ELECTROMAGNETIC FLOW CONTROL IN THE CONTINUOUS CASTING OF STEEL SLABS

BY

KEVIN JOSEPH CUKIERSKI

THESIS

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NOMENCLATURE

| 4 | $\Lambda = (m^2)$ |
|---------------------------------|---|
| A → | Area (m) |
| b | Induced magnetic field (T) |
| \vec{B}_o | Applied magnetic field (T) |
| \vec{B} | Total magnetic field |
| C_1 | Turbulence theory empirical constant (=1.44) |
| C_2 | Turbulence theory empirical constant (=1.92) |
| C_{μ} | Turbulence theory empirical constant (=0.09) |
| ε | Turbulent dissipation rate (m^2/s^3) |
| \vec{F} | Momentum source term from FLUENT MHD module |
| g | Gravitational acceleration (=9.81m/s ²) |
| G_k | Turbulent kinetic energy generation |
| \vec{j} | Current density (A/m ²) |
| Κ | Turbulent kinetic energy (m^2/s^2) |
| п | Empirical constant |
| σ | Electrical conductivity $(1/\Omega-m)$ |
| $\sigma_{arepsilon}$ | Turbulence theory empirical constant (=1.3) |
| $\sigma_{_k}$ | Turbulence theory empirical constant (=1.0) |
| р | Pressure (N/m ²) |
| P_{static} | Static pressure (N/m ²) |
| \overline{P}_{static} | Average static pressure across a chosen surface (N/m^2) |
| ρ | Fluid density (kg/m ³) |
| $ ho_{\scriptscriptstyle slag}$ | Slag layer density (kg/m ³) |
| r | Nozzle radius (m) |
| S_m | Mass source term |
| S_{mom} | Momentum source term |

| $u_{i,j}$ | Fluctuating velocity components (m/s) |
|--------------------|--|
| μ | Dynamic fluid viscosity (kg/m-s) |
| $\mu_{_{e\!f\!f}}$ | Turbulence-adjusted effective fluid viscosity (kg/m-s) |
| μ_o | Laminar fluid viscosity (kg/m-s) |
| μ_t | Turbulent fluid viscosity (kg/m-s) |
| \vec{v} | Velocity (m/s) |
| V _{cast} | Casting speed (m/s) |
| ${\cal V}_{f\!S}$ | Nozzle average velocity (m/s) |
| x | Direction along width of mold (m) |
| x_{char} | Characteristic length defined as nozzle inlet radius (m) |
| У | Direction along height of mold (m) |
| Ζ | Direction along thickness of mold (m) |

CHAPTER 1: INTRODUCTION

1.1 Overview of the Continuous Casting Process

Continuous casting is a steady-state process that transforms molten metal into solid. Mass-production of various metals is prevalent in the continuous casting industry, as evidenced by the over 500 million tons of steel, 20 million tons of aluminum, and 1 million tons of copper, nickel, and other metals produced by the continuous casting process each year [1]. This thesis will focus on the continuous casting of steel. Over 90% of the world's steel is cast using the method of continuous casting [2], and improvements in the process could have an influential impact on the industry.

Figure 1.1 shows a schematic of the continuous casting process, which begins when molten steel is poured from the ladle into the tundish. The tundish acts as a holding area for the steel as it awaits deposition into the mold cavity; this assures that there will be no interruption in the casting process between ladle pourings. The steel then flows through a bifurcated or trifurcated submerged entry nozzle (SEN) into the mold cavity. Inert gas may be bubbled through the SEN at this point to prevent nozzle clogging and to aid in removing impurities. The flow rate of steel through the nozzle is controlled by either a slide gate located within the SEN or by a stopper rod located at the top of the SEN. Figure 1.2 shows a close-up of the tundish, SEN (including flow-control mechanisms), and upper mold region, including the meniscus. The meniscus is the top surface of molten steel in the mold cavity that is exposed to the outside environment. It is covered with a mold powder designed to provide lubrication and insulation [3]. Once inside the

mold cavity, the steel begins to solidify near the water-cooled mold walls, creating a solidified steel shell that prevents molten steel from escaping. Sticking of this shell to the mold walls is prevented by both the lubrication provided by the mold slag layer and the continuous vertical oscillation of the mold walls themselves. The process continues as drive rolls extract the solidifying steel strand out of the mold cavity and into a spray-cooling zone at a rate called the casting speed, which is dependent on the flow rate through the SEN. While in this region, the strand is sprayed with water, consequently increasing heat transfer from the strand and helping solidify its interior. Also, support rolls gradually bend the strand into a desired shape in the spray-cooling region. Once the strand is completely solidified, a torch is used to cut it into desired lengths.

1.2 Factors Influencing the Continuous Casting Process

A multitude of factors influence the continuous casting process, particularly the flow in the mold cavity. These factors include, but are not limited to, flow control mechanism, SEN design, SEN depth (distance from top of nozzle ports to mold top surface), inert gas injection rate, application of electromagnetics, mold size, and casting speed. Each factor must be adjusted with regard to the other factors in order to produce the desired flow pattern in the mold cavity [4]. For example, increasing casting speed while holding all other factors constant will increase velocity at the meniscus, which could cause an increase in undesirable inclusions, i.e. mold flux or bubbles, in the finished product [4]. Conversely, increasing SEN submergence depth while holding all other factors constant will cause a decrease in meniscus velocity, which could bring about meniscus freezing and shell thinning [4]. Both are detrimental consequences. The definitive goal is to obtain the optimal combination of the factors influencing flow in the mold cavity to produce the highest quality finished product.

1.2.1 Effects of Electromagnetics on Mold Cavity Flow

Adding electromagnetics to the continuous casting process improves the ability to control fluid flow in the mold cavity. Electromagnetics can produce stirring, accelerating, and/or braking of flow, and can be divided into two categories: electromagnetic stirrers (EMS) and electromagnetic brakes (EMBr). EMS is normally used to encourage mixing and to homogenize temperatures by stirring the molten steel, although variations can also be used to control the flow pattern. EMBr is normally used to control the flow pattern and meniscus characteristics of fluid in the mold cavity. There are multiple types of both EMS and EMBr, and they are presented in detail in Chapter 2.

1.3 The Use of Computational Modeling of Continuous Casting

By nature, the high temperatures and harsh environment of a steel caster makes it impossible to witness steel flow inside the mold cavity firsthand. The widespread use of computational modeling of the continuous casting process emerged from this issue. Computational simulations allow for the visualization and characterization of fluid flow in the mold cavity. Computational models offer a great deal of flexibility. Flow in multiple types of nozzles and molds can be simulated, and casting parameters can be changed quickly and easily. However, it must be noted that computational models should be validated using any available experimental data and/or previous work before being assumed realistic.

1.4 Focus and Investigations of this Thesis

The objective of this thesis is to discover how and why the addition of an electromagnetic brake and the variation of SEN submergence depth affect steel flow in the continuous casting mold cavity. The three phases of this project, experimental, computational, and validation, are discussed in the following chapters.

Chapter 2 offers a literature review, which gives background information and summarizes previous work on the computational modeling of continuous casting and electromagnetics. The equations governing fluid flow, turbulence, and electromagnetics in the mold cavity will be presented.

Chapter 3 illustrates the procedures and results of experimental measurements conducted at Nucor Steel in Decatur, AL. The following experiments were performed:

- EMBr magnetic field measurement
- Nail board dip test
- Slab crop sandblasting and oscillation mark categorization

This experimental data was used to run accurate computational simulations as well as to validate computational results.

Chapter 4 gives the conditions and results of various steady-state computational simulations of flow in both the SEN and the mold cavity, which were conducted using FLUENT. FLUENT is a commercial computational fluid dynamics (CFD) code that solves the three-dimensional Navier-Stokes equations with the $K - \varepsilon$ turbulence model,

as well as the equations of electromagnetics. The effects of adding an EMBr to a continuous casting mold and varying SEN submergence depth are studied, reported, and discussed.

Chapter 5 shows the methods of validation used to confirm the findings of the computational model. Simulated meniscus velocity was compared to meniscus velocity obtained using the nail board dip test. The simulated meniscus profile was compared to slab crop oscillation marks.

Chapter 6 offers conclusions as well as suggestions for future work.



1.5 Figures

Figure 1.1: The continuous casting process [1]



Figure 1.2: View of the tundish, SEN, and upper mold region [5]

CHAPTER 2: LITERATURE REVIEW AND GOVERNING EQUATIONS

2.1 Literature Review

2.1.1 Computational Modeling of Continuous Casting Nozzles and Mold Cavities

The complexity of the continuous casting process and difficulties of direct observation have led to a large number of computational studies of fluid flow in the nozzle and mold cavity. Methods such as large eddy simulation (LES), direct numerical simulation (DNS), and Reynolds averaging (RANS) have been used to model flow [6].

2.1.1.1 Nozzle Flow

Flow in the nozzle prominently affects the continuous casting process, and can be influenced by factors such as nozzle geometry, submergence depth, flow control mechanism, and inert gas bubbling. Najjar *et al* studied the effect that changing nozzle port shape, angle, height, width, and thickness has on flow pattern [7]. This characterization of nozzle flow is useful in designing effective nozzles. Bai used an Eulerian multiphase model to investigate how the inclusion of argon bubbling in the nozzle affects flow [8]. A swirling outlet flow was witnessed and confirmed using particle image velocimetry (PIV) measurements. Mahmood explored flow asymmetries caused by nozzle clogging and the use of a slide gate [9]. The slide gate causes a significant swirling effect in the nozzle outflow, while clogging of the nozzle bore, well, and/or port causes an asymmetry in nozzle port flowrates.

2.1.1.2 Mold Cavity Flow

Understanding flow in the mold cavity is critical to understanding and improving the continuous casting process as a whole. Thomas *et al* used a two-dimensional RANS model to simulate flow in the mold cavity [10]. Results compared favorably with PIV data, but variations in the thickness of the mold cannot be observed using a two-dimensional model. Thomas *et al* later compared three-dimensional DNS, LES, and RANS models with PIV water model results [11]. While each model showed quantitative and qualitative results similar to each other and to the PIV data, each has its own advantages and disadvantages. LES and DNS are able to solve for transient effects, but have a high computational cost. Conversely, the RANS model has a low computational cost, but cannot show transient phenomena. Mahmood also showed an agreeable comparison between LES and RANS models [9] for the time-averaged flow velocities.

2.1.2 Computational Modeling of Electromagnetics in Continuous Casting

2.1.2.1 Electromagnetic Stirrers

Electromagnetic stirrers employ an alternating current to generate a continuously-varying magnetic field to control flow in the mold cavity. There are multiple types of EMS that have various uses. Figure 2.1 shows a Slab-Mold EMS, which employs two stirrers on each wide side of the mold at the meniscus. These magnetic systems sequence the forces to circulate the flow around the mold perimeter, which homogenizes meniscus temperature, thus improving the quality of the finished slab [12]. Nakashima *et al* observed this improvement in a steel plant [13].

