain, 2);
/* get the phase level cell thread for steel (can be found in phase panel) */
sub_thread = THREAD_SUB_THREAD(mix_thread, 1);

/* loop over all cells in phase level cell threads for steel */
begin_c_loop_all (cell, sub_thread)
{
    C_CENTROID(xc, cell, sub_thread);
    if (xc[0] < gap || (xc[0] > gap && xc[1] > fr))
        C_VOF(cell, sub_thread) = 0.0;
    else if (xc[1] < shell tip)
        C_VOF(cell, sub_thread) = 1.0;
    else
    {
        yBK = fr - xc[1];
        xBK = xo - sqrt(2.0*b+b*yBK*yBK)*sqrt(2.0... + log((b*sqrt(2.0)+sqrt(2.0+b*b*yBK*yBK))/yBK);
        x = xBK + shift;
        if (xc[0] < x)
            C_VOF(cell, sub_thread) = 0.0;
        else
            C_VOF(cell, sub_thread) = 1.0;
    }
}end_c_loop_all (cell, sub_thread)

/* VOF Values will be opposite in the same positions for the slag phase */
/* get the phase level cell thread for slag */
sub_thread=THREAD_SUB_THREAD(mix_thread,0);

/* loop over all cells in phase level cell threads for slag */
begin<loop_all (cell, sub_thread)
{
  C_CENTROID(xc, cell, sub_thread);
  if (xc[0]<gap || (xc[0]>=gap && xc[1]>=fr))
    C_VOF(cell, sub_thread) = 1.0;
  else if (xc[1]<shelltip)
    C_VOF(cell, sub_thread) = 0.0;
  else{
    yBK = fr-xc[1];
xBK = xc-sqrt(2.0+b*b-yBK*yBK)/(b/sqrt(2.0))...
  log ((b*sqrt(2.0)+sqrt(2.0+b*b-yBK*yBK))/yBK);
x = xBK + shift;
  if (xc[0]<x)
    C_VOF(cell, sub_thread) = 1.0;
  else
    C_VOF(cell, sub_thread) = 0.0;
  }
}end<loop_all (cell, sub_thread)

/**************************************************************************************/
/* FIX STEEL TEMPERATURE at INITIALIZATION */
/**************************************************************************************/

/* Adjust UDF hooked only in the initialization steady state simulation */
DEFINE_ADJUST(fix_temp_initial, mixture_domain)
{
  real gap = 1.3e-3;  /* gap thickness */
  real shelltip = 100.0e-3;
  real shellposition = 0.0;
  real xc[ND,ND];
  real temp;
  real st;

  Thread *cell_thread;
  cell_thread=

  /* get the fluid cell thread */
cell_thread=Lookup_Thread(mixture_domain,2);
  /* get the cell thread for phase steel */
cell_thread=THREAD_SUB_THREAD(cell_thread,1);

  begin<loop_all (cell, cell_thread)
  {
    C_CENTROID(xc, cell, cell_thread);
    shellposition=xc[1]*(1000);
    shellposition=sqrt(shellposition+100);
    shellposition=shellposition*(0.56e-3)*gap;

    /* check if the cell is within the shell shape */
    if (xc[1]<shelltip && xc[0]>gap && xc[0]<=(shellposition+0.02e-3))
    {
      if (C_T(cell, cell_thread)>Tsol)
  
}
C_T(cell, cell_thread) = Tsol;
{
    st = C_VOF(cell, cell_thread);
    if (st > 0.1) /* if steel (outside the shell)*/
    {
        if (C_T(cell, cell_thread) < Tliq)
            C_T(cell, cell_thread) = Tliq;
        if (xc[1] > 0.105 && C_T(cell, cell_thread) < Tliq + 0.3)
            C_T(cell, cell_thread) = Tliq + 0.3;
        if (xc[1] < 0.06 && xc[0] > 0.01 && ...
            C_T(cell, cell_thread) = Tliq + supheat)
            C_T(cell, cell_thread) = Tliq + supheat;
    }
}
end_c_loop_all (cell, cell_thread)

/*****************************/
/> fix shell velocity to casting speed
/*****************************/
DEFINE_ADJUST(fix_shell_vel, mixture_domain)
{
    real st;
    cell_t cell;
    real Ycor;
    real timeCycle;
    Thread *mix_thread;
    Thread *sub_thread;
    real xc[ND];

    /* get the fluid zone cell thread */
    mix_thread = Lookup_Thread(mixture_domain, 2);
    /* get the phase level cell thread for steel */
    sub_thread = THREAD_SUB_THREAD(mix_thread, 1);

    timeCycle = N_TIME - 8725000/3600000;
    if (timeCycle > 10000)
        Ycor = 105.0e-3;
    else if (timeCycle > 15000)
        Ycor = (99.5e-3) + ((timeCycle - 15000)/40000)*(5.5e-3);
    else if (timeCycle > 10000)
        Ycor = 99.5e-3;
    else
        Ycor = (105.0e-3) - ((timeCycle)/10000)*(5.5e-3);

    /* loop over all cells in secondary phase cell threads */
    begin_c_loop_all (cell, sub_thread)
    {
        C_CENTROID(xc, cell, sub_thread);
        if (xc[1] < Ycor && xc[0] < 10.0e-3)
        {
            st = C_VOF(cell, sub_thread);
            if (st > 0.9)
            {
                if (C_T(cell, mix_thread) < 179.4.5)
                {
                    C_U(cell, mix_thread) = 0.0;
                    C_V(cell, mix_thread) = PullVel;
                }
            }
        }
    }
}
/* FIX STEEL TEMPERATURE to PROVIDE SUPERHEAT */

/* fix the right hand side of domain with superheat, 
also provide heat to part of the interface 
to make sure it stays above liquidus */

DEFINE_ADJUST (fix_steel_temp, mixture_domain)
{
    real domain_size = 100.0e-3; /* fluid domain width */
    real xlimit = domain_size - fixzone;

    real st:
    cell * cell;
    Thread * mix_thread;
    Thread * sub_thread;
    real xc[ND];

    /* get the fluid zone cell thread */
    mix_thread = Lookup_Thread (mixture_domain, 2);
    /* get the phase level cell thread for steel */
    sub_thread = THREAD_SUB_THREAD (mix_thread, 1);

