A Coupled Thermal – Fluid Flow Model of the Horizontal Direct Chill Casting Process for T-Ingot

by
Malcolm D. Lane
B.A.Sc. The University of British Columbia, 2004

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF APPLIED SCIENCE
in
THE FACULTY OF GRADUATE STUDIES
(Materials Engineering)

THE UNIVERSITY OF BRITISH COLUMBIA

March 2007
©Malcolm Lane, 2007
Abstract

In recent years, Horizontal Direct Chill (HDC) casting has gained popularity as a method for processing primary aluminum. In an attempt to further develop the knowledge and understanding necessary to enhance HDC casting capabilities in industry and improve its economic viability, a coupled thermal-fluid flow model of T-ingot casting has been developed. The model, developed using the commercial computational fluid dynamics software, ANSYS CFX-10.0, predicts the temperature and flow fields which occur during aluminum T-ingot HDC casting under steady-state operational conditions. Buoyancy, turbulence, solidification effects including flow damping and latent heat release, and boundary conditions were accounted for using methods that represent the physics occurring in the industrial process.

Predictions for HDC T-ingot casting of pure and foundry (alloy A356) aluminum were compared to measurements made on industrially cast ingots. The measurements conducted included: drained sump profiles (6 in total), secondary dendrite arm spacings (SDAS), and location of macrostructure features. In all cases, the predictions matched the measurements well, providing confidence in the model and the methodology used.

Throughout development of the model, sensitivity to modelling methodology as well as process and numerical parameters were explored. To simplify comparison, an extensive analysis was conducted by varying single features of a baseline model to show the importance of the modelling methodologies and process parameters.
Table of Contents

ABSTRACT ......................................................................................................................... ii

TABLE OF CONTENTS ................................................................................................. iii

LIST OF TABLES ............................................................................................................ vi

LIST OF FIGURES ......................................................................................................... vii

LIST OF SYMBOLS ....................................................................................................... xiii

ACKNOWLEDGMENTS .................................................................................................... xiv

1 INTRODUCTION ........................................................................................................ 1

2 LITERATURE REVIEW ............................................................................................... 4

2.1 Modeling Direct Chill (DC) casting ...................................................................... 4

2.2 Thermal Boundary Conditions in Direct Chill Casting ..................................... 11

2.2.1 Primary Cooling ........................................................................................... 12

2.2.2 Secondary Cooling ....................................................................................... 13

2.3 Validation Techniques ......................................................................................... 14

3 SCOPE AND OBJECTIVE ........................................................................................ 17

4 MATHEMATICAL MODEL DEVELOPMENT ......................................................... 19

4.1 Governing Equations ......................................................................................... 19

4.2 Domain ................................................................................................................. 22

4.3 Thermophysical Properties of Aluminum ....................................................... 23

4.3.1 Foundry Alloy ............................................................................................ 24

4.3.2 Commercially Pure Aluminum ................................................................ 27

4.4 Boundary Conditions ......................................................................................... 30

4.4.1 Flow Boundary Conditions .......................................................................... 30

4.4.2 Thermal Boundary Conditions .................................................................. 32
### List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-1</td>
<td>Baseline mesh information</td>
<td>23</td>
</tr>
<tr>
<td>4-2</td>
<td>Composition ranges of A356 and LM25 alloys (wt%)</td>
<td>24</td>
</tr>
<tr>
<td>5-1</td>
<td>Predicted and measured SDAS of industrially cast A356 T-ingot, at near surface (A) and center (B) locations on the symmetry plane</td>
<td>66</td>
</tr>
<tr>
<td>6-1</td>
<td>Mesh and computational data</td>
<td>83</td>
</tr>
<tr>
<td>6-2</td>
<td>Single parameter summary of sensitivity</td>
<td>90</td>
</tr>
</tbody>
</table>
List of Figures