Figure 2.2 shows a Multi-Mode EMS (MM-EMS) which uses two stirrers on each wide side of the mold located near the SEN ports [12]. This complex EMS system has three modes of operation. The electromagnetic level stabilizer (EMLS) mode sequences the motion of electromagnetic forces to oppose the flow exiting the SEN, and is used to reduce meniscus velocity and stabilize the meniscus profile. The electromagnetic level accelerator (EMLA) mode accelerates the flow exiting the SEN, and is used to increase meniscus velocity and heat transfer to the meniscus. Finally, the electromagnetic rotary stirrer (EMRS) mode stirs the flow to encourage mixing. Dauby *et al* showed that if used optimally, MM-EMS can effectively maintain a favorable double-roll flow pattern in the mold cavity and reduce breakouts as well as the number of inclusions, cracks, and slivers present in the final product [14]. Ishii et al used a RANS model to simulate the EMLS mode [15]. It was found that the use of EMLS can effectively suppress meniscus velocity, especially for thin-slab casters. Okazawa et al used an LES model and an experimental mercury model to study the effect that the placement of the EMS magnets has on flow circulation. The LES velocity results matched well with the mercury model velocity results obtained through the use of a Vives-type sensor [16]. Kubota *et al* found that the use of both EMLS and EMLA, depending on casting conditions, can effectively control meniscus velocity and reduce mold slag entrapment [17].

2.1.2.2 Electromagnetic Brakes

Electromagnetic brakes employ coils with direct current to generate a static magnetic field to affect flow in the mold cavity. Like EMS, there are multiple types of EMBr that have various uses. Figure 2.3 shows a local EMBr. This type of EMBr uses two magnets

on each wide side of the mold that aim to create rectangular regions of magnetic field located near the SEN ports. This system is used to slow and diffuse the jet exiting the nozzle in order to decrease meniscus velocity and fluctuations in the meniscus profile [18]. Ha *et al* used a RANS model to perform a three-dimensional simulation of flow in the mold cavity with EMBr, including heat transfer and shell solidification [19]. It was found that the addition of EMBr effectively slows flow exiting the nozzle, reduces impingement impact of the jet on the narrow face, and shortens the penetration depth of the lower recirculation zone. Takatani *et al* used a similar method and found that the addition of EMBr causes an overall decrease of fluid velocities in the mold cavity, and that imposing a strong magnetic field can cause the jet to bend and dissipate before impinging against the narrow face [20]. Kim *et al* showed that the addition of a local EMBr caused a vast decrease in jet momentum and velocity [21].

Figure 2.4 shows a ruler EMBr. This type of EMBr uses two thin rectangular magnets located below the SEN ports on opposite sides of the mold, each of which spans across the entire wide side. Like the local EMBr, this is used to stabilize the meniscus velocity and meniscus profile [18]. Harada *et al* modeled and compared mold cavity flow with the local EMBr and the ruler EMBr [22]. It was found that, although both types of EMBr lowered meniscus velocity and penetration depth, the ruler EMBr more effectively stabilized meniscus flow. Zeze *et al* showed good comparison between a physical mercury model and a numerical model to illustrate that the addition of a ruler EMBr causes a plug-like flow, i.e. a non-recirculating flow with a relatively constant velocity, to develop in the mold cavity [23].

Figure 2.5 shows a Flow-Control Mold (FC-Mold). This type of EMBr uses two thin, rectangular magnets spanning the wide side on each side of the mold. One is located at the meniscus, and the other is located beneath the SEN ports [18]. This type of EMBr aims to control the fluid flow both exiting the nozzle and at the meniscus, and thus to control meniscus velocity. Hackl et al, using plant measurements, showed that the use of an FC-Mold reduces meniscus fluctuations and surface defects on finished coils [18]. Idogawa et al used numerical simulations to show that the FC Mold decreases overall velocities in the mold cavity [24]. These results were confirmed with the use of a mercury model. Li *et al* simulated flow in a caster with an FC-Mold while incorporating argon bubbling. It was found that the EMBr reduces the velocities of the bubbles, but does not significantly hinder bubble flotation [25]. While the FC-Mold is usually employed to decrease velocities at the meniscus [18, 24, 25], it might also be able to increase meniscus velocity. A strong magnetic field across the mold below the SEN ports combined with a weak or nonexistent magnetic field at the meniscus could cause an upward deflection of the jets exiting the SEN, and therefore a higher velocity at the meniscus.

2.1.3 Need for Current Work

In previous work, researchers have routinely made assumptions regarding how the EMBr field varies throughout the mold cavity [19, 20]. For example, a local EMBr is often modeled as having a magnetic field strength which decreases linearly with radial distance from the point of maximum field strength, which is assumed to be the center point of the magnet used to create the field [19, 20]. The magnetic field is typically assumed to be

nonexistent outside of the area enclosed by this magnet. In actuality, the accuracy of the flow computations depends on the accuracy of the EMBr field. In the present work, this accuracy is achieved by direct measurement of the EMBr field in the mold cavity.

Validation of numerical simulations with experimental results is needed to prove the numerical model is correct. Unfortunately, this step has been skipped in many publications, although occasionally velocities from numerical models are compared to those from experimental models for validation purposes [16, 24]. In the present work, validation of the numerical simulations is accomplished through comparison of both velocities and oscillation mark profile with measurements in the steel plant. The use of an exact EMBr field and two separate means of validation make the investigations of this thesis unique.

2.2 Governing Equations

In this thesis, a RANS model is used to simulate fluid flow in order to understand and optimize the time-averaged flow pattern in a 90-mm thick slab-casting mold with a local EMBr. By utilizing the K- ε turbulence model with wall laws, the RANS approach allows for the use of a mesh much coarser than is required for either LES or DNS simulations, which substantially decreases computational cost. Previous work has shown that the results of a RANS model compare well with the time-averaged results obtained by both DNS and LES models for turbulent flow in a continuous casting mold cavity [9, 11].

2.2.1 Navier-Stokes Equations for Fluid Flow

The steady-state, incompressible, three-dimensional Navier-Stokes equations are outlined below. Refer to the *Nomenclature* section for definitions of the variables, including units.

The continuity equation for conservation of mass is given as:

$$\rho(\nabla \cdot \vec{v}) = S_m \tag{2.1}$$

where S_m is a mass source/sink term used to model shell solidification. The equation for conservation of momentum is defined by:

$$\rho\left(\nabla \cdot (\vec{v}\vec{v})\right) = -\nabla p + \nabla\left(\mu_{eff}\left(\nabla \cdot \vec{v}\right)\right) + \rho \vec{g} + S_{mom} + \vec{F}$$
(2.2)

where S_{mom} is a momentum source/sink term used to model shell solidification, \vec{F} is a momentum source/sink term used to model the calculated electromagnetic force (see Section 2.2.3), and μ_{eff} is the effective viscosity, calculated by:

$$\mu_{eff} = \mu_o + \mu_t \tag{2.3}$$

 μ_o is the molecular viscosity and μ_i is the turbulent viscosity, which will be discussed in Section 2.2.2.

2.2.2 K-E Turbulence Model

Launder and Spalding's *K*- ε model is used to model turbulence [26], which requires solving the following two additional transport equations to determine turbulent kinetic energy *K* and turbulent dissipation rate ε .

$$\rho\left(\nabla\left(K\vec{v}\right)\right) = \nabla \cdot \left(\left(\mu_{o} + \frac{\mu_{t}}{\sigma_{K}}\right)\nabla K\right) + G_{K} - \rho\varepsilon$$
(2.4)

$$\rho\left(\nabla\left(\varepsilon\vec{v}\right)\right) = \nabla \cdot \left(\left(\mu_{o} + \frac{\mu_{t}}{\sigma_{\varepsilon}}\right)\nabla\varepsilon\right) + C_{1}\frac{\varepsilon}{K}G_{K} + C_{2}\rho\frac{\varepsilon^{2}}{K}$$
(2.5)

 G_{K} represents the generation of turbulence kinetic energy due to the mean velocity gradients. It is defined as:

$$G_{K} = -\rho \overline{u_{i} u_{j}} \frac{\partial u_{j}}{\partial x_{i}}$$
(2.6)

The turbulent viscosity can now be solved for using the following equation:

$$\mu_t = \rho C_\mu \frac{K^2}{\varepsilon} \tag{2.7}$$

The empirical constants are given as [27]:

$$C_{\mu} = 0.09, \ C_1 = 1.44, \ C_2 = 1.92, \ \sigma_K = 1.0, \ \sigma_{\varepsilon} = 1.3$$
 (2.8)

2.2.3 Magnetic Induction Method

The magnetic induction method for solving for electromagnetic force is derived from Ohm's law and Maxwell's equation [27]. A magnetic field is induced when a conducting fluid, such as molten steel, moves through an applied magnetic field \vec{B}_o with a velocity \vec{v} . This induced field \vec{b} is calculated by solving:

$$\left(\vec{v} \cdot \nabla\right) \cdot \vec{b} = \frac{1}{\mu\sigma} \nabla^2 \vec{b} \cdot \left(\left(\vec{B}_o + \vec{b}\right) \cdot \nabla\right) \cdot \vec{v} - \left(\vec{v} \cdot \nabla\right) \cdot \vec{B}_o$$
(2.9)

The total magnetic field is then:

$$\vec{B} = \vec{B}_a + \vec{b} \tag{2.10}$$

Current density can then be obtained through:

$$\vec{j} = \frac{1}{\mu} \nabla \times \vec{B} \tag{2.11}$$

The Lorentz force, or induced electromagnetic force, is determined using:

$$\vec{F} = \vec{j} \times \vec{B} \tag{2.12}$$

This term is subsequently added into the momentum equations as a source/sink term. The solution of these equations is discussed in Section 4.3.

2.3 Figures



Figure 2.1: Slab-Mold EMS [12]



Figure 2.2: MM-EMS (a) EMLS mode, (b) EMLA mode, (c) EMRS mode, and (d) schematic of EMLS mode [12]



Figure 2.2 (cont'd): MM-EMS (a) EMLS mode, (b) EMLA mode, (c) EMRS mode, and (d) schematic of EMLS mode [12]



Figure 2.3: Local EMBr (a) schematic of magnets and coils and (b) idealized effect on flow field [16]



Figure 2.3 (cont'd): Local EMBr (a) schematic of magnets and coils and (b) idealized effect on flow field [16]



Figure 2.4: Ruler EMBr (a) schematic and (b) effect on flow field [16]



Figure 2.4 (cont'd): Ruler EMBr (a) schematic and (b) effect on flow field [16]



Figure 2.5: FC Mold (a) schematic and (b) effect on flow field [16]



Figure 2.5 (cont'd): FC Mold (a) schematic and (b) effect on flow field [16]

CHAPTER 3: EXPERIMENTAL PROCEDURES AND RESULTS

3.0 Experimental Conditions

Plant measurements were obtained on a conventional continuous slab caster: the South caster at Nucor Steel in Decatur, AL. This caster features a standard two-port SEN and a 90mm thick, straight, parallel mold with a sinusoidal oscillator. A local EMBr is used on this caster. Table 3.1 gives the casting conditions under which each of the following experiments was performed.