    /* loop over all cells in secondary phase cell threads */
    begin_loop_all (cell, sub_thread)
    {
        st = C_VOF (cell, sub_thread);
        if (st > 0.1)
        {
            C_CENTROID (xc, cell, sub_thread);
            if (xc[0] > xlimit & & xc[1] < 94.0e-3)
                C_T (cell, mix_thread) = Tliq + supheat;
            else if (xc[1] > 103.0e-3 & & xc[0] > 5.0e-3)
            {
                if (C_T (cell, mix_thread) < Tliq)
                    C_T (cell, mix_thread) = Tliq;
                }
            else if (st <= 0.98 & & xc[0] > 3.0e-3 & & xc[1] > 100.0e-3)
            {
                if (C_T (cell, mix_thread) > Tliq + 5)
                    C_T (cell, mix_thread) = Tliq + 5;
                if (C_T (cell, mix_thread) < Tliq - 0.05)
                    C_T (cell, mix_thread) = Tliq - 0.05;
                if (C_LIQF (cell, sub_thread) < 0.99)
                    C_LIQF (cell, sub_thread) = 0.99;
            }
        }
    } end_loop_all (cell, sub_thread)
}
/ UDF for Steel inlet mass flow rate /
/**
 DEFINE_PROFILE(steel_inlet_mass,t,i)
{
 Domain *d;
 Thread *out1_thread;
 Thread *out2_thread;
 face,t f;

 real MFRsum=0.0;
 //Mass flow rate of steel from the two outlet combine, which need to the compensated from the inlet/
 real MassFlowRate=0.0;

 //Phase level domain for steel/
 d=Get_Domain(3);
 //get the face thread for BC "steel outlet"/
 out1_thread=Lookup_Thread(d,5);
 //get the face thread for BC "slag outlet"/
 out2_thread=Lookup_Thread(d,4);

 / calculating the mass flow rate of steel at boundary "steel outlet"/
 begin_f_loop(f, out1_thread)
 { 
   MassFlowRate=MassFlowRate+FLUX(f, out1_thread);
 } end_f_loop(f, out1_thread)

 / calculating the mass flow rate of steel at boundary "slag outlet"/
 begin_f_loop(f, out2_thread)
 { 
   MassFlowRate=MassFlowRate+FLUX(f, out2_thread);
 } end_f_loop(f, out2_thread)

 / sum the mass flow from all computing cores/
 { 
   MFRsum=PRF_GRSUM(MassFlowRate);
   begin_f_loop(f,t)
   { 
     F_PROFILE(f,t,i) = MFRsum;
   } end_f_loop(f,t)
 }
}

/********************
 UDF for backflow Temp & VOF at outlet /
/********************
 DEFINE_PROFILE(backflow_temp, slag,t,i)
{
 real gap1=0.4e-3;
 real gap2=1.3e-3;
 real xc[ND,ND];
 real Temp;
 face,t f;

 begin_f_loop(f,t)
 {
   F_CENTROID(xc,f,t);
   if (xc[0]<gap1)
     Temp = 480.0+xc[0]/(gap1)*(1080-480.0);
   else if (xc[0]<gap2)
     /*...*/
   else
     Temp = 480.0;
 }
Temp = 1080.0 + (x - gap1)/(gap2 - gap1) * (1530.0 - 1080.0);
else
    Temp = 1530.0;
end_f_loop(f, t)

DEFINE_PROFILE (backflow temp, steel, t, i)
{
    real x[ND];
    real Temp;
    face t f;

    begin_f_loop (f, t)
    {
        F_CENTROID (xc, f, t);
        if (xc[0] < 10e-3)
            Temp = Tliq + 0.5 * supheat;
        else if (xc[0] < 25.0e-3)
            Temp = Tliq + 0.5 * supheat + (xc[0] - (10e-3)) / ((25 - 10) * 1e-3) * supheat;
        else
            Temp = Tliq + supheat;
        F_PROFILE (f, t, i) = Temp;
    }
    } end_f_loop (f, t)

{/***********************************************************/
  * MATERIAL PROPERTIES */
/***********************************************************/

/* viscosity temperature dependent and different in two zones */
DEFINE_PROPERTY (slag viscosity, c, t)
{
    real xc[2];
    real x; /* coordinate */
    real mu_lam; /* Viscosity */
    real temp = C_T (c, t); /* temperature */

    /* Dimension variables: Should be changed based on Case */
    real solreg = 3.0e-3; /* Solidification region thickness */

    C_CENTROID (xc, c, t);
    x = xc[0];

    if (x < solreg) /* SOLIDIFYING BEHAVIOR */
        {
            if (temp >= 1873.0)
                mu_lam = 0.1;
            else if (temp >= 1800.0)
                mu_lam = pow(10, log10(0.1) + (log10(0.15) - log10(0.1))*(1873.0 - temp)/(1873.0 - 1800.0));
            else if (temp >= 1600.0)
                mu_lam = pow(10, log10(0.15) + (log10(0.35) - log10(0.15))*(1800.0 - temp)/(1800.0 - 1600.0));
            else if (temp >= 1550.0)
                mu_lam = pow(10, log10(0.35) + (log10(0.5) - log10(0.35))*(1600.0 - temp)/(1600.0 - 1550.0));
            else if (temp >= 1500.0)
                mu_lam = pow(10, log10(0.5) + (log10(1.0) - log10(0.5))*(1550.0 - temp)/(1550.0 - 1500.0));
            else if (temp >= 1350.0)
                mu_lam = pow(10, log10(1.0) + (log10(1000.0) - log10(1.0))*(1500.0 - temp)/(1500.0 - 1350.0));
            else if (temp >= 900.0)
                mu_lam = pow(10, log10(1000.0) + (log10(1.0e5) - log10(1000.0))*(1350.0 - temp)/(1350.0 - 900.0));
        } /* we consider that the slag is solid when viscosity is 1e8 Pa.s */
else
    mu_lam = 1.0e5;