Figure 1-1: 2-dimensional schematic of HDC caster................................. 2
Figure 2-1: Permeability, $K$ [m$^{-2}$], calculated based on Carman-Kozeny
equation for a SDAS of 75 microns.............................................. 8
Figure 2-2: Cross-section of primary cooling region, illustrating the
meniscus, liquid-mould, solid-mould, and air gap regions............. 13
Figure 2-3: Typical ingot surface temperatures for hot and cold casting
practice in vertical DC casting.................................................... 14
Figure 4-1: Model domain used to simulate T-ingot HDC casting
including geometry and surface mesh........................................... 22
Figure 4-2: Fraction solid of A356 and LM25 as a function of
temperature................................................................................. 25
Figure 4-3: Specific heat (Cp) in addition to latent heat and density
corrected effective specific heat (eff Cp) as a function of
temperature for foundry aluminum.............................................. 25
Figure 4-4: Viscosity of foundry aluminum as a function of temperature...... 26
Figure 4-5: Thermal conductivity of foundry aluminum as a function of
temperature................................................................................... 26
Figure 4-6: Density and modified density of foundry aluminum as a
function of temperature.................................................................. 27
Figure 4-7: Specific heat (Cp) in addition to latent heat and density
corrected effective specific heat (eff Cp) as a function of
temperature for commercial purity aluminum................................. 28
Figure 4-8: Viscosity of commercial purity aluminum as a function of
temperature...................................................................................... 28
Figure 4-9: Thermal conductivity of commercial purity aluminum as a
function of temperature.................................................................. 29
Figure 4-10: Density of commercial purity aluminum and modified
density variations as a function of temperature................................ 29
Figure 4-11: Fluid flow boundary conditions........................................... 30
Figure 4-12: Primary cooling heat transfer coefficients for foundry aluminum................................................................. 33

Figure 4-13: Schematic of secondary water cooling jet impingement occurring on the bottom surface................................................. 34

Figure 4-14: Schematic of secondary water cooling impingent, flow, and ejection on a T-ingot. ................................................................. 34

Figure 4-15: Arbitrary description of boiling water heat transfer behaviour using linear variation between 4 points: 1) Onset of convection, 2) Onset of nucleate boiling, 3) Critical heat transfer / temperature, 4) Onset of film boiling ........................................... 35

Figure 4-16: Heat transfer coefficients occurring during steady state operation. Top, bottom, and side sample locations illustrated in top right domain diagram........................................................................... 36

Figure 4-17: Enthalpy and effective specific heat as a function of temperature for A356 ........................................................................... 38

Figure 4-18: Location of the liquid / solid interface predicted by CFX and calculated using an analytical solution to the Stefan problem..... 43

Figure 4-19: Conduction with bulk flow case study...................................................... 44

Figure 4-20: Temperature distribution between plates for different modeling methods.............................................................................. 44

Figure 5-1: Steady state temperature distribution over the surface of the domain.................................................................................. 46

Figure 5-2: Translucent temperature distribution over the domain, with solidus (yellow) and liquidus (orange) isotherm surfaces.............. 47

Figure 5-3: Isotherms representing the liquidus, 15% solid, 30% solid, and solidus on the symmetry plane. Top right shows the 3D domain and the symmetry plane sump profiles................................................. 48

Figure 5-4: Symmetry plane isotherms representing liquidus (red), 15% solid (green), 30% solid (light blue), and solidus (dark blue); in addition to velocity vectors which are coloured and sized based on velocity................................................................. 49

Figure 5-5: Translucent temperature distribution over the domain, with solidus (yellow), 30% solid (grey) and liquidus (orange)
isosurfaces, in addition to streamlines coloured based on velocity which start at the inlets.

Figure 5-6: Photograph of an end of cast ingot (viewed in the casting direction).

Figure 5-7: Location of foundry alloy sump profile measurement planes. Solidus (blue) and liquidus (red) sump isotherm profiles shown are shown on the symmetry plane.

Figure 5-8: Comparison of predicted sump profile with measured sump data for A356 at the 0 mm plane (symmetry plane).

Figure 5-9: Comparison of predicted sump profile with measured sump data for A356 at the 100 mm plane.

Figure 5-10: Comparison of predicted sump profile with measured sump data for A356 at the 200 mm plane.

Figure 5-11: Comparison of predicted sump profile with measured sump data for A356 at the 295 mm plane.

Figure 5-12: Comparison of predicted sump profile with measured sump data for A356 at the 365 mm plane.

Figure 5-13: Comparison of predicted sump profile to measured profile for commercial purity aluminum at the 0 mm plane (symmetry plane) using casting practice 1.

Figure 5-14: Comparison of predicted sump profile to measured profile for commercial purity aluminum at the 332 mm plane using casting practice 1.

Figure 5-15: Comparison of predicted sump profile to measured profile for commercial purity aluminum at the 71 mm plane using casting practice 2.

Figure 5-16: Comparison of predicted sump profile to measured profile for commercial purity aluminum at the 150 mm plane using casting practice 2.