3.1 EMBr Field Measurement

3.1.1 Experimental Procedure

A Gauss meter like the one shown in Figure 3.1 was used to measure the EMBr field in the mold cavity without molten steel. The tool consists of a small console used for unit selection and calibration, and a 1.2m flexible wire ending in a 5mm wide, 1mm thick metal probe. When the wide face of this probe is positioned perpendicular to a magnetic field, the console displays the field strength. An apparatus, shown in Figure 3.2, was constructed to accurately move and position the probe tip to desired locations within the thin mold cavity to measure the local EMBr field strength. It consisted of a hollow PVC pipe with the Gauss meter affixed to the top end, and its probe and wire fed through the pipe and affixed to the bottom end. The pipe was labeled with markers at 5cm vertical increments to measure probe depth. The pipe was stabilized vertically by feeding it through a small sheath attached to a block of wood. The EMBr on the caster was turned on and tuned to a desired field strength. The probe was then calibrated to read zero magnetic field at ambient conditions far from the caster. Figure 3.3 illustrates the measurement technique. At every 10cm across the center of the mold cavity, measurements were recorded, lowering the probe downward in 5cm increments. Measurements started 2cm below the top of the mold and extended to a depth of 72cm into the mold cavity, spanning the width of the mold up to 2cm from either narrow face. Figure 3.4 shows the number of data points taken in each direction. Magnetic field strength across the thickness of the mold was measured to vary by a maximum of 3%, so it was neglected.

3.1.2 Experimental Results

Table 3.2 lists the *z*-component (component perpendicular to the wide faces) of the measured EMBr field at 225 points in the mold cavity. As stated above, components of the magnetic field in the *x* and *y* directions are considered negligible. Figure 3.5 utilizes linear interpolation between data points to offer a three-dimensional graphical visualization of this field. Notice that although the magnitudes of the magnetic fields are about the same on each mold half, the directions are opposite. Figure 3.6 shows a contour plot of the measured EMBr field, along with the location of the magnets that create the field. These results clearly show that the magnetic field extends far beyond the boundaries of the magnets and is present in the entire upper mold region. This is contrary to the assumption made in many previous studies.

3.2 Nail Board Dip Test

The nail board dip test is a method of characterizing flow at the meniscus. The test is performed by inserting a number of nails into a long board, and dipping them perpendicularly into the top surface of the molten steel for 3-5 seconds. Upon removal, a knob of steel has solidified on the end of each nail. Figure 3.7 shows a schematic of this process. Nail board dip tests have commonly been used to determine the depth of the liquid flux layer that lies atop the molten steel [29]. This can be found by affixing aluminum wire alongside the nails prior to performing the dip test, and recording the difference between the melted wire height and the solidified knob.

The angular profile of the knob can be further analyzed to gain insight into the flow pattern. The direction of the flow can be found by recognizing that the high end of the angular knob profile represents the direction from which steel impinges on the nail. Recently, Rietow used a carefully-validated computational model to determine a relation to correlate knob height difference and nail diameter to surface velocity of the molten steel across the top of the mold [30]. Knob height difference is the difference in height between the low end and the high end of the knob profile. This correlation allows for an accurate, fast measurement of meniscus velocity in a plant setting, which is compared with computational results of the current study for validation purposes.

3.2.1 Experimental Procedure

Ten 7.5cm long, 5mm diameter nails were hammered into a 6.2cm wide, 2cm thick, 550cm long pine board to a depth of approximately 2.5cm. The nails were spaced 5cm

apart, and 5cm from each end of the board. Note that the width of the board is about 15cm less than the width of the mold to ensure that the board and nails will not interfere with the steel shell or SEN upon insertion into the mold cavity. A diagram of the nail board assembly can be seen in Figure 3.8. The nails were then dipped into the mold cavity for approximately 4 seconds, removed, and allowed to cool.

3.2.2 Experimental Results

The results of the nail board dip test can be seen in Figure 3.9. The sides of the board near the SEN and narrow face are labeled for reference. The knob height difference can be noticed primarily near the narrow face, where velocities are the highest. The post-processing of the solidified knobs to determine meniscus velocity is performed and discussed in Chapter 5.

3.3 Oscillation Mark Categorization

Oscillation marks are small depressions in the surface of a steel slab caused by the partial freezing of the meniscus during a mold oscillation cycle [31]. These marks show the shape of the meniscus at the instant in time they are formed. This gives another opportunity for validation of a computational model; the simulated meniscus shape caused by the fluid flow pattern can be compared with the meniscus shape obtained from oscillation marks.

3.3.1 Experimental Procedure

A sample slab of steel approximately 1.5m in length was cut and allowed to cool. Due to oxidation, the surface of the slab was covered with a layer of dark scale, which made the oscillation marks difficult to observe. The slab was sandblasted to remove this layer of scale. Sandblasting utilizes a high-pressure stream of small sand particles to abrasively remove the oxidation layer. After sandblasting, the oscillation marks were outlined in dark marker to increase visibility, and photographed with a ruler to provide scale.

3.3.2 Experimental Results

Figure 3.10 shows the photographed oscillation marks.

3.4: Tables and Figures

| Mold Width | Mold | SEN | Casting | EMBr |
|------------|-----------|-------|----------|---------|
| | Thickness | Depth | Speed | Setting |
| 1374mm | 90mm | 300mm | 3.3m/min | 0.3550T |

Table 3.1: Experimental casting conditions

| ble 3.2: EMBr field data for 0.3550T field strength | MBr Field Measurement (T) | Distance from Contar of Mold Wide Face (om) |
|---|---------------------------|---|
| Table 3.2 | | ï |

| | | | | | | | | r mein | leasur | | L) | | | | | |
|------------|----|-------|-------|-------|-------|-------|-----------------|--------|---------|----------|-----------------------|--------|--------|--------|--------|--------|
| | | | | | | Γ | Distance | from C | enter o | f Mold V | <mark>Wide Fac</mark> | e (cm) | | | | |
| | | -70 | -60 | -50 | -40 | -30 | -20 | -10 | 0 | 10 | 20 | 30 | 40 | 50 | 60 | 70 |
| | 2 | 0.004 | 0.005 | 0.005 | 0.005 | 0.004 | 0.003 | 0.002 | 0 | -0.002 | -0.003 | -0.004 | -0.005 | -0.005 | -0.005 | -0.004 |
| (| 7 | 0.007 | 0.01 | 0.016 | 0.016 | 0.017 | 0.012 | 0.006 | 0 | -0.006 | -0.012 | -0.017 | -0.016 | -0.016 | -0.01 | -0.007 |
| (พ. | 12 | 0.013 | 0.023 | 0.035 | 0.037 | 0.038 | 0.026 | 0.013 | 0.001 | -0.013 | -0.026 | -0.038 | -0.037 | -0.035 | -0.023 | -0.013 |
|) / | 17 | 0.019 | 0.036 | 0.059 | 0.071 | 0.066 | 0.044 | 0.021 | 0.002 | -0.021 | -0.044 | -0.066 | -0.071 | -0.059 | -0.036 | -0.019 |
| ti. | 22 | 0.028 | 0.057 | 0.104 | 0.118 | 0.111 | 0.072 | 0.033 | 0.003 | -0.033 | -0.072 | -0.111 | -0.118 | -0.104 | -0.057 | -0.028 |
| vr' | 27 | 0.037 | 0.083 | 0.182 | 0.203 | 0.19 | 0.118 | 0.047 | 0.004 | -0.047 | -0.118 | -0.19 | -0.203 | -0.182 | -0.083 | -0.037 |
|) p | 32 | 0.044 | 0.115 | 0.266 | 0.303 | 0.282 | 0.173 | 0.06 | 0.005 | -0.06 | -0.173 | -0.282 | -0.303 | -0.266 | -0.115 | -0.044 |
| 0]0] | 37 | 0.051 | 0.137 | 0.309 | 0.334 | 0.321 | 0.205 | 0.069 | 0.006 | -0.069 | -0.205 | -0.321 | -0.334 | -0.309 | -0.137 | -0.051 |
| N | 42 | 0.054 | 0.145 | 0.324 | 0.345 | 0.326 | 0.213 | 0.072 | 0.005 | -0.072 | -0.213 | -0.326 | -0.345 | -0.324 | -0.145 | -0.054 |
| 01U | 47 | 0.054 | 0.144 | 0.311 | 0.334 | 0.305 | 0.196 | 0.063 | 0.004 | -0.063 | -0.196 | -0.305 | -0.334 | -0.311 | -0.144 | -0.054 |
| li d | 52 | 0.05 | 0.13 | 0.265 | 0.291 | 0.271 | 0.16 | 0.056 | 0.004 | -0.056 | -0.16 | -0.271 | -0.291 | -0.265 | -0.13 | -0.05 |
| Dtl | 57 | 0.045 | 0.096 | 0.173 | 0.204 | 0.182 | 0.115 | 0.044 | 0.004 | -0.044 | -0.115 | -0.182 | -0.204 | -0.173 | -0.096 | -0.045 |
| De | 62 | 0.036 | 0.064 | 0.112 | 0.131 | 0.113 | 0.074 | 0.034 | 0.003 | -0.034 | -0.074 | -0.113 | -0.131 | -0.112 | -0.064 | -0.036 |
| - | 67 | 0.029 | 0.049 | 0.074 | 0.087 | 0.077 | 0.049 | 0.024 | 0.003 | -0.024 | -0.049 | -0.077 | -0.087 | -0.074 | -0.049 | -0.029 |
| | 72 | 0.021 | 0.034 | 0.046 | 0.055 | 0.049 | 0.031 | 0.016 | 0.002 | -0.016 | -0.031 | -0.049 | -0.055 | -0.046 | -0.034 | -0.021 |


Figure 3.1: Gauss meter used to conduct magnetic field measurements [28]



Figure 3.2: Schematic of apparatus used to conduct EMBr in-mold field measurements



Figure 3.3: Demonstration of measurement technique



Figure 3.4: Diagram of EMBr field measurement location











Figure 3.7: Schematic of nail board dip test [30]



Figure 3.8: Diagram of assembled nail board



Figure 3.9: Nail board dip test results





Figure 3.10: Oscillation mark photographs

CHAPTER 4: COMPUATIONAL MODELING AND RESULTS

4.1 Model Formulation

Fluid flow in the nozzle and mold cavity was simulated by solving the governing equations outlined in Chapter 2 using FLUENT. To ease convergence, the nozzle and the mold cavity domains were modeled separately, with the flow at the outlet of the nozzle being prescribed as the flow at the inlet of the mold cavity. Hershey *et al* showed that results using this method match well with results of simulations of the combined nozzle and mold cavity domains [7].

The entire nozzle was modeled, starting from just below the stopper rod. To reduce computational cost, one quarter of the mold cavity was modeled by taking twofold symmetry into account. The solidified shell profile was calculated using an in-house heat transfer program, CON1D [33], and incorporated into the mold cavity. Mass and momentum sinks were added at the shell boundaries to simulate extraction of fluid into the solidifying shell.

4.1.1 Boundary Conditions

4.1.1.1 Nozzle Inlet

It was assumed that a fully-developed velocity profile was present at the nozzle inlet. Standard equations for fully-developed flow in a pipe were used to prescribe this profile, and are outlined below (adopted from Rietow [30]).