return mu_lam;
}

} /* MELTING BEHAVIOR */

} /* MELTING BEHAVIOR */

} /* MELTING BEHAVIOR */

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} /* MELTING BEHAVIOR */

} /* MELTING BEHAVIOR */

} /* MELTING BEHAVIOR */

} /* MELTING BEHAVIOR */

if (temp >= 1873.0)
    mu_lam = 0.1;
else if (temp >= 1800.0)
    mu_lam = pow(10, log10(0.15) + ((log10(1.0) − log10(0.15)) + (1873.0 − temp)/(1873.0−1800.0)));
else if (temp >= 1600.0)
    mu_lam = pow(10, log10(0.15) + ((log10(0.35) − log10(0.15)) + (1800.0 − temp)/(1800.0−1600.0)));
else if (temp >= 1550.0)
    mu_lam = pow(10, log10(0.35) + ((log10(0.5) − log10(0.35)) + (1600.0 − temp)/(1600.0−1550.0)));
else if (temp >= 1500.0)
    mu_lam = pow(10, log10(0.5) + ((log10(0.7) − log10(0.5)) + (1550.0 − temp)/(1550.0−1500.0)));
else if (temp >= 1300.0)
    mu_lam = pow(10, log10(0.7) + ((log10(1.0) − log10(0.7)) + (1500.0 − temp)/(1500.0−1300.0)));
else if (temp >= 1250.0)
    mu_lam = pow(10, log10(1.0) + ((log10(0.40) − log10(1.0)) + (1300.0 − temp)/(1300.0−1250.0)));
else if (temp >= 1100.0)
    mu_lam = pow(10, log10(80.0) + ((log10(80.0) − log10(80.0)) + (1250.0 − temp)/(1250.0−1100.0)));
else if (temp >= 900.0)
    mu_lam = pow(10, log10(35.0) + ((log10(0.0) − log10(35.0)) + (1100.0 − temp)/(1100.0−900.0)));
else if (temp >= 600.0)
    mu_lam = pow(10, log10(10.0) + ((log10(0.40) − log10(10.0)) + (900.0 − temp)/(900.0−600.0)));
else
    mu_lam = 0.4;

return mu_lam;

} /* conductivit temperature dependant and different in two zones */
DEFINE_PROPERTY(slag_conductivity, c, t)
{
  real xc[2];
  real x;       /* co-ordinate */
  real kn;      /* Conductivity */
  real temp = C_T(c, t);  /* temperature */

  /* Dimension variables : Should be changed based on Case */
  real solreg = 3.0e−3;  /* Solidification region thickness */

  C_CENTROID(xc, c, t);
  x = xc[0];

  if (x<solreg) /* SOLIDIFYING BEHAVIOR */
  {
    if (temp >= 1173.0)
      kn = 3.0;
    else if (temp >= 1073.0)
      kn = 3.0 + ((1.0−3.0)*(1173.0−temp)/(1173.0−1073.0));
    else if (temp >= 300.0)
      kn = 1.0 + ((0.5−1.0)*(1073.0−temp)/(1073.0−300.0));
    else
      kn = 0.5;

    return kn;
  }
else /*MELTING BEHAVIOR*/
{
    if (temp >= 1877.0)
        kn = 3.0;
    else if (temp >= 1173.0)
        kn = 3.0 + (0.8 - 3.0) * (1173.0 - temp) / (1173.0 - 1073.0);
    else if (temp >= 1073.0)
        kn = 0.8 + (0.3 - 0.8) * (1173.0 - temp) / (1173.0 - 1073.0);
    else
        kn = 0.3;
    return kn;
}

DEFINE PROPERTY (steel viscosity, c, t)
{
    real mu[7] = {6.3e-3, 0.2, 0.5, 2.0, 3.0, 5.0e+2, 1.0e+3};
    real T[7] = {Tliq + 1.0, Tliq, Tliq - 0.05, Tliq - 0.5, Tliq - 2.0, Tsol, 1755.0};
    real mu_lam; /* Viscosity */
    real temp = C_T(c, t); /* temperature */
    if (temp >= T[0])
        mu_lam = mu[0];
    else if (temp >= T[1])
        mu_lam = pow(10, log10(mu[0]) + (log10(mu[1]) - log10(mu[0])) * (T[0] - temp) / (T[0] - T[1]));
    else if (temp >= T[2])
    else if (temp >= T[3])
    else if (temp >= T[4])
    else if (temp >= T[5])
    else if (temp >= T[6])
    else
        mu_lam = mu[6];
    return mu_lam;
}

/***************************************************************/
/ = SOLIDIFICATION MOMENTUM SINK PARAMETER /*
/***************************************************************/
DEFINE SOLIDIFICATION_PARAMS (solid_params, c, t, Amush, Gamma)
{
    real xc[ND,ND];
    int Alow = 4;
    int Amid = 5;
    int Ahigh = 7;
    real timeCycle;
    real Ycor;
    real Xlow = 5.0e-3;
    real Xmid = 3.0e-3;
    real Xhigh = 1.0e-3;
    C_CENTROID(xc, c, t);

timeCycle = (N_TIME - 872500) / 60000;
    if (timeCycle > 19000)
\[ Y_{cor} = 105.0e^{-3}; \]

else if (timeCycle > 15000)

\[ Y_{cor} = (98.5e^{-3} \times \frac{\text{timeCycle} - 15000}{4000}) + (6.5e^{-3}); \]

else if (timeCycle > 1000)

\[ Y_{cor} = 98.5e^{-3}; \]

else

\[ Y_{cor} = (105.0e^{-3} \times \frac{\text{timeCycle}}{1000}) + (6.5e^{-3}); \]

if (xc[1] >= Y_{cor} && xc[1] < 110.0e^{-3})

if (xc[0] >= Xlow)

\*Amush = pow(10, Alow);

else if (xc[0] >= Xmid)

\*Amush = pow(10, Alow + ((Amid-Alow) \times (Xlow-xc[0])/(Xlow-Xmid))) ;

else if (xc[0] >= Xhigh)

\*Amush = pow(10, Amid + ((Ahigh-Amid) \times (Xmid-xc[0])/(Xmid-Xhigh)));

else

\*Amush = pow(10, Ahigh);

if (xc[1] <= Y_{cor} + 3.0e^{-3})