Figure 5-17: Comparison of predicted sump profile to measured profile for commercial purity aluminum at the 261 mm plane using casting practice 2.
Figure 5-18: Comparison of predicted sump profile to measured profile for commercial purity aluminum at the 0 mm plane (symmetry plane) using casting practice 3 ........................................... 59

Figure 5-19: Comparison of predicted sump profile to measured profile for commercial purity aluminum at the 100 mm plane using casting practice 3 ........................................................................... 59

Figure 5-20: Comparison of predicted sump profile to measured profile for commercial purity aluminum at the 357 mm plane using casting practice 3 ................................................................. 60

Figure 5-21: Maximum change in liquidus symmetry plane sump profile after 20s when casting is stopped and adiabatic (blue) or full cooling (red) thermal boundary conditions are applied, relative to steady state casting conditions (green) ........................................................................... 62

Figure 5-22: Maximum change in 30% f_s symmetry plane sump profile after 20s when casting is stopped and adiabatic (blue) or full cooling (red) thermal boundary conditions are applied, relative to steady state casting conditions (green) ........................................................................... 62

Figure 5-23: Maximum change in solidus symmetry plane sump profile after 20s when casting is stopped and adiabatic (blue) or full cooling (red) thermal boundary conditions are applied, relative to steady state casting conditions (green) ........................................................................... 63

Figure 5-24: Schematic of sample location and the corresponding average SDAS ......................................................................................................................... 64

Figure 5-25: Sample micrograph showing A356 microstructure (primary phase is light colour, eutectic phase is dark colour) with two SDAS measurement locations and the number of secondary dendrite arm spaces measured ........................................................................... 65

Figure 5-26: Post-cast microstructure – pure Al ................................................................................................................................. 67

Figure 5-27: Macrostructure of ingot slice with observed features marked ......................................................................................................................... 67

Figure 5-28: Images parallel to the casting direction for model predictions of a) solidus isothermal surface coloured based on sump depth (red - deep, dark blue - shallow); b) streamlines from inlets (red - high velocity; dark blue – slow velocity) ........................................................................... 68

Figure 6-1: Full-buoyancy with density variation at temperatures greater than the liquidus (identical to baseline case) ................................................................. 72
Figure 6-2: Non-buoyant with density variation at temperatures greater than the liquidus ................................................................. 73

Figure 6-3: Full-buoyancy with density variation at temperatures greater than 50% solid........................................................................ 73

Figure 6-4: Full-buoyancy with density variation at temperatures greater than the solidus, showing a shifted sump profile in the wing region (see arrow) ................................................................. 74

Figure 6-5: Boussinesq buoyancy model (CFX implementation) .................. 74

Figure 6-6: Isotherms representing the 30% solid profile on the symmetry plane for various buoyancy methods ................................ 75

Figure 6-7: Isotherms representing the 30% solid profile on the symmetry plane, showing the effect of density variation methods on non-buoyant simulations. Case-1: \( \rho = f(T > T_{sol}) \), Case-2: \( \rho = f(T > T_{liq}) \), Case-3: \( \rho = f(T > T_{liq}) \)-energy corrected ............ 77

Figure 6-8: Isotherms representing the liquidus profile on the symmetry plane for SDAS of 0.01, 0.05, 0.1, 0.5 mm........................................ 78

Figure 6-9: Isotherms representing the 30% solid profile on the symmetry plane for SDAS of 0.01, 0.05, 0.1, and 0.5 mm .................................. 78

Figure 6-10: Isotherms representing the liquidus profile on the symmetry plane for Darcy source term coefficient cut off at \( 10^4 \), \( 10^5 \), \( 10^6 \), and \( 10^7 \) kg m\(^{-3}\) s\(^{-1}\) ........................................ 80

Figure 6-11: Isotherms representing the 30% solid profile on the symmetry plane for Darcy source term coefficient cut off at \( 10^4 \), \( 10^5 \), \( 10^6 \), and \( 10^7 \) kg m\(^{-3}\) s\(^{-1}\) ........................................ 80

Figure 6-12: Solidus isotherm (white line) and clipped casting direction velocity contours of solidified material for models where the Darcy momentum source term coefficient has been cut off at: a) \( 10^4 \), b) \( 10^5 \), c) \( 10^6 \), and d) \( 10^7 \) kg m\(^{-3}\) s\(^{-1}\). The intended casting speed was 0.00175 m s\(^{-1}\) and the contours were clipped approximately 3% above and below, 0.0018 m s\(^{-1}\) and 0.0017 m s\(^{-1}\), respectively ..................................................... 81