The nozzle average velocity can be found by:

$$v_{fs} = \frac{A_{mold \ outlet}}{A_{nozzle \ inlet}} v_{cast} \tag{4.1}$$

However, since the velocity of the fluid will be zero at the nozzle walls, the center of the velocity profile must be larger than the average velocity to maintain the desired constant mass flow rate. This maximum velocity can be found using:

$$v_{\max} = \frac{(1+n)(1+2n)}{2n^2} v_{fs}$$
(4.2)

where *n* is an empirical constant calculated by [30]:

$$n = 2.81 \left(\frac{\rho * v_{fs} * x_{char}}{\mu_o}\right)^{0.084}$$
(4.3)

 x_{char} is the diameter at the nozzle inlet. The nozzle inlet velocity profile can then be calculated using:

$$v_k(x_i, x_j) = v_{\max} \left(1 - \frac{\sqrt{(x_i + x_j)}}{r} \right)^{\frac{1}{n}}$$
(4.4)

The method of implementing this profile as a boundary condition in FLUENT via userdefined function (UDF) can be found in Appendix A.2.1. Values of *K* and ε were both set to arbitrary small values, 10^{-4} m²/s² and 10^{-4} m²/s³ respectively, to allow turbulence to develop naturally.

4.1.1.2 Mold Cavity Inlet

The velocity and turbulence parameters at the mold cavity inlet are specified using the results calculated at the outlet plane of the port from the nozzle simulation. A text file containing the nozzle right port velocity, K, and ε values at each node was written. This

file was then read into FLUENT, and the values were used as the inlet conditions for the mold cavity simulations.

4.1.1.3 Nozzle and Mold Cavity Outlets

Bai *et al* has shown that using pressure boundary conditions allows for an accurate flow simulation, including the velocities near the outlet boundaries [32]. The use of a pressure boundary condition allows for recirculation zones to appear at the outlets, which has a large effect on flow in the domain. With this in mind, the gauge pressure at both the nozzle and the mold cavity outlets was set to zero, which is an arbitrary value that acts as a reference pressure for the rest of the domain. Values of *K* and ε were set to $10^{-4} \text{ m}^2/\text{s}^2$ and $10^{-4} \text{ m}^2/\text{s}^3$, respectively.

4.1.1.4 Walls

The boundaries defined as walls include the inner walls of the nozzle in the nozzle simulation, and the exterior walls of the nozzle, top surface, and shell boundaries in the mold cavity simulations. A no-slip condition and standard wall laws were used at these locations [27]. The gradients of all electromagnetic variables are equal to zero at all walls, which are assumed to be stationary. Additional conditions were prescribed at selected wall areas, as defined below.

4.1.1.4.1 Mold Cavity Top Surface

A zero-shear condition is specified at the top surface, which assumes the effect of the mold flux is negligible. Standard wall laws are still used.

4.1.1.4.2 Shell Boundaries

To simulate the continuous extraction of the solidifying steel shell, the shell wall boundaries are given a downward velocity equal to the casting speed.

4.1.1.5 Mass/Momentum Sink Cells

The method of extracting mass and momentum to model the solidification of steel into the shell is that which was used by Rietow for flow in a funnel mold cavity [30]. In this method, thin (0.1mm thick) cells are created along the faces of the solidified shell boundaries. The curvature of the shell can then be used to calculate the amount of mass and momentum removed at each cell location. This is implemented in FLUENT using a UDF, which adds these mass and momentum sinks to their representative governing equations. A detailed explanation of this method, as well as the UDF used in FLUENT, can be found in Appendices A.1 and A.2.2.

4.1.1.6 Magnetic Field

FLUENT allows for 3-D magnetic fields to be imported using a format outlined in Appendix B.1. The magnetic field measured at Nucor Steel in Chapter 3 was imported in this manner and applied to the fluid domain.

4.1.1.7 Symmetry

At planes of symmetry, normal velocities, as well as all gradients, are equal to zero [27].

4.2 Solution Procedure

4.2.1 Software

4.2.1.1 Gambit

Gambit (version 2.3.16), by Fluent, Inc., is a preprocessor and mesh generator for FLUENT. Gambit allows for the creation of a hexahedral or tetrahedral mesh, as well as the application of boundary conditions.

4.2.1.2 FLUENT

FLUENT (version 6.3.26) is a commercial CFD code. The steady, three-dimensional, double precision, segregated solver was used for all cases in this thesis to solve the time-averaged, three-dimensional, inviscid Navier-Stokes equations with the K- ε turbulence model. The electromagnetic equations are solved using the add-on MHD module in FLUENT with the magnetic induction method.

4.2.2 Fluid Domains and Mesh Generation

4.2.2.1 Nozzle

The nozzle that was simulated is the one used at Nucor Steel in Decatur, AL. A schematic of this bifurcated nozzle can be seen in Figure 4.1. The nozzle fluid domain was meshed in Gambit using a hexahedral mesh of approximately 200,000 "brick" cells. This mesh is illustrated in Figure 4.2.

4.2.2.2 Mold Cavities

The dimensions of the simulated mold cavities including the solidified shell profile can be found in Figure 4.3. The shell thickness was calculated using CON1D [33], and the curves representing this thickness as a function of distance downward into the mold cavity on both the wide and narrow faces are shown in Figure 4.4. Because three separate SEN depths were studied, three separate mold cavities were meshed. About 50,000 hexahedral "brick" cells were used to mesh one quarter of each mold cavity. Figure 4.5 shows the mesh of the mold cavity for the 300mm SEN depth case. The meshes for the remaining two SEN depths are similar.

4.3 Solution Method and Convergence Strategy

The governing equations presented in Chapter 2 are discretized in FLUENT using an implicit, first-order upwinding scheme and the SIMPLE algorithm for pressure-velocity coupling [27]. FLUENT's segregated solver is used to solve the discretized equations in the following order. Initial conditions (if calculating the first iteration) or values from the previous iteration step are used to solve for the velocities in each cell using the conservation of momentum equations. The continuity equation is then imposed to correct any mass flow imbalances present in the cells. Turbulence equations are subsequently solved for *K* and ε , followed by the electromagnetic equations for the Lorentz force using the magnetic induction method. The calculated Lorentz force is then added into the momentum equations as a source term at the next iteration step.

Iteration toward a steady-state solution was achieved by reducing the under-relaxation factors in a manner that can be seen in Table 4.1. Under-relaxation factors are defined as follows [9]:

$$\phi = \phi_{old} + \alpha \Delta \phi \tag{4.5}$$

 α is the under-relaxation factor, ϕ is the value of a variable, i.e. pressure or x-velocity, to be used in the next iteration step, ϕ_{old} is the value of the variable from the previous iteration step, and $\Delta \phi$ is the difference between ϕ_{old} and the value of the variable calculated at the current iteration step. Large under-relaxation factors speed convergence, but also increase the chance of a divergent solution. For this reason, the under-relaxation factors were reduced as the simulations progressed in order to ease convergence.

Model convergence is determined by monitoring scaled residuals in FLUENT. Scaled residuals are defined for any variable ϕ as follows:

$$R^{\phi} = \frac{\sum_{cells} (RHS - LHS)_{discretized equation}}{\sum_{cells} LHS_{discretized equation}}$$
(4.6)

RHS and LHS represent "right-hand side" and "left-hand side," respectively.

This iterative procedure was continued until all of the residuals dropped below a convergence criterion that was set to 10^{-5} . Although FLUENT uses a default convergence value of 10^{-3} for all residuals, it was observed that the flow fields continued to change until a residual of at least 10^{-4} was met.

4.4 Model Validation

4.4.1 Flow Model Validation

Before accepting the results of any computational model, the model and code must be validated using previous experimental and/or numerical results to ensure that it is working properly. Rietow and Mahmood have both shown that solving the RANS equations and the K- ε turbulence model with FLUENT gives results that compare well to both time-averaged LES simulations and water model measurements compiled by Yuan [9, 30, 34]. The model for fluid flow using the FLUENT code is thus assumed to be accurate for the following simulations.

4.4.2 MHD Model Validation

4.4.2.1 Test Problem

To determine whether or not the Lorentz force and coupling equations using the FLUENT MHD module were being solved correctly, a simple test simulation was performed. The specific test problem, as well as the corresponding experimental and numerical data, was provided by Cho and Moreau [35]. The geometry is given in Figure 4.6. It consists of a 40mm-thick, infinitely wide channel with a constant magnetic field applied uniformly over a 304mm long rectangular region near its center. It was modeled with two thin layers of the same 3-D elements used in the real problem of interest in this work and a 704mm long domain. Material properties and boundary conditions can be found in Table 4.2. The domain was meshed in Gambit using a hexahedral mesh of 11,000 cells, which can be seen in Figure 4.8. The mesh was refined near the top and

bottom of the channel as well as near the edges of the region of applied magnetic field in order to capture the high velocities and steep gradients present at those locations.

4.4.2.2 Results

Figure 4.9 shows the results of the FLUENT simulation. They can be compared with the numerical results obtained by Cho, shown in Figure 4.7. The magnetic field induces a Lorentz force which appears at the edges of the region of magnetic field and opposes the flow. This force changes the shape of the velocity profile from fully-developed to "M-shaped" within the region of applied magnetic field. High velocities are observed near the channel walls and relatively low velocities are observed in the center of the channel. The vectors of Lorentz force qualitatively match well with the previous numerical results by Cho; however, no quantitative data was available to compare values of Lorentz force.

Quantitative analysis of the flow results was performed through comparison of the vertical domain centerline velocity profile among the previous numerical (Cho) and experimental (Moreau) results and the current results using the FLUENT MHD module. The velocity profiles of all three cases match well. An "M-shaped" profile is observed, with high velocities near the walls and relatively low velocities near the center of the channel. Because the results of this test problem agree with previously obtained numerical and experimental results, the fluid flow modeling procedure including the coupled effects of the applied electromagnetic field is assumed to be accurate for all simulations in this thesis.

4.5 Continuous Caster Simulation Details

Table 4.3 lists the relevant dimensions and operating conditions for all nozzle and mold cavity simulations. All simulations were performed on a PC with a 2.8GHz dual-core Intel Pentium IV processor and 2.0GB RAM. The nozzle simulation converged in about four hours and required approximately 1,100 iterations. The mold cavity simulations without the EMBr converged in about five hours and required approximately 3,700 iterations each, while the mold cavity simulations with the EMBr required about 24 hours and 20,000 iterations each to reach convergence. Convergence histories for the scaled residual errors of all cases can be found in Figures 4.10 (a) - (g).

4.6 Fluid Flow Results

4.6.1 Nozzle Flow

Velocity Contours

Figures 4.11 (a) and (b) show velocity contours on planes through the center of the SEN width and thickness, respectively. Velocity is relatively constant throughout the top half of the nozzle. However, this velocity doubles in magnitude (0.8m/s to 1.6m/s) as the nozzle's cylindrical cross-section is tapered into a thin, rectangular cross-section. This high velocity is maintained throughout the lower half of the nozzle until the flow exits the ports. Notice that the highest velocity gradients are seen near the walls, due to the no-slip boundary condition at those locations. Figure 4.11 (c) shows velocity contours at the right port. The highest velocity is found near the center of the port, and velocity decreases with radial distance from this point. Areas at the top and the bottom of the port

exhibit extremely low velocities and are zones of recirculation where fluid re-enters the nozzle.

Velocity Vectors

Figure 4.12 shows vectors of velocity on a plane through the center of the width of the lower SEN region and at the right outlet port. The fluid jets exiting the SEN approximately follow the angle of the ports (45° downward), but outward flow is not observed at every outlet location. The zones of recirculation are clearly seen at both the top and the bottom of the SEN ports. This recirculation might be beneficial, as it helps to prevent nozzle clogging [36]. Flow behavior in the nozzle well can also be observed. Flow velocity decreases rapidly as molten steel approaches the well. The steel then flows upward along the well wall, and joins the main jet exiting the nozzle.