\*Amush = pow(10, log10(\*Amush) + ((Ahigh-log10(\*Amush)) \times ((Y_{cor} + 3.0e^{-3}) - \*xc[1])/(3.0e^{-3})));

else

\*Amush = pow(10, Ahigh);
APPENDIX B
ALTERNATE MODEL 1 USER DEFINED FUNCTIONS

This appendix includes the user defined functions used in alternate model 1.

```c
#include <stdio.h>
#include "udf.h"
#include <math.h>

#define supheat 10.0 /* still need to change in the GUI for "steel_inlet"*/
#define fixzone 5.0e-3 /* steel temp fix zone width, from right handside, also affect steel outlet backflow temp*/
#define Tliq 1800.0 /* Steel Liquidus Temperature*/
#define Tsol 1795.0 /* Steel Solidus Temperature*/
#define StartTime 4.654 /* The physical time when the mold start to oscillate, should be changed for each new run*/
#define PullVel -0.01 /* pull velocity in y direction*/
#define str 0.01 /* stroke*/
#define frq 1.67 /* oscillation frequency*/

/****************************************************************************/
/* MOLD OSCILLATION PROFILE UDF */
/****************************************************************************/

/* For sliding mesh in cell zone condition */
DEFINE_TRANSIENT_PROFILE(Mesh_vel, time)
{
    real mold_vel=0.0;
    real pi = 3.1415926;
    mold.vel=(str*pi*frq)*sin(frq*2.0*pi*(time-StartTime));
    return mold_vel;
}

/* For BC of the mold hot face on the fuel side */
DEFINE_PROFILE(Mold_oscillation.t.w)
{
    face,t f;
    real pi = 3.1415926;

    begin_f_loop(f,t)
    {
        PROFILE(f,t.w)=(str*pi*frq)*sin(frq*2.000*pi*(CURRENT_TIME-StartTime));
    }
    end_f_loop(f,t)
}

/****************************************************************************/
/* Temperature profile for the right side of the slag */
/****************************************************************************/

DEFINE_PROFILE(slag_rhs_temp.t.i)
{
    real xc[ND,ND];
    real Temp;
    face,t f;

    begin_f_loop(f,t)
    {
        F_CENTROID(xc,f,t);
    }
    ```
\[
\text{Temp} = 410.6 \times xc[1] + 1766.9;
\]

\[
F_{\text{PROFILE}}(f,t,i) = \text{Temp};
\]

```c
}
```

/

/* Temperature profile for the top of the slag */

/

DEFINE_PROFILE(slag_top_temp,t,i)
{
    real xc[ND,ND];
    real Temp;
    face f;

    begin_f_loop(f,t)
    {
        F_CENTROID(xc,f,t);

        Temp = 1161538 \times xc[0] + 300.0;
        F_PROFILE(f,t,i) = Temp;
    }

    end_f_loop(f,t)

}
```

/

/* Velocity Profile for the Bottom of the Slag */

/

DEFINE_PROFILE(slag_vel_bot,t,i)
{
    real xc[ND,ND];
    real Vel;
    face f;

    begin_f_loop(f,t)
    {
        F_CENTROID(xc,f,t);

        if (xc[0] <= 0.0008)
            Vel = 0;
        else
            Vel = -0.01;
        F_PROFILE(f,t,i) = Vel;
    }

    end_f_loop(f,t)

}
```

/

/* UDF for backflow Temp & VOF at outlet */

/

DEFINE_PROFILE(backflowtemp_slag,t,i)
{
    real gap1=0.4e-3;
    real gap2=1.3e-3;
    real xc[ND,ND];
    /* this will hold the position vector */
    real Temp;
    face f;

    begin_f_loop(f,t)
    {

F_CENTROID(xc, f, t);
    if (xc[0]<gap1)
        Temp = 480.0 + xc[0]/(gap1)*(1080.0 - 480.0);
    else if (xc[0]<gap2)
        Temp = 1080.0 + (xc[0] - gap1)/(gap2 - gap1)*(1530.0 - 1080.0);
    else
        Temp = 1530.0;
    F_PROFILE(f, t, i) = Temp;
}
end_f_loop(f, t)

/*******************************
 MATERIAL PROPERTIES */
/*****************************/
/* viscosity temperature dependent and different in two zones */
DEFINE_PROPERTY(slag_viscosity, c, t)
{
    real xc[2];
    real x;    /*co-ordinate*/
    real mulam;  /*Viscosity*/
    real temp = C_TEMP(c, t); /*temperature*/

    /* Dimension variables: Should be changed based on Case*/
    real solregx = 3.0e-3; /*Solidification region thickness */

    C_CENTROID(xc, c, t);
    x = xc[0];

    if (x<solregx) /*SOLIDIFYING BEHAVIOR*/
    {
        if (temp >= 1873.0)
            mulam = 0.1;
        else if (temp >= 1800.0)
            mulam = pow(10.0, log10(0.1)+((log10(0.15)-log10(0.1))*(1873.0-temp)/(1873.0-1800.0)));
        else if (temp >= 1600.0)
            mulam = pow(10.0, log10(0.15)+((log10(0.35)-log10(0.15))*(1800.0-temp)/(1800.0-1600.0)));
        else if (temp >= 1550.0)
            mulam = pow(10.0, log10(0.35)+((log10(0.5)-log10(0.35))*(1600.0-temp)/(1600.0-1550.0)));
        else if (temp >= 1500.0)
            mulam = pow(10.0, log10(0.5)+((log10(1.0)-log10(0.5))*(1550.0-temp)/(1550.0-1500.0)));
        else if (temp >= 1300.0)
            mulam = pow(10.0, log10(1.0)+((log10(1000.0)-log10(1.0))*(1500.0-temp)/(1500.0-1300.0)));
        else if (temp >= 900.0)
            mulam = pow(10.0, log10(1000.0)+((log10(1.0e5)-log10(1000.0))*(1300.0-temp)/(1300.0-900.0)));
        /*we consider that the slag is solid when viscosity is 1e8Pa.s*/
        else
            mulam = 1.0e5;

        return mulam;
    }
    else /*MELTING BEHAVIOR*/
    {
        if (temp >= 1873.0)
            mulam = 0.1;
        else if (temp >= 1800.0)
            mulam = pow(10.0, log10(0.1)+((log10(0.15)-log10(0.1))*(1873.0-temp)/(1873.0-1800.0)));
        else if (temp >= 1600.0)
            mulam = pow(10.0, log10(0.15)+((log10(0.35)-log10(0.15))*(1800.0-temp)/(1800.0-1600.0)));
        else if (temp >= 1550.0)
            mulam = pow(10.0, log10(0.35)+((log10(0.5)-log10(0.35))*(1600.0-temp)/(1600.0-1550.0)));
        else if (temp >= 1500.0)
            mulam = pow(10.0, log10(0.5)+((log10(1.0)-log10(0.5))*(1550.0-temp)/(1550.0-1500.0)));
    }
}
mu_lam = pow(10, log10(0.5)*(log10(0.7)−log10(0.5))*(1550.0−temp)/(1550.0−1500.0));
else if (temp >= 1300.0)
    mu_lam = pow(10, log10(0.7)*(log10(40.0)−log10(0.7))*(1500.0−temp)/(1500.0−1300.0));
else if (temp >= 1250.0)
    mu_lam = pow(10, log10(0.7)*(log10(80.0)−log10(0.7))*(1300.0−temp)/(1300.0−1250.0));
else if (temp >= 1100.0)
    mu_lam = pow(10, log10(0.7)*(log10(35.0)−log10(0.7))*(1100.0−temp)/(1100.0−1073.0));
else if (temp >= 900.0)
    mu_lam = pow(10, log10(0.7)*(log10(30.0)−log10(0.7))*(900.0−temp)/(900.0−600.0));
el

return mu_lam;
}

/* conductivity temperature dependant and different in two zones*/
DEFINE_PROPERTY(slag, conductivity, c, t)
{
    real xc[2];
    real x;  /*co-ordinate*/
    real kn;  /*Conductivity*/
    real temp = CT(c, t);  /*temperature*/

    /* Dimension variables: Should be changed based on Case*/
    real solregx = 3.0e−3;  /*Solidification region thickness*/
    C_CENTROID(xc, c, t);
    x = xc[0];

    if (x<solregx) /*SOLIDIFYING BEHAVIOR*/
    {
        if (temp >= 1173.0)
            kn = 3.0;
        else if (temp >= 1073.0)
            kn = 3.0+((1.0−3.0)*(1173.0−temp)/(1173.0−1073.0));
        else if (temp >= 300.0)
            kn = 1.0+((0.5−1.0)*(1073.0−temp)/(1073.0−300.0));
        else
            kn = 0.5;
        return kn;
    }
    else /*MELTING BEHAVIOR*/
    {
        if (temp >= 1877.0)
            kn = 3.0;
        else if (temp >= 1173.0)
            kn = 3.0+((0.8−3.0)*(1877.0−temp)/(1877.0−1173.0));
        else if (temp >= 1073.0)
            kn = 0.8+((0.3−0.8)*(1173.0−temp)/(1173.0−1073.0));
        else
            kn = 0.3;
        return kn;
    }
}
APPENDIX C
ALTERNATE MODEL 2 USER DEFINED FUNCTIONS

This appendix includes the user defined functions used in alternate model 2.