Figure 6-13: Temperature distribution along red line shown in modeling domain (top right) ................................................................. 83
Figure 6-14: Thermal distribution on the symmetry plane for 20 mm, 15 mm, 10 mm, and 7 mm maximum edge length mesh. 85

Figure 6-15: Isotherms representing the 30% solid profile on the symmetry plane for casting temperatures of 660°C, 670°C, 680°C, and 690°C. a) Full plot of isotherms, b) Local (top of ingot) plot of isotherm, c) Local (bottom of ingot) plot isotherm. 87

Figure 6-16: Isotherms representing the liquidus isotherm on the Symmetry plane for casting speeds of 0.00125, 0.0015, 0.00175, and 0.002 m s⁻¹. 88

Figure 6-17: Isotherms representing 30% solid on the symmetry plane for casting speeds of 0.00125, 0.0015, 0.00175, and 0.002 m s⁻¹. 89

Figure 6-18: Maximum depth of the 30% solid and liquidus isotherms occurring on the symmetry plane for casting speeds of 0.00125, 0.0015, 0.00175, and 0.002 m s⁻¹, with corresponding linear trend lines. 89
## List of Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu )</td>
<td>Dynamic Viscosity</td>
<td>Pa s</td>
</tr>
<tr>
<td>( \mu_T )</td>
<td>Eddy Viscosity</td>
<td>Pa s</td>
</tr>
<tr>
<td>( \rho )</td>
<td>True Density</td>
<td>kg m(^{-3})</td>
</tr>
<tr>
<td>( \rho_{\text{ref}} )</td>
<td>Reference Density</td>
<td>kg m(^{-3})</td>
</tr>
<tr>
<td>( \rho_{\text{mod}} )</td>
<td>Modified Density</td>
<td>kg m(^{-3})</td>
</tr>
<tr>
<td>( \lambda_1 )</td>
<td>Primary Dendrite Arm Spacing</td>
<td>m</td>
</tr>
<tr>
<td>( \lambda_2 )</td>
<td>Secondary Dendrite Arm Spacing</td>
<td>m</td>
</tr>
<tr>
<td>( \tau )</td>
<td>Shear Stress</td>
<td>Pa</td>
</tr>
<tr>
<td>( \beta )</td>
<td>Thermal Expansivity</td>
<td>K(^{-1})</td>
</tr>
<tr>
<td>( C_p )</td>
<td>Specific Heat</td>
<td>J kg(^{-1}) K(^{-1})</td>
</tr>
<tr>
<td>( C_p^* )</td>
<td>Effective Specific Heat</td>
<td>J kg(^{-1}) K(^{-1})</td>
</tr>
<tr>
<td>( \varepsilon )</td>
<td>Turbulent Eddy Dissipation</td>
<td>m(^2) s(^{-3})</td>
</tr>
<tr>
<td>( f_s )</td>
<td>Fraction Solid</td>
<td>-</td>
</tr>
<tr>
<td>( f_l )</td>
<td>Fraction Liquid</td>
<td>-</td>
</tr>
<tr>
<td>( g )</td>
<td>Gravitational</td>
<td>9.8 m s(^{-2})</td>
</tr>
<tr>
<td>( H )</td>
<td>Enthalpy</td>
<td>J kg(^{-1})</td>
</tr>
<tr>
<td>( h )</td>
<td>Heat Transfer Coefficient</td>
<td>W m(^{-2}) K(^{-1})</td>
</tr>
<tr>
<td>( i, j )</td>
<td>Cartesian Directions</td>
<td>-</td>
</tr>
<tr>
<td>( k )</td>
<td>Thermal Conductivity</td>
<td>W m(^{-1}) K(^{-1})</td>
</tr>
<tr>
<td>( k_t )</td>
<td>Turbulent Thermal Conductivity</td>
<td>W m(^{-1}) K(^{-1})</td>
</tr>
<tr>
<td>( K_{\text{tke}} )</td>
<td>Turbulent Kinetic Energy</td>
<td>m(^2) s(^{-2})</td>
</tr>
<tr>
<td>( K )</td>
<td>Permeability</td>
<td>m(^2)</td>
</tr>
<tr>
<td>( L )</td>
<td>Latent Heat of Fusion</td>
<td>J kg(^{-1})</td>
</tr>
<tr>
<td>( P )</td>
<td>Pressure</td>
<td>Pa</td>
</tr>
<tr>
<td>( q )</td>
<td>Heat Flux</td>
<td>W m(^{-2})</td>
</tr>
<tr>
<td>( S_E )</td>
<td>Energy Source</td>
<td>W m(^{-3})</td>
</tr>
<tr>
<td>( S_M )</td>
<td>Momentum Source</td>
<td>kg m(^{-2}) s(^{-2})</td>
</tr>
<tr>
<td>( S_{\text{Darcy}} )</td>
<td>Darcy Momentum Source</td>
<td>kg m(^{-2}) s(^{-2})</td>
</tr>
<tr>
<td>( t )</td>
<td>Time</td>
<td>s</td>
</tr>
<tr>
<td>( T )</td>
<td>Temperature</td>
<td>K</td>
</tr>
<tr>
<td>( T_{\text{ref}} )</td>
<td>Reference Temperature</td>
<td>K</td>
</tr>
<tr>
<td>( u_{\text{ref}} )</td>
<td>Specified Velocity</td>
<td>m s(^{-1})</td>
</tr>
<tr>
<td>( u )</td>
<td>Velocity</td>
<td>m s(^{-1})</td>
</tr>
<tr>
<td>( x, y, z )</td>
<td>Distance</td>
<td>m</td>
</tr>
</tbody>
</table>
Acknowledgments