Note on Symmetry

Because a time-averaged simulation was performed, twofold symmetry can be observed among the various nozzle results. This is expected for a steady-state simulation. It must be noted; however, that asymmetries may have been observed had a transient simulation been conducted on the entire nozzle and mold.

4.6.2 Mold Cavity Flow

Simulations of flow in the mold cavity are conducted for three different SEN depths both with and without the applied EMBr. Refer to Table 4.3 for descriptions of each of the six cases. The results are shown together for each SEN depth to aid comparisons.

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4.6.2.1 250mm SEN Depth: Case 1 - No EMBr and Case 2 - EMBr Applied

Magnetic Field Computations

Figure 4.13 shows contour plots of the applied magnetic field and the induced magnetic field for Case 2. The applied field is exactly the same as the field measured in Chapter 3 and seen in Figure 3.6. According to Equation 2.9, the magnitude of the induced field is proportional to the velocity magnitude in the mold cavity and the applied field. The induced field, therefore; is largest just beyond the SEN ports, which is where the largest velocities in the mold cavity enter the region of the applied field. The magnitude of the induced field then lowers as the jet moves through the applied field, dissipates, and impinges on the narrow face. An important observation regarding the induced field is its magnitude relative to the applied field. The maximum magnitude of the induced field (0.007T) is just 2% of the maximum value of the applied field (0.32T). Thus, the induced field does not have a significant impact on flow in the mold cavity, and the coupling between the flow equations and the electromagnetic equations is small.

Streamline Plots

Figure 4.14 shows streamline plots on the mold centerplane for Cases 1 and 2 to offer a macroscopic view of the flow pattern in the mold cavity. Both sets of streamlines exhibit the classic double-roll flow pattern. The jet exiting the nozzle travels across the mold cavity and, upon impingement on the narrow face, splits into upward and downward flowing "secondary" jets. This diverted flow creates the classic upper and lower recirculation zones of a double-roll flow pattern. In the upper recirculation zone, fluid flows up the narrow face, across the meniscus, and downward along the SEN wall,

usually rejoining the jet exiting the nozzle. In the lower recirculation zone, fluid flows down the narrow face, across the mold cavity width, and up the center of the mold cavity. The lower recirculation zones are much larger and less pronounced than the corresponding upper zones. This occurs because the size of the upper recirculation zone is constrained by the meniscus and the jet exiting the SEN. The lower recirculation zone, on the other hand, does not have a confined lower boundary. These phenomena can be observed in both streamline plots.

The addition of the EMBr causes the jet to impinge deeper into the mold cavity (490mm below the meniscus for Case 1 vs. 660mm below the meniscus for Case 2). This, in turn, causes the jet to impinge on the narrow face at a steeper downward angle, sending less fluid upward when the jet splits at the impingement point. It also creates a larger upper recirculation zone compared to the one seen without the EMBr applied. The strength of this zone is reduced due to the EMBr slowing velocities in that region. The net result is slower flow and less momentum near the top surface. The lower recirculation zone is also affected. It widens and shifts upward and to the left, and exhibits a shallower penetration into the mold cavity than the recirculation zone observed without the EMBr applied.

Velocity Vectors

Figure 4.15 shows vectors of velocity in the upper mold region for Cases 1 and 2. The boxes are drawn to give an idea of relative regions of the applied magnetic field to better compare the cases. The inner box represents a region where the average magnetic field is

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0.3T (area of strong magnetic field), while the outer box represents the extents of the applied magnetic field. The difference between the two cases is distinct. In Case 1, the jet exits the nozzle at a 45° angle and proceeds to flatten out halfway across the mold cavity width. The jet also exhibits an upward bend near the narrow face, caused by a low pressure area located in the center of the upper recirculation zone. The jet stays fairly consistent with minimal diffusion and impacts almost straight onto the narrow face with relatively high velocities. Much of the flow deflects upward so the upper recirculation zone is strong, with high velocities observed in the fluid moving upward along the narrow face, across the meniscus, and downward along the SEN walls.

The addition of the EMBr brings about a dramatic change in the flow pattern. The most obvious difference is the direction of the jet exiting the SEN and its impingement point on the narrow face (quantified in the *Streamlines* section). In Case 1, the jet flows through the bottom half of the inscribed inner box, which represents the region of strongest applied magnetic field in Case 2. Because the jet wants to flow through that region, the addition of the EMBr induces a large Lorentz force that opposes the flow. To satisfy continuity, the jet deflects downward, away from the center of the strong magnetic field. This can be seen in Figure 4.16 (a). The jet exits the SEN and proceeds to bend downward around the region of strong magnetic field. This creates a jet that does not flatten out as in Case 1 and an impingement point deeper into the mold cavity. Although it bends downward, the jet still passes through the bottom left corner of the region of high magnetic field, which leads to jet dissipation and loss of velocity, caused by the high Lorentz forces in this region. Figure 4.16 (b) illustrates the presence of high force caused

by the jet passing through this small area of strong magnetic field. Due to this loss of velocity and momentum in the jet, as well as the deeper impingement point, the upper recirculation zone is much weaker in this case than in Case 1. Relatively low velocities are observed everywhere in this region.

Lorentz Force Vectors

Figure 4.17 (a) shows vectors of Lorentz force colored by magnitude for Case 2. It is obvious that these forces are acting to oppose fluid velocity, thus effectively braking the flow. By looking at the governing equations, it is expected that the Lorentz force be the strongest in regions of high velocity and high magnetic field. This can be investigated by viewing Figures 4.17 (b) and (c), which show vectors of Lorentz force colored by applied field and velocity, respectively. The values of Lorentz force are relatively larger in areas of high applied field and high velocity than in other regions.

Comparison of Velocity at Various Distances below the Meniscus

Figure 4.18 shows a plot of velocity magnitude measured 10mm below the meniscus across the center of the wide face for both Case 1 and Case 2. Although the velocity profiles show a common trend, their magnitudes are different. The maximum velocity at the meniscus without the EMBr applied (Case 1) is 0.47m/s, while the maximum meniscus velocity with the EMBr applied (Case 2) is 0.18m/s, or 38% of the Case 1 value. This is mainly caused by the dissipation and downward diversion of the jet that occurs when it encounters the region of strong magnetic field. When the jet is diverted downward, it impacts the narrow face at a steeper angle than it does when EMBr is

applied. This steeper impingement angle will cause less fluid, and therefore momentum, to flow upward, which will decrease velocity and momentum in the upper recirculation zone and at the meniscus.

Figures 4.19-4.21 show plots of downward velocity measured 0.5m, 1.0m, and 1.5m below the meniscus across the center of the wide face, respectively. As seen in the plots of meniscus velocity, the profiles in each figure show common trends but have different magnitudes. Downward velocity at 0.5m below the meniscus is larger with the EMBr applied than without. This occurs because the application of the EMBr causes a downward deflection of the jet, thus increasing velocities in this region.

At 1.0m below the meniscus; however, a different trend is observed. Maximum downward velocity, which is located near the narrow face, is decreased by 50% when the EMBr is activated. The velocity profile is flatter with the EMBr on than without it, and exhibits almost equal width regions of upward flow (beneath the SEN) and downward flow (near the narrow face). This is indicative of a wide, relatively weak recirculation zone. With the EMBr off, on the other hand, the downward flow is biased toward the narrow face, and there is a relatively large region of upward flow.

The same trends are seen at 1.5m below the meniscus, though the region of upward flow at this depth is smaller than that seen at 1.0m below the meniscus both with and without the EMBr applied. This shows that the recirculation zone decreases in size as depth into the mold cavity increases. The decrease in maximum velocity near the narrow face is important because it reduces the penetration depth of possible inclusions, which, if entrapped, can cause defects in the final product [4].

Comparison of Meniscus Profiles

Figure 4.22 shows a plot of meniscus profiles for Cases 1 and 2 measured across the outer edge of the wide face. The profiles, or "standing waves", were calculated using the following approximation based on potential energy [34]:

$$Meniscus Height = \frac{P_{static} - \overline{P}_{static}}{\left(\rho_{steel} - \rho_{slag}\right)^* g}$$
(4.7)

where slag density, ρ_{slag} , is assumed to be 3000kg/m³. Standing wave height is defined as the absolute difference between the maximum meniscus profile height and the minimum meniscus profile height. The addition of the EMBr shrinks the standing wave height from 19.87mm (Case 1) to 3.51mm (Case 2). This great decrease in standing wave height occurs because of the decrease in pressure at the top surface caused by the application of the EMBr. The combination of the reduced velocities in the upper mold region and the loss of momentum and dissipation of the jet brought about by its passage through the magnetic field causes the pressure drop.

4.6.2.2 300mm SEN Depth: Case 3 - No EMBr and Case 4 - EMBr Applied

The effect of submergence depth was investigated in Cases 3 and 4 by repeating Cases 1 and 2 but lowering the submergence depth from 250mm to 300mm. The trends observed in comparing Cases 3 and 4 are the same as those found in the previous section, and will not be repeated. Contours of applied and induced magnetic field can be found in Figure 4.23. Streamlines can be observed in Figure 4.24. Velocity vectors can be seen in Figure

4.25 and 4.26. Figure 4.27 illustrates vectors of Lorentz force. Figures 4.28 through 4.31 show velocity profiles across the center of the wide face at the meniscus, 0.5m below the meniscus, 1.0m below the meniscus, and 1.5m below the meniscus, respectively, for both Cases 3 and 4. Figure 4.32 compares meniscus profiles for Cases 3 and 4.

4.6.2.3 350mm SEN Depth: Case 5 - No EMBr and Case 6 - EMBr Applied

The effect of submergence depth was investigated further in Cases 5 and 6 by repeating Cases 3 and 4 but lowering the submergence depth from 300mm to 350mm. The trends observed in comparing Cases 5 and 6 are the same as those found in the previous two sections, and will not be repeated. Contours of applied and induced magnetic field can be found in Figure 4.33. Streamlines can be observed in Figure 4.34. Velocity vectors can be seen in Figure 4.35 and 4.36. Figure 4.37 illustrates vectors of Lorentz force. Figures 4.38 through 4.41 show velocity profiles across the center of the wide face at the meniscus, 0.5m below the meniscus, 1.0m below the meniscus, and 1.5m below the meniscus, respectively, for both Cases 5 and 6. Figure 4.42 compares meniscus profiles for Cases 5 and 6.

4.6.3 Effect of Submergence Depth with and without EMBr

The results from all six simulations are evaluated in this section. Table 4.4 compiles the significant comparative data for the six cases.

4.6.3.1 Meniscus Velocity Comparison

Figure 4.43 is a compilation of all meniscus velocity plots for each of the six mold cavity simulations. It can be observed that for all three SEN depths, meniscus velocity decreases with the addition of the EMBr. Figure 4.44 plots maximum meniscus velocity versus SEN depth for cases with and without the EMBr applied. The general trend for the cases without the EMBr is that meniscus velocity decreases as SEN depth increases. A deeper SEN depth will cause a deeper impingement point, which will give fluid more time to slow down as it flows upward along the narrow face into the upper recirculation zone. A deeper impingement point also means that the jet exiting the SEN has to travel a further distance to the narrow face compared to a jet with a shallow impingement point, thus increasing the chance that the jet will dissipate and lose velocity.