```c
#include <stdio.h>
#include "udf.h"
#include <math.h>

#define supheat 10.0 /* still need to change in the GUI for "steel_inlet" */
#define fixzone 5.0e-3 /* steel temp fix zone width, from right handsise, also affect steel outlet backflow temp */
#define Tiq 1800.0 /* Steel Liquidus Temperature */
#define Tsol 1795.0 /* Steel Solidus Temperature */
#define StartTime 0.1206 /* The physical time when the mold start to oscillate, should be changed for each new run */
#define PullVel -0.01 /* pull velocity in y direction */
#define str 0.01 /* stroke */
#define frq 1.67 /* oscillation frequency */

/* MOLD OSCILLATION PROFILE UDF */

#define TRANSIENT_PROFILE (Mesh_vel, time)
{
    real mold_vel=0.0;
    real pi = 3.1415926;
    mold_vel=(str*pi*frq)*sin(frq*2.0*pi*(time-StartTime));
    return mold_vel;
}

/* For sliding mesh in cell zone condition */
DEFINE_PROFILE(Mesh_vel, time)
{
    real mold_vel=0.0;
    real pi = 3.1415926;
    mold_vel=(str*pi*frq)*sin(frq*2.0*pi*(time-StartTime));
    return mold_vel;
}

/* For BC of the mold hot face on the fluid side */
DEFINE_PROFILE(Mold_oscillation, t, w)
{
    face, t f;
    real pi = 3.1415926;

    begin_f_loop(f, t)
    {
        PROFILE(f, t, w)=(str*pi*frq)*sin(frq*2.000*pi*(CURRENT_TIME-StartTime));
    }
    end_f_loop(f, t)
}

/* INITIAL INTERFACE POSITION FIX - BASED ON BIKERMAN EQUATION */

/* Initial Profile using Bikerman’s Equation */
DEFINE_INIT(interface, mixture_domain)
{
    real gamma = 1.3; /* Surface Tension between Steel and Slag */
    real g = 9.81; /* Gravity */
    real rhosteel = 7000.0;
    real rhoslag = 2500.0;
    real rhod= rhosteel-rhoslag; /* Density difference between Steel and slag */
    real b = sqrt((12.0*gamma)/(g*rhod)); /* Theoretical Height of the Interface from contact point */
}
```

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on a vertical wall, in Bikerman's equation/*
real xo = b-(b/sqrt(2.0))*log(sqrt(2.0)+1.0);
/*Constant in bikerman equation which Depends on b*/

/* Dimension variables: Should be changed based on Case*/
real gap = 1.3e−3;    /*slag gap thickness*/
real shelltip = 100.0e−3;    /*Y value of Shell Tip*/
real h=6.0e−3;

/*Height of Interface from shell tip used in this particular model, which is set to be a bit smaller than b (b=7.7e−3)*/
real fr=shelltip+h;    /*Y value of the Interface at infinite x*/

/* Shift Value has to be calculated based on the height of free surface over shell*/
/* x value of x in Bikerman equation, when y=h the following calculation should result in xsh = 3.53124e−4 m, for y = 6e−3 m*/
real xsh = xo−sqrt(2.0+b*b−yBK*yBK)*log((b+sqrt(2.0)+sqrt(2.0+b*b−yBK*yBK))/yBK);  
x = xBK + shift;
if (x<0)
    C_VOF(cell , sub_thread) = 0.0;
else
    C_VOF(cell , sub_thread) = 1.0;

/* get the fluid zone cell thread, (cell thread id=2, can be found in cell zone condition panel)*/
mix_thread=Lookup_Thread(mixture_domain , 6);
/* get the phase level cell thread for steel, which has a phase domain index of 1, and can be found in phase panel*/
sub_thread=THREAD_SUB_THREAD(mix_thread , 1);
/* loop over all cells in phase level cell threads for steel */
begin_c-loop_all(cell , sub_thread)
{
    C_CENTROID(xc , cell . sub_thread);
    if (xc[0]<gap || (xc[0]>gap && xc[1]−=fr))
        C_VOF(cell , sub_thread) = 0.0;
    else if (xc[1]<shelltip)
        C_VOF(cell , sub_thread) = 1.0;
    else
    {
        yBK = fr−xc[1];
xBK = xo−sqrt(2.0+b*b−yBK*yBK)*log((b+sqrt(2.0)+sqrt(2.0+b*b−yBK*yBK))/yBK);  
x = xBK + shift;
        if (xc[0]<x)
            C_VOF(cell , sub_thread) = 0.0;
        else
            C_VOF(cell , sub_thread) = 1.0;
    }
}end_c-loop_all(cell , sub_thread)

/* VOF Values will be opposite in the same positions for the slag phase*/
/* get the phase level cell thread for slag.*/
which has a phase domain index of 0, and can be found in phase panel

sub_thread=THREAD|SUB THREAD( mix_thread, 0);

/* loop over all cells in phase level cell threads for slag */
begin< loop_all ( cell, sub_thread)
{
    C|CENTROID( xc, cell, sub_thread);
    if ( xc[0]<gap || (xc[0]><gap && xc[1]>fr))
        C|VOF(cell, sub_thread) = 1.0;
    else if ( (xc[1]<shelltip)
        C|VOF(cell, sub_thread) = 0.0;
    else
    {
        yBK = fr- xc[1];
        xBK = xc- sqrt(2.0+b+b*yBK+yBK)*b/sqrt(2.0)+sqrt(2.0+b+b*yBK+yBK))/yBK;
        x = xBK + shift;
        if ( (xc[0]<x)
            C|VOF(cell, sub_thread) = 1.0;
        else
            C|VOF(cell, sub_thread) = 0.0;
    }
} end< loop_all ( cell, sub_thread)

******************************************************************************
/* FIX STEEL TEMPERATURE at INITIALIZATION */
******************************************************************************

/* Adjust UDF hooked only in the initialization steady state simulation */
DEFINE_ADJUST( fix_temp, initial, mixture_domain)
{
    real gap = 1.3e-3;  /* gap thickness */
    real shelltip = 100.0e-3;

    real shellposition=0.0;
    real xc[ND,ND];
    real temp;
    real st;

    Thread *cell_thread;
    cell = cell;

    cell_thread=Lookup_Thread( mixture_domain, 2);  /* get the fluid cell thread */
    cell_thread=THREAD|SUB THREAD( cell, thread, 1);  /* get the cell thread for phase steel */

    begin< loop_all ( cell, cell, thread)
{
    C|CENTROID( xc, cell, cell, thread);
    /* Wang Paper has 4mm shell in 50mm, so 5.6mm shell in 100mm */
    shellposition*y[1] = (-1000);  
    shellposition = sqrt( shellposition +100);  
    shellposition = shellposition *(0.56e-3+gap);

    /* check if the cell is within the shell shape */
    if ( xc[1]<shelltip && xc[0]>gap && xc[0]<=(shellposition+0.02e-3))
        /* if inside the shell */
        { if (C_T(cell, cell, thread)>Tsol)
            C_T(cell, cell, thread)=Tsol;
        }
    }

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make sure temperature to the right of the shell is higher than solidus temp, also we don’t want any meniscus freeze at the beginning
else /*else means outside the shell, within fluid cell thread*/
{
    st = CVOF(cell,cell_thread);
    if (st > 0.1) /*if steal (outside the shell)*/
    {
        if (C_T(cell,cell_thread) < T_liq)
        /*make sure shell shape is correct*/
            C_T(cell,cell_thread) = T_liq;
        if (xc[1] > 0.105 && C_T(cell,cell_thread) < T_liq + 0.3)
        /*provide additional heat to interface*/
            C_T(cell,cell_thread) = T_liq + 0.3;
        if (xc[1] < 0.06 && xc[0] > 0.03 && C_T(cell,cell_thread) < T_liq + supheat)
        /*provide additional heat to interface*/
            C_T(cell,cell_thread) = T_liq + supheat;
    }
}
}end_<loop_all (cell,cell_thread)

/* Velocities for the Steel*/
/*==================================================================================*/
DEFINE_ADJUST(fix_steel_vel,mixture_domain)
{
    real xc[ND,ND];
    real st;
    Thread = cell_thread;
    cell_thread = L_5_cel1;
    cell_thread = Lookup_Thread(mixture_domain, 0.6);
    /*get the fluid cell thread*/
    cell_thread = THREAD_SUB_THREAD(cell_thread, 1);
    /*get the cell thread for phase steel*/

    begin_<loop_all (cell,cell_thread)
    {
        C_CENTROID(xc,cell,cell_thread);
        st = CVOF(cell,cell_thread);
        if (st > 0.1)
        {
            C_V(cell,cell_thread) = -0.01;
        }
    }end_<loop_all (cell,cell_thread)
}

/* Temperature profile for the right side of the slag*/
/*==================================================================================*/
DEFINE_PROFILE(slag_rhs_temp,t,i)
{ 
    real xc[ND,ND];
    real Temp;
    face f;

    begin_f_loop(f,t) 
    { 
        F_CENTROID(xc,f,t);

        Temp = 410.6*xc[1]+1766.9;

        F_PROFILE(f,t,i) = Temp;
    } end_f_loop(f,t)
}

/* Pressu re profile for the right side of the slag */
******************************************************************************

DEFINE_PROFILE(slag_rhs_pressure,f,t,i) 