The trend is directly opposite when the EMBr is applied; meniscus velocity increases as SEN depth increases. This trend is caused by the change in location of the SEN ports relative to the location of the applied EMBr field, which does not change with SEN depth. Initially, when at a 250mm SEN depth, the jet tends to flow directly through the bottom half of the region of strong magnetic field with the EMBr off, and therefore encounters a large Lorentz force that diverts, slows, and dissipates the jet. Thus, the jet tends to flow below the area of strong magnetic field, encountering less magnetic force with increasing depth. This can be seen in Figures 15, 25, and 35. With less flow through the inner box (area of strong magnetic field), both the amount and magnitude of forces acting to divert, slow, and dissipate the jet become smaller. Because the jet avoids the strong braking

region and experiences a relatively small amount of braking force, it is less altered, thus leading to the higher meniscus velocities as SEN depth increases.

4.6.3.2 Comparison of Downward Velocities at Various Depths

Figures 4.45 through 4.47 show velocity profiles across the center of the wide face at 0.5m below the meniscus, 1.0m below the meniscus, and 1.5m below the meniscus, respectively, for all simulated cases. At all three depths below the meniscus, velocity generally increases as SEN depth increases without the EMBr. This happens because the jet itself is lower in the caster at deeper submergence depths. The same trend is observed with the EMBr applied; overall velocity increases as SEN depth increases.

Studying the differences between the velocity profiles at a given submergence depth yields more intriguing results. As SEN depth increases, the difference between the velocity profiles decreases; i.e. the velocity profiles at the 350mm submergence depth are nearly identical, while the profiles at the 250mm submergence depth are quite different. This occurs because as SEN depth increases with the EMBr applied, the jets, and therefore the velocities, are less altered.

4.6.3.3 Meniscus Profile Comparison

Figure 4.48 is a compilation of the meniscus profile plots for all six of the mold cavity simulations. It can be observed that for all SEN depths, standing wave height decreases with the addition of the EMBr. Figure 4.49 plots standing wave height versus SEN depth for cases with and without the EMBr applied. The general trend for the cases without the

EMBr is that standing wave height decreases slightly as SEN depth increases. This slight difference in meniscus profile was also observed by Creech [37]. This occurs because of the deeper jet impingement, decreasing upward flow, and slower meniscus velocity that follows an increase in SEN depth.

Again, the trend is reversed for the cases with the EMBr applied; standing wave height increases as SEN depth increases. This happens for the same reasons stated in the previous section. The jet encounters less of the region of strong magnetic field as SEN depth increases, thus inducing less Lorentz forces to slow, divert, and dissipate the jet. This less-affected jet will cause more momentum to flow upward into the upper recirculation zone, which will increase velocity and pressure at the meniscus and expand the height differences in the meniscus profile. The profiles are still always much flatter with the EMBr applied than without it for any depth.

4.6.3.4 Impingement Point Comparison

Figure 4.50 shows a plot of impingement point versus SEN depth for cases with and without the EMBr applied. It can be observed that for all SEN depths, the jet impinges deeper into the mold cavity with the addition of the EMBr. Without the EMBr applied, the jet impinges deeper as SEN depth increases, which is expected. With the EMBr applied, impingement point decreases from the 250mm SEN depth to the 300mm SEN depth.

4.7 Summary

Flow in the Nucor nozzle and mold cavity for three SEN depths both with and without the EMBr applied was simulated using FLUENT. The following observations were made:

Addition of the EMBr causes:

- An induced magnetic field $\sim 2\%$ of the value of the applied magnetic field
- Deeper jet impingement
- Increased jet dissipation
- Steeper jet angle at narrow face
- Expanded upper recirculation zone
- Widening and upward shift of the lower recirculation zone
- Shallower penetration of the lower recirculation zone
- Reduced velocity at the meniscus and throughout the upper recirculation zone
- Reduced velocity and flatter velocity profiles at depths greater than 1.0m
- Smaller standing wave height at the meniscus

Increasing SEN depth with the EMBr off causes:

- Expanded upper recirculation zone
- Steeper jet angle at the narrow face
- Decrease in meniscus velocity
- Smaller standing wave height at the meniscus
- Relatively continuous increase in jet impingement depth
- Increase in downward velocity at depths larger than 0.5m into the mold cavity
- Deeper penetration of lower recirculation zone

Increasing SEN depth with the EMBr on causes:

- Expanded upper recirculation zone
- Increase in meniscus velocity
- Larger standing wave height at the meniscus
- Increase in downward velocity at depths larger than 0.5m into the mold cavity
- Deeper penetration of lower recirculation zone

4.8 Tables and Figures

| | B_z | 1 | 1 | 1 | 0.8 | 0.7 | 0.5 |
|--------------|----------------------------------|-----|--------------|--------------|-----|------|-------|
| | B_y | 1 | 1 | 1 | 0.8 | 0.7 | 0.5 |
| | B_x | 1 | 1 | 1 | 0.8 | 0.7 | 0.5 |
| | Turbulent Viscosity | 1 | 0.8 | 0.7 | 0.6 | 0.5 | 0.4 |
| Factor | Turbulent Dissipation Rate | 1 | 0.7 | 0.6 | 0.6 | 0.5 | 0.4 |
| r-Relaxation | Turbulent Kinetic Energy | 8.0 | 0.7 | 9.0 | 9.0 | 0.5 | 0.4 |
| Unde | Momentum | 0.6 | 0.5 | 0.4 | 0.4 | 0.4 | 0.4 |
| | Body Force | 8.0 | L^{0} | L^{0} | 9.0 | 5.0 | 0.4 |
| | Density | 8.0 | $L^{\cdot}0$ | $L^{\cdot}0$ | 9.0 | 5.0 | 0.4 |
| | Pressure | 0.5 | 0.5 | 0.5 | 0.5 | 0.4 | 0.3 |
| | Iteration | 1 | 40 | 160 | 220 | 3000 | 10000 |

Table 4.1: Under-relaxation factor strategy

Table 4.2: Material properties and boundary conditions for MHD test case

| ρ | 13550kg/m ³ |
|------------------|--|
| h | 0.00155825kg/m- |
| U | $1.05E+06(\Omega-m)^{-1}$ |
| Vinlet | 1.16141m/s |
| Kinlet | $5.99 \text{E} - 05 \text{m}^2/\text{s}^2$ |
| Einlet | $7.529E-05m^{2}/s^{3}$ |
| Pgauge, outlet | 0MPa |
| \mathbf{B}_{0} | 1.3483T |

Table 4.3: Simulation parameters (a) for all cases and (b) variations by case

(a)

| v _{cast} (m/min) | 3.3 |
|---|---------|
| Mold Width (mm) | 687 |
| Mold Thickness (mm) | 06 |
| Mold Length (mm) | 2500 |
| ρ _{steel} (kg/m ³) | 7000 |
| ρ _{slag} (kg/m ³) | 3000 |
| μ (kg/m-s) | 0.006 |
| σ (Ω-m) ⁻¹ | 714,000 |
| Gravity (m/s ²) | 9.81 |

| | | (q) | |
|-----|--------|----------------------|------------------------|
| | | Paran | neter |
| | | SEN Depth (mm) | EMBr Setting (T) |
| | Case 1 | 250 | 0 |
| | Case 2 | 250 | 0.355 |
| 201 | Case 3 | 300 | 0 |
| - | Case 4 | 300 | 0.355 |
| | Case 5 | 350 | 0 |
| | Case 6 | 350 | 0.355 |

Table 4.4: Mold cavity simulation results

| | Maximum Meniscus Velocity (m/s) | Standing Wave Height (mm) | Impingement Point (mm below meniscus) |
|--------|------------------------------------|------------------------------|--|
| Case 1 | 0.48 | 19.9 | 490 |
| Case 2 | 0.19 | 3.5 | 660 |
| Case 3 | 0.44 | 20.0 | 560 |
| Case 4 | 0.24 | 5.3 | 700 |
| Case 5 | 0.41 | 19.3 | 620 |
| Case 6 | 0.28 | 9°L | 700 |



Figure 4.1: Nucor nozzle dimensions



Figure 4.2: Nucor nozzle mesh (a) full front view, (b) top view, (c) bottom view, (d) isometric port view, and (e) zoom front view at outlet



Figure 4.3: One-quarter mold cavity dimensions



Figure 4.4: Shell thickness profiles from CON1D [33]


Figure 4.5: One-quarter mold cavity mesh for 300mm SEN depth



Figure 4.6: Geometry of MHD model validation case



Figure 4.7: Previous MHD test case results (a) vectors of Lorentz force and (b) velocity profiles at selected locations



Figure 4.8: Mesh used for MHD test case



Figure 4.9: MHD test case results using FLUENT (a) vectors of Lorentz force and (b) comparison of vertical centerline velocity profile with previous numerical and experimental results



Figure 4.10: Convergence plots for (a) nozzle, (b) Case 1, (c) Case 2, (d) Case 3, (e) Case 4, (f) Case 5, and (g) Case 6



Figure 4.10 (cont'd): Convergence plots for (a) nozzle, (b) Case 1, (c) Case 2, (d) Case 3, (e) Case 4, (f) Case 5, and (g) Case 6



Figure 4.10 (cont'd): Convergence plots for (a) nozzle, (b) Case 1, (c) Case 2, (d) Case 3, (e) Case 4, (f) Case 5, and (g) Case 6















Note: Unless specified otherwise, the following streamline, contour, and vector plots are viewed

Figure 4.13: Contours of (a) applied and (b) induced magnetic field for Case 2



Figure 4.14: Streamline plots for (a) Case 1 and (b) Case 2



















Figure 4.18: Comparison of velocities 10mm below the meniscus across the center of the wide face for Cases 1 and 2



Figure 4.19: Comparison of velocities 500mm below the meniscus across the center of the wide face for Cases 1 and 2



Figure 4.20: Comparison of velocities 1m below the meniscus across the center of the wide face for Cases 1 and 2



Figure 4.21: Comparison of velocities 1.5m below the meniscus across the center of the wide face for Cases 1 and 2







Figure 4.23: Contours of (a) applied and (b) induced magnetic field for Case 4



Figure 4.24: Streamline plots for (a) Case 3 and (b) Case 4















Figure 4.27 (cont'd): Vectors of Lorentz force for Case 4 colored by (a) magnitude, (b) applied magnetic field, and (c) velocity



Figure 4.28: Comparison of velocities 10mm below the meniscus across the center of the wide face for Cases 3 and 4



Figure 4.29: Comparison of velocities 500mm below the meniscus across the center of the wide face for Cases 3 and 4



Figure 4.30: Comparison of velocities 1m below the meniscus across the center of the wide face for Cases 3 and 4



Figure 4.31: Comparison of velocities 1.5m below the meniscus across the center of the wide face for Cases 3 and 4



Figure 4.32: Comparison of meniscus profiles across the outer edge of the wide face for Cases 3 and 4



Figure 4.33: Contours of (a) applied and (b) induced magnetic field for Case 6

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Figure 4.34: Streamline plots for (a) Case 3 and (b) Case 6



Note: Inner box encloses an area with an average magnetic field of 0.3T, and outer box represents extents of applied field. Figure 4.35: Velocity vectors (a) Case 5 and (b) Case 6















Figure 4.38: Comparison of velocities 10mm below the meniscus across the center of the wide face for Cases 5 and 6



Figure 4.39: Comparison of velocities 500mm below the meniscus across the center of the wide face for Cases 5 and 6



Figure 4.40: Comparison of velocities 1m below the meniscus across the center of the wide face for Cases 5 and 6



Figure 4.41: Comparison of velocities 1.5m below the meniscus across the center of the wide face for Cases 5 and 6



Figure 4.43: Meniscus velocities of all cases


Figure 4.44: Plot of meniscus velocity vs. SEN depth both with and without EMBr



Figure 4.45: Comparison of velocities 500mm below the meniscus across the center of the wide face for all cases



Figure 4.46: Comparison of velocities 1m below the meniscus across the center of the wide face for all cases



Figure 4.47: Comparison of velocities 1.5m below the meniscus across the center of the wide face for all cases







Figure 4.49: Plot of standing wave height vs. SEN depth both with and without EMBr



Figure 4.50: Plot of impingement point vs. SEN depth both with and without EMBr

CHAPTER 5: VALIDATION OF COMPUTATIONAL RESULTS WITH EXPERIMENTAL DATA

5.1 Nail Board Validation

Using a correlation by Rietow, the nail board dip test performed in Chapter 3 was used to estimate meniscus velocity [30]. Figure 5.1 shows a correlation between knob height difference and velocity at the meniscus; once knob height difference is known, meniscus velocity can be found from the graph. An example of how knob height difference was determined can be found in Figure 5.2. Zoomed photographs of each nail were taken, along with a ruler for scaling and measuring purposes. From these photos, knob height difference was accurately measured using the ruler, and correlated to meniscus velocity. Table 5.1 documents each knob height difference and corresponding velocity. The velocities at each nail were then plotted versus distance from the SEN. This velocity profile can be seen in Figure 5.3, which also shows the meniscus velocity profile obtained in FLUENT for the same casting conditions (Case 4). The numerical results show surprisingly good matching with the experimental results both near the narrow face and near the SEN. Negative velocity is measured for one nail near the center of the meniscus, which indicates that flow was swirling or flowing toward the narrow face at that point. This is a transient effect that cannot be simulated by the steady-state model. Both the shape of the velocity profile and the magnitude of the velocities are consistent between both plots.

5.2 Oscillation Mark Validation

Validation with experimental data was also obtained by comparing oscillation marks found on the finished steel slab with the calculated meniscus profile found using FLUENT for the same casting conditions (Case 4). Figure 5.4 shows the comparison of the calculated meniscus profile with eight separate oscillation marks. The oscillation marks were placed on the graph such that the total "area under the curve" of each oscillation mark is equal to zero. The shape of the calculated profile roughly matches that of the oscillation marks. The trend of a high wave at the narrow face that slopes downward and stabilizes about halfway across the wide face before sloping slightly upward near the SEN is witnessed in both the experimental and numerical cases. The scale of the numerically calculated profile also matches that of the oscillation marks. One reason there is not exact matching is that the oscillation marks are transient by nature, as one mark is made during each mold oscillation cycle. This transience is apparent when viewing all eight oscillation marks; each mark has different characteristics. Table 5.2 shows the standing wave height of each oscillation mark, as well as the average standing wave height of the oscillation marks and the corresponding computational result (Case 4). The transience among the oscillation marks is again seen here, as the standing wave heights range from a minimum of 2.25mm to a maximum of 6.0mm. However, the average standing wave height of the oscillation marks is 4.41mm, which is only 0.85mm smaller than the calculated time-averaged standing wave height from FLUENT (5.26mm). This shows that the model can roughly predict the average, both qualitatively and quantitatively, which is the best that can be expected from a steady-state model.

5.3 Tables and Figures

| Nail Distance from Narrow Face (mm) | Knob Height Difference (mm) | Velocity Magnitude (m/s) |
|---|-----------------------------------|--------------------------------|
| 117 | 2 | 0.23 |
| 167 | 2.5 | 0.25 |
| 217 | 3 | 0.26 |
| 267 | 2.5 | 0.25 |
| 317 | 2 | 0.23 |
| 367 | 0 | 0 |
| 417 | -1.5 | -0.22 |
| 467 | 1 | 0.20 |
| 517 | 0.5 | 0.13 |
| 567 | 0 | 0 |

Table 5.1: Correlation of knob height difference to velocity magnitude

Table 5.2: Standing wave heights of oscillation marks

| Oscillation Mark | Standing Wave Height (mm) |
|-----------------------------|------------------------------|
| 1 | 3.75 |
| 2 | 5.25 |
| 3 | 6.0 |
| 4 | 4.0 |
| 5 | 2.25 |
| 6 | 4.0 |
| 7 | 4.25 |
| 8 | 5.75 |
| Oscillation Mark Average | 4.41 |
| CFD Result (Case 4) | 5.26 |



Figure 5.1: Correlation of knob height difference to meniscus velocity [30]



Figure 5.2: Example of how knob height difference is determined



Figure 5.3: Comparison of calculated meniscus velocity with meniscus velocity obtained from nail board measurements



Figure 5.4: Comparison of calculated meniscus profile with oscillation marks

CHAPTER 6: CONCULSIONS AND RECOMMENDATIONS

6.1 Conclusions

Fluid flow in a continuous casting nozzle and mold cavity under an electromagnetic brake was investigated. The three-dimensional, time-averaged, inviscid Navier-Stokes equations with the K- ε turbulence model were solved using FLUENT. The EMBr field at Nucor Steel in Decatur, AL was measured for use in the mold cavity simulations. The FLUENT MHD module employing the magnetic induction method was used to incorporate this electromagnetic field and to solve the corresponding equations. The model and solution method were validated by comparing the results of a test case with previous experimental and numerical data. The effect of the addition of an EMBr and varying SEN depth on mold cavity flow was studied, resulting in the following observations.

Addition of the EMBr causes:

- An induced magnetic field $\sim 2\%$ of the value of the applied magnetic field
- Deeper jet impingement
- Increased jet dissipation
- Steeper jet angle at narrow face
- Expanded upper recirculation zone
- Widening and upward shift of the lower recirculation zone
- Shallower penetration of the lower recirculation zone
- Reduced velocity at the meniscus and throughout the upper recirculation zone
- Reduced velocity and flatter velocity profiles at depths greater than 1.0m
- Smaller standing wave height at the meniscus

Increasing SEN depth with the EMBr off causes:

- Expanded upper recirculation zone
- Steeper jet angle at the narrow face
- Decrease in meniscus velocity
- Smaller standing wave height at the meniscus
- Relatively continuous increase in jet impingement depth
- Increase in downward velocity at depths larger than 0.5m into the mold cavity
- Deeper penetration of lower recirculation zone

Increasing SEN depth with the EMBr on causes:

- Expanded upper recirculation zone
- Increase in meniscus velocity
- Larger standing wave height at the meniscus
- Increase in downward velocity at depths larger than 0.5m into the mold cavity
- Deeper penetration of lower recirculation zone

Further validation was performed by comparing computational results to experimental data collected at Nucor Steel. A nail board dip test was performed, and gave a velocity profile at the meniscus, which matched numerical results well in both shape and magnitude. Oscillation marks were photographed from sandblasted slab crops, and roughly matched with the calculated meniscus profile.

6.2 Future Work

There are many phenomena that can be added to these simulations to better understand the continuous casting process. Argon bubbles or particles (inclusions) can be added to see how the

use of an EMBr affects their flow throughout the nozzle and the mold cavity. An LES simulation can be performed to see the effect an EMBr has on transient flow in the mold cavity. LES can also be used to study electromagnetic stirring and compare its effect on mold cavity flow to that caused by EMBr. Finally, modeling can be applied to investigate and optimize the application of electromagnetic forces, including those utilized in MM-EMS and FC-Mold EMBr.

APPENDIX A.1: Mass/Momentum Sink Derivation

The following implementation of mass and momentum sink elements along the shell wall boundaries was first derived by Creech [37], who showed that velocities in the caster are significantly affected by the losses of mass and momentum inherent in shell solidification. Rietow adapted Creech's method to incorporate the downward movement of the shell caused by the constant extraction of the strand from the mold [30].

The schematic of the shell and sink elements is shown in Figure A.1 [30]. The amount of mass and momentum to be removed at the wall is calculated using the physical dimensions of the shell element, while the loss will occur in FLUENT within the attached sink element. The sink elements are thin (0.1mm) in order to minimize their effect on the fluid flow in the mold. A noslip wall boundary condition is prescribed on face A_s , with the *y*-velocity set to the casting speed. The *x* and *z*-velocities equal zero at face A_s to prevent fluid from passing through the solid wall. Note that all faces in the model are approximated by flat surfaces, which is reasonable if enough cells are used in the mesh to approximate the curved shell.



Figure A.1: Schematics for the shell and sink elements [30]

Conservation of mass will be used as follows to determine the amount of mass removed [30]:

$$\dot{m}_i - \dot{m}_o = \dot{S}_{mass} \tag{A.1}$$

$$\left[A_{t}V_{c}\right] - \left[A_{b}V_{c}\right] = \dot{S}_{mass} \tag{A.2}$$

$$\left[\Delta S_1 \Delta w V_c \rho_{steel,solid}\right] - \left[\Delta S_2 \Delta w V_c \rho_{steel,solid} + \Delta S_3 \Delta w V_c \rho_{steel,solid}\right] = \dot{S}_{mass}$$
(A.3)

 \dot{S}_{mass} represents the mass flowing through surface $A_{s.}$ The lengths ΔS_2 and ΔS_3 can be reduced into the following components [30]:

$$\Delta S_2 = \Delta S_1 - \Delta H_m \sin(90 - \theta_2) \tag{A.4}$$

$$\Delta S_3 = \Delta L \sin(\theta_1) \tag{A.5}$$

Inputting Equations A.4 and A.5 into Equation A.3, the simplified equation becomes [30]:

$$\Delta H_m \Delta w \sin(90 - \theta_2) V_c \rho_{steel, solid} - \Delta L \Delta w \sin(\theta_1) V_c \rho_{steel, solid} = \dot{S}_{mass}$$
(A.6)

$$V_c \rho_{steel,solid} \left(\Delta H_m \Delta w \sin(90 - \theta_2) - \Delta L \Delta w \sin(\theta_1) \right) = \dot{S}_{mass}$$
(A.7)

In effort to relate Equation A.7 to the surface projections in the *y*-direction, the following equations are used:

$$N_{A_s \to y} = A_s \sin \theta_1 = \Delta L \Delta w \sin(\theta_1)$$
(A.8)

$$N_{A_w \to y} = A_w \sin(90 - \theta_2) = \Delta H_m \Delta w \sin(90 - \theta_2)$$
(A.9)

Substituting in Equations A.8 and A.9 and simplifying, Equation A.7 becomes:

$$\dot{S}_{mass} = V_c \rho_{steel,solid} \left(N_{A_w \to y} - N_{A_s \to y} \right)$$
(A.10)

The momentum sink amount is a simple extension of the mass sink amount, as momentum equals mass times velocity. Using an iterative process, the mass sink amount determines the steel velocity through the element surface. This velocity is subsequently coupled with the mass source term (which determines the mass flow rate through the surface) to calculate the momentum loss [30]:

$$\dot{S}_{momentum} = V_N \dot{S}_{mass} = V_N V_c \rho_{steel,solid} \left(N_{A_w \to y} - N_{A_s \to y} \right)$$
(A.11)

The normal projection in the *y*-direction for the shell surface (A_s) will always be larger than that for the mold wall (A_w) . Because all other terms are positive, the source terms will be negative, becoming "sinks" rather than "sources". Refer to Appendix A.2.2 for the Fluent UDF.