{ 
    real xc[ND,ND];
    real pressure;
    face f;

    begin_f_loop(f,t) 
    { 
        F_CENTROID(xc,f,t);

        pressure = (7000*(.105-xc[1])+9.81)*(2500+9.81+0.045);

        F_PROFILE(f,t,i) = pressure;
    } end_f_loop(f,t)
}

/* Temperature profile for the top of the slag */
******************************************************************************

DEFINE_PROFILE(slag_top_temp,f,t,i) 
{ 
    real xc[ND,ND];
    real Temp;
    face f;

    begin_f_loop(f,t) 
    { 
        F_CENTROID(xc,f,t);

        if (xc[0] < 0.0013) 
            Temp = 1161538*xc[0]+300.0;
        else 
            Temp = 1810;

        F_PROFILE(f,t,i) = Temp;
    } end_f_loop(f,t)
}

******************************************************************************
/* UDF for backflow Temp VOF at outlet */
/*******************************************************************************/

DEFINE_PROFILE(backflowtemp,slag,t,i)
{
    real gap1=0.4e-3;
    real gap2=1.3e-3;
    real xc[ND,ND];        /* this will hold the position vector */
    real Temp;
    face, f;

    begin_f_loop(f,t)
    {
        F_CENTROID(xc,f,t);
        if (xc[0]<gap1)
            Temp = 480.0+xc[0]/(gap1)*(1080.0-480.0);
        else if (xc[0]<gap2)
            Temp = 1080+(xc[0]-gap1)/(gap2-gap1)*(1530.0-1080.0);
        else
            Temp=Tliq+0.5+supheat;
        F_PROFILE(f,t,i) = Temp;
    }end_f_loop(f,t)
}

*******************************************************************************/

/* Velocity Profile for the Bottom of the Slag*/
*******************************************************************************/

DEFINE_PROFILE(slag_vel_bot,t,i)
{
    real xc[ND,ND];
    real Vel;
    face, f;

    begin_f_loop(f,t)
    {
        F_CENTROID(xc,f,t);
        if (xc[0] <= 0.0008)
            Vel = 0;
        else
            Vel = -0.01;
        F_PROFILE(f,t,i) = Vel;
    }end_f_loop(f,t)
}

*******************************************************************************/

/* Material Properties */
*******************************************************************************/

/* viscosity temperature dependant and different in two zones*/
DEFINE_PROPERTY(slag_viscosity, c, t)
{
    real x[2];        /*co-ordinate*/
    real muaJam;    /* Viscosity*/
    real temp = C_T(c, t);    /*temperature*/

    /* Dimension variables: Should be changed based on Case*/
    real solregx = 3.0e-3;    /*Solidification region thickness*/

    C_CENTROID(xc,c,t);

    x = xc[0];

}
if (x<solreg) /*SOLIDIFYING BEHAVIOR*/
{
    if (temp >= 1873.0)
        mu_lam = 0.1;
    else if (temp >= 1600.0)
        mu_lam = pow(10, log10(0.1) + (log10(0.7) - log10(0.1)) * (1873.0 - temp) / (1873.0 - 1600.0));
    else if (temp >= 1550.0)
        mu_lam = pow(10, log10(0.15) + (log10(0.5) - log10(0.15)) * (1600.0 - temp) / (1600.0 - 1550.0));
    else if (temp >= 1500.0)
        mu_lam = pow(10, log10(0.35) + (log10(0.5) - log10(0.35)) * (1550.0 - temp) / (1550.0 - 1500.0));
    else if (temp >= 1300.0)
        mu_lam = pow(10, log10(1.0) + (log10(1.0) - log10(1.0)) * (1500.0 - temp) / (1500.0 - 1300.0));
    else if (temp >= 900.0)
        mu_lam = pow(10, log10(1000.0) + (log10(1000.0) - log10(1000.0)) * (1300.0 - temp) / (1300.0 - 900.0));
    /*we consider that the slag is solid when viscosity is 1e8 Pa.s*/
    else
        mu_lam = 1.0e5;
    return mu_lam;
}
else /*MELTING BEHAVIOR*/
{
    if (temp >= 1873.0)
        mu_lam = 0.1;
    else if (temp >= 1800.0)
        mu_lam = pow(10, log10(0.1) + (log10(0.7) - log10(0.1)) * (1873.0 - temp) / (1873.0 - 1800.0));
    else if (temp >= 1600.0)
        mu_lam = pow(10, log10(0.15) + (log10(0.5) - log10(0.15)) * (1800.0 - temp) / (1800.0 - 1600.0));
    else if (temp >= 1550.0)
        mu_lam = pow(10, log10(0.35) + (log10(0.5) - log10(0.35)) * (1600.0 - temp) / (1600.0 - 1550.0));
    else if (temp >= 1500.0)
        mu_lam = pow(10, log10(0.5) + (log10(1.0) - log10(0.5)) * (1550.0 - temp) / (1550.0 - 1500.0));
    else if (temp >= 1300.0)
        mu_lam = pow(10, log10(0.7) + (log10(0.7) - log10(0.7)) * (1500.0 - temp) / (1500.0 - 1300.0));
    else if (temp >= 1250.0)
        mu_lam = pow(10, log10(0.1) + (log10(0.1) - log10(0.1)) * (1250.0 - temp) / (1250.0 - 1250.0));
    else if (temp >= 1100.0)
        mu_lam = pow(10, log10(0.0) + (log10(0.0) - log10(0.0)) * (1100.0 - temp) / (1100.0 - 1100.0));
    else if (temp >= 900.0)
        mu_lam = pow(10, log10(0.5) + (log10(0.5) - log10(0.5)) * (900.0 - temp) / (900.0 - 900.0));
    else if (temp >= 600.0)
        mu_lam = pow(10, log10(10.0) + (log10(10.0) - log10(10.0)) * (600.0 - temp) / (600.0 - 600.0));
    else
        mu_lam = 0.4;
    return mu_lam;
}

/*conductivity temperature dependant and different in two zones*/
DEFINE_PROPERTY(slag,conductivity, c, t)
{
    real x[2];
    real x; /*co-ordinate*/
    real kn; /*Conductivity*/
    real temp = C_P(c, t); /*temperature*/

    /* Dimension variables: Should be changed based on Case*/
    real solreg = 3.0e-3; /*Solidification region thickness*/
C.CENTROID(xc,c,t);

x = xc[0];

if (x<solregx) /*SOLIDIFYING BEHAVIOR*/
{
    if (temp >= 1173.0)
        kn = 3.0;
    else if (temp >= 1073.0)
        kn = 3.0 + (1.0 - 3.0) * (1173.0 - temp) / (1173.0 - 1073.0);
    else if (temp >= 300.0)
        kn = 1.0 + (0.5 - 1.0) * (1173.0 - temp) / (1173.0 - 300.0);
    else
        kn = 0.5;
    return kn;
}
else /*MELTING BEHAVIOR*/
{
    if (temp >= 1877.0)
        kn = 3.0;
    else if (temp >= 1173.0)
        kn = 3.0 + (0.8 - 3.0) * (1877.0 - temp) / (1877.0 - 1173.0);
    else if (temp >= 1073.0)
        kn = 0.8 + (0.3 - 0.8) * (1173.0 - temp) / (1173.0 - 1073.0);
    else
        kn = 0.3;
    return kn;
}

DEFINEPROPERTY(steel.viscosity , c, t)
{
    real mu[7] = {6.3e-3, 0.2, 0.5, 2.0, 30.0, 5.0e+2, 1.0e+3};
    real T[7] = {Tliq + 1.0, Tliq, Tliq - 0.05, Tliq - 0.5, Tliq - 2.0, Tsol, 1755.0};
    real mumat; /* Viscosity */
    real temp = C.T(c, t); /* temperature */

    if (temp >= T[0])
        mumat = mu[0];
    else if (temp >= T[1])
        mumat = pow(10, log10(mu[0]) + (log10(mu[1]) - log10(mu[0])) * (T[0] - temp) / (T[0] - T[1]));
    else if (temp >= T[2])
    else if (temp >= T[3])
    else if (temp >= T[4])
    else if (temp >= T[5])
    else if (temp >= T[6])
    else
        mumat = mu[6];

    return mumat;
}
APPENDIX D

STEPPED AND ANGLED CASE USER DEFINED FUNCTION

This appendix includes the user defined functions used in the model verification case that uses a stepped and angled mass flow inlet.