APPENDIX A.2.1: Nozzle Inlet Velocity Profile FLUENT UDF Adapted from

Mahmood [9] and Rietow [30]

Below is the UDF used to compute the nozzle inlet velocity profile in FLUENT. This

UDF solves Equation 4.4 for all cells at the nozzle inlet boundary. Notice that in order to

run this UDF, values of v_{maz} and n must first be computed for a given nozzle using

Equations 4.1-4.3.

#include "udf.h" #include "math.h" #define vmax 3.24//maximum nozzle velocity [m] #define r 0.0575//nozzle bore radius [m] #define n 8.45//empirical constant //NOTE that numerical values above should be replaced with values corresponding to the //nozzle under current consideration DEFINE PROFILE(inlet z velocity, thread, position) { real coord[3]; /* this will hold the position vector */ face t f; real x,y; begin f loop(f, thread) F CENTROID(coord,f,thread); x = coord[0];y = coord[1];F PROFILE(f, thread, position) = -vmax*pow((1-(pow((x*x+y*y),0.5))/r),(1/n));/*Message("%d \t %d \t %d\n", x,y,f);*/ end f loop(f, thread) }

APPENDIX A.2.2: Mass/Momentum Sink FLUENT UDF Adapted from

Mahmood [9] and Rietow [30]

#include "udf.h" #include "math.h" #include "sg.h" #define density 7800 //solid steel density [kg/m3] #define castingspeed .055 //[m/s] #define nx s 35 #define ny s 37 #define py s 36 #define nx i 51 #define ny i 50 #define py i 49 #define nx w 23 #define ny w 25 #define py w 24 DEFINE SOURCE(mass source ny,c,t,dS,eqn) { real A1[ND ND],A2[ND ND],X[ND_ND],xx,yy,zz; real source; real x s,y s,z s,x w,y w,z w,ds,es[ND ND],A by es,dr0[ND ND],dr1[ND ND]; int n,nn; face t f, ff; cell t c0, c1, cn;Thread *tf, *t0, *t1, *tn, *tff; C CENTROID(X,c,t); xx=X[0];yy=X[1]; zz=X[2];c face loop(c,t,n){ f = C FACE(c,t,n);tf = C FACE THREAD(c,t,n); if (THREAD ID(C FACE THREAD(c,t,n)) == ny s){ F AREA(A1,f,tf); x s = A1[0]/NV MAG(A1);y = A1[1]/NV MAG(A1);z s = A1[2]/NV MAG(A1);else if (THREAD ID(C FACE THREAD(c,t,n)) == ny i){ c0 = F CO(f,tf);c1 = F C1(f,tf);t0 = THREAD TO(tf);t1 = THREAD T1(tf);if (c0 == c){

```
cn = c1;
tn = t1;
else {
cn = c0;
tn = t0;
c face loop(cn,tn,nn){
f = C FACE(cn,tn,nn);
tf = C FACE THREAD(cn,tn,nn);
if(THREAD ID(C FACE THREAD(cn,tn,nn)) == ny w){
//Message("%i\t\n",THREAD ID(C FACE THREAD(cn,tn,nn)));
F AREA(A2,f,tf);
x w = A2[0]/NV MAG(A2);
y w = A2[1]/NV MAG(A2);
z w = A2[2]/NV MAG(A2);
source = -density*castingspeed*(fabs(z \ s)-fabs(z \ w))*NV MAG(A1)/C VOLUME(c,t);
dS[eqn]=0;
return source;
return dS[eqn];
ł
DEFINE SOURCE(xmom source ny,c,t,dS,eqn)
{ real A1[ND ND],A2[ND ND],X[ND ND],xx,yy,zz;
real source;
real x s,y s,z s,x w,y w,z w,ds,es[ND ND],A by es,dr0[ND ND],dr1[ND ND];
int n,nn;
face t f, ff;
cell t c0, c1, cn;
Thread *tf, *t0, *t1, *tn, *tff;
C CENTROID(X,c,t);
xx = X[0];
yy=X[1];
zz=X[2];
c face loop(c,t,n){
f = C FACE(c,t,n);
tf = C FACE THREAD(c,t,n);
if(THREAD ID(C FACE THREAD(c,t,n)) == ny s){
F AREA(A1,f,tf);
x s = A1[0]/NV MAG(A1);
y = A1[1]/NV MAG(A1);
z = A1[2]/NV MAG(A1);
else if (THREAD ID(C FACE THREAD(c,t,n)) == ny i){
c0 = F CO(f,tf);
c1 = F C1(f,tf);
```

```
t0 = THREAD TO(tf);
t1 = THREAD T1(tf);
if (c0 == c){
cn = c1;
tn = t1;
else {
cn = c0;
tn = t0;
c face loop(cn,tn,nn){
f = C FACE(cn,tn,nn);
tf = C FACE THREAD(cn,tn,nn);
if(THREAD ID(C FACE THREAD(cn,tn,nn)) == ny w){
//Message("%i\t\n",THREAD ID(C FACE THREAD(cn,tn,nn)));
F AREA(A2,f,tf);
x w = A2[0]/NV MAG(A2);
y = A2[1]/NV MAG(A2);
z w = A2[2]/NV MAG(A2);
source = -\text{density}^{*}castingspeed*(fabs(z s)-
fabs(z w))*NV MAG(A1)/C VOLUME(c,t)*fabs(C U(c,t));
dS[eqn] = -density*castingspeed*(fabs(z s)-
fabs(z w))*NV MAG(A1)/C VOLUME(c,t);
return source;
return dS[eqn];
}
DEFINE SOURCE(ymom source ny,c,t,dS,eqn)
{ real A1[ND ND],A2[ND ND],X[ND ND],xx,yy,zz;
real source:
real x s,y s,z s,x w,y w,z w,ds,es[ND ND],A by es,dr0[ND ND],dr1[ND ND];
int n,nn;
face t f, ff;
cell t c0, c1, cn;
Thread *tf, *t0, *t1, *tn, *tff;
C CENTROID(X,c,t);
xx=X[0];
yy=X[1];
zz=X[2];
c face loop(c,t,n){
f = C FACE(c,t,n);
tf = C FACE THREAD(c,t,n);
if (THREAD ID(C FACE THREAD(c,t,n)) == ny s){
F AREA(A1,f,tf);
x s = A1[0]/NV MAG(A1);
```

```
y s = A1[1]/NV MAG(A1);
z = A1[2]/NV MAG(A1);
else if (THREAD ID(C FACE THREAD(c,t,n)) == ny i){
c0 = F CO(f,tf);
c1 = F C1(f,tf);
t0 = THREAD TO(tf);
t1 = THREAD T1(tf);
if (c0 == c){
cn = c1;
tn = t1;
else {
cn = c0;
tn = t0;
c face loop(cn,tn,nn){
f = C FACE(cn,tn,nn);
tf = C FACE THREAD(cn,tn,nn);
if(THREAD ID(C FACE THREAD(cn,tn,nn)) == ny w){
//Message("%i\t\n",THREAD ID(C FACE THREAD(cn,tn,nn)));
F AREA(A2,f,tf);
x w = A2[0]/NV MAG(A2);
y = A2[1]/NV MAG(A2);
z w = A2[2]/NV MAG(A2);
source = -density*castingspeed*(fabs(z s)-
fabs(z w))*NV MAG(A1)/C VOLUME(c,t)*fabs(C V(c,t));
dS[eqn] = -density*castingspeed*(fabs(z s)-
fabs(z w))*NV MAG(A1)/C VOLUME(c,t);
return source;
return dS[eqn];
DEFINE SOURCE(zmom source ny,c,t,dS,eqn)
{ real A1[ND ND],A2[ND ND],X[ND ND],xx,yy,zz;
real source;
real x s,y s,z s,x w,y w,z w,ds,es[ND ND],A by es,dr0[ND ND],dr1[ND ND];
int n,nn;
face t f, ff;
cell t c0, c1, cn;
Thread *tf, *t0, *t1, *tn, *tff;
C CENTROID(X,c,t);
xx = X[0];
yy=X[1];
zz=X[2];
c face loop(c,t,n){
```

```
f = C FACE(c,t,n);
tf = C FACE THREAD(c,t,n);
if(THREAD ID(C FACE THREAD(c,t,n)) == ny s){
F AREA(A1,f,tf);
x s = A1[0]/NV MAG(A1);
y s = A1[1]/NV MAG(A1);
z = A1[2]/NV MAG(A1);
else if (THREAD_ID(C_FACE_THREAD(c,t,n)) == ny_i)
c0 = F CO(f,tf);
c1 = F C1(f,tf);
t0 = THREAD TO(tf);
t1 = THREAD T1(tf);
if (c0 == c){
cn = c1;
tn = t1;
else {
cn = c0;
tn = t0;
c face loop(cn,tn,nn){
f = C FACE(cn,tn,nn);
tf = C FACE THREAD(cn,tn,nn);
if(THREAD ID(C FACE THREAD(cn,tn,nn)) == ny w){
//Message("%i\t\n",THREAD ID(C FACE THREAD(cn,tn,nn)));
F AREA(A2,f,tf);
x w = A2[0]/NV MAG(A2);
y = A2[1]/NV MAG(A2);
z w = A2[2]/NV MAG(A2);
source = -density*castingspeed*(fabs(z s)-
fabs(z w))*NV MAG(A1)/C VOLUME(c,t)*fabs(C W(c,t));
dS[eqn] = -density*castingspeed*(fabs(z s))-
fabs(z w))*NV MAG(A1)/C VOLUME(c,t);
return source;
return dS[eqn];
```

```
}
```

APPENDIX B.1: Magnetic Field Input Format

The applied magnetic field is input as a text file (*.txt) and has the following format [27] (note that comments in parenthesis are not part of the format, and are used to explain terms):

MAG-DATA (file name)nXnYnZ (number of data points in x, y, and z directions)X1 (minimum value of x)Xn (maximum value of x)Y1 (minimum value of y)Yn (maximum value of y)Z1 (minimum value of z)Zn (maximum value of z)(Note that data points are assumed to be evenly distributed along each direction)nAC (=0 if DC current, =1 if AC current)Freq (frequency in Hz if nAC=1) BX_{re-1} BZ_{re-1} BZ_{re-1} BZ_{im-1} BX_{re-n} BZ_{re-n} BZ_{im-n} BZ_{im-n} (last magnetic field data point)

Imaginary components are only necessary for AC fields, and are set to zero if a DC field is being used. The data points are indexed as [27]:

$$i = 1,...,nX; j = 1,...,nY; k = 1,...,nZ$$

Data point = $i + nX((j-1) + nY(k-1))$

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