```cpp
#define PROFILE (steel.inlet, mass, t, i)  
{  
    Domain *d;
    Thread *out1_thread;  
    Thread *out2_thread;
    face_t f;
    real x[NDND];
    real y;
    real MFRsum=0.0;
    real MassFlowRate=0.0;
    /* Mass flow rate of steel from the two outlet combine, which need to the compensated from the inlet*/

d=Get_Domain(3); /* Phase level domain for steel, id=3 can be found in phase panel*/
out1_thread=Lookup_Thread(d, 5); /* get the face thread for BC "steel outlet", id=5 can be found in BC panel*/
out2_thread=Lookup_Thread(d, 4); /* get the face thread for BC "slag outlet", id=4 can be found in BC panel*/

    /* calculating the mass flow rate of steel at boundary "steel outlet"*/
    begin_f_loop(f, out1_thread)
    {
        MassFlowRate=MassFlowRate+F.FLUX(f, out1_thread);
    }end_f_loop(f, out1_thread)

    /* calculating the mass flow rate of steel at boundary "slag outlet"*/
    begin_f_loop(f, out2_thread)
    {
        MassFlowRate=MassFlowRate+F.FLUX(f, out2_thread);
    }end_f_loop(f, out2_thread)

    /* sum the mass flow from all computing cores*/
    {
        MFRsum=PRF.GRSUM1(MassFlowRate);
        begin_f_loop(f, t)
        {
            F.CENTROID(x, f, t);
            y=x[1];
            if (y > 0.078)
                F_PROFILE(f, t, i) = 0.1*MFRsum;
            else if (y <= 0.078)
                F_PROFILE(f, t, i) = 0.9*MFRsum;
        }end_f_loop(f, t)
    }
} 
```
This appendix includes the user defined function used to determine the temperature dependent surface tension in the Marangoni Effect study.

```java
/* Surface tension coefficient temperature dependent */
DEFINEPROPERTY(sfcT, c, t)
{
  real T = C_T(c, t); /* This is the reference surface tension at 1873 K, should be changed when the steel is changed */
  real C_0 = 0.01; /* This is the bulk flow sulfur content, and should be changed when the steel is changed */
  real D_s = 3.4e-9; /* This is the Diffusivity Constant for Sulfur */
  real gamma_o_st; /* This is the reference surface tension at 1873 K, should be changed when the steel is changed */
  real gamma_o = 0.05; /* This is the ratio of sulfur content in solid versus liquid */
  real r_d; /* Place Holder for the Surface Tension Gradient */
  real r_s; /* Street Radius */
  real C_s; /* Place Holder for the variable C_star */
  real d gamma_sT; /* Place Holder for the Sulfur Content of any given cell */
  real r; /* Place Holder for the position of the cell */
  real gamma_s; /* Defining the Surface Tension for Steel--Air */
  real gamma_u_st = .659; /* Surface tension of slag--gas */
  real gamma_o_st = -.15; /* Surface tension of slag--gas */
  real gamma_sT = -.126e-4; /* Slag tension gradient */
  real gamma_s; /* Defining the Surface Tension for Steel--Air */
  real phi = 0.434; /* Found for this specific slag composition */
  real V_s = 5e-4; /* Dendrite Growth Velocity for Steel */
  real gamma; /* Overall Surface Tensions between slag and steel */
  real x[N, ND];
  real delta_x;
  real delta_y;
  real Ycor;
  real timeCycle;
  real r_tot = 100*r_d; /* This should be changed for each run, this corresponds to about a quarter of the meniscus arc */

  /* timeCycle = (N_TIME - 481400) % 600000;
  if (timeCycle == 0)
    Ycor = .103;
  else
    Ycor = .103 - (N_TIME - 481400) * 1E-7; */

  Ycor = .103;

  C_star = C_0/(1 - (V_s * r_d * (1 - k) / (2 * D_s)));
  gamma_sT = gamma_o_st + T*d gamma_sT;
  gamma_sT = gamma_o + (T - 1873.00) * d gamma_sT;
  C CENTROID (x, c, t)
  delta_x = x[0] - .002;
  delta_y = x[1] - Ycor;
  r = pow(pow(delta_x, 2) + pow(delta_y, 2), 1/2);
  C_s = C_0 + (r tot / r) *(C_star-C_0);
  d gamma_sT = -.5e-4 + 6.7e-2*C_s;
  gamma_oT = -.15 + log(C_s) + 0.85;
  gamma_sT = gamma_oT + T*1873.00 + d gamma_sT;
}
```
gamma = \gamma_{st} \gamma_{sl} - 2 \phi \cdot \text{pow}((\gamma_{st} \gamma_{sl})^{1/2});
C_{UDMI}(c, t, 0) = \gamma_{st} \gamma_{sl};
return \gamma;