I would like to thank my supervisor Dr. Daan Maijer for his guidance and support throughout this master’s degree. Dr. Steven Cockcroft, Mr. Massimo DiCiano, and Mr. André Larouche were also directly involved in this research project and made significant contributions.

Funding for this project came from Alcan International Limited and the National Science and Engineering Research Council (NSERC) through a Collaborative Research and Development (GRD) grant. In addition, Alcan Inc. should also be thanked for awarding me the 2005 UBC Alcan Inc. research fellowship.
1 Introduction

In 2005, approximately 2.9 million metric tons of primary aluminum was produced in Canada by Alcan Inc, Alcoa Inc and Aluminerie Alouette Inc. Prior to producing consumer products, most primary aluminum is cast into an intermediate form. There are various methods used to cast the primary aluminum including: casting belts, vertical direct chill (VDC) casting, and horizontal direct chill (HDC) casting. Casting belts involve a carousel arrangement where moulds travel around a track. The moulds are filled with liquid aluminum at one location and bars are extracted at another once the aluminum has solidified. Casting belts can be run continuously to produce bars (~10kg) intended for re-melt. For some casting operations, bars are useful. However if large quantities of aluminum are required it is advantageous to use ingots (~500kg). Throughout the last 60 years, aluminum alloy extrusion and rolling ingots have primarily been cast using the vertical direct chill (VDC) casting technique. The VDC technique works well. However, the maximum cast length and the cast duration of this process is limited by the depth of the casting pit (~10m), making the process semi-continuous. With the desire for increased production efficiency, the horizontal direct chill (HDC) casting method has gained popularity because it can be run continuously.

During operation of a HDC caster, liquid aluminum flows from a holding furnace into a tundish, during which degassing and other treatments may be conducted. From the tundish, the molten aluminum then flows through insulated pipes into the sump of the ingot contained inside a water cooled mould. As solidification occurs, the ingot is continuously extracted from the mould. The extraction process is aided by lubrication at the mould-ingot interface. Similar to VDC, there are two key regions of cooling, primary
and secondary. Primary cooling consists of heat removal through the water cooled mould, while secondary cooling consists of water jets impinging on the ingot as it emerges from the mould (i.e. direct chill). It is important to note that as the ingot exits the mould, only an outer shell will have solidified and the inside of the ingot is still liquid. A schematic of the HDC process is presented in Figure 1-1. As the casting process proceeds, a ‘flying saw’ cuts sections from the solidified ingot.

![Figure 1-1: 2-dimensional schematic of HDC caster.](image-url)

Alcan’s Alma works, located in the Saguenay region of Quebec, has two HDC casting machines (3 strands each) which are being used to cast pure aluminum and A356 T-section ingots (900x300mm). To improve the understanding of the HDC casting process and to provide a tool to answer questions that will arise if further developments are undertaken (i.e. casting alternate alloys or section shapes), a mathematical model is needed that can predict the thermal–fluid phenomena occurring throughout the process.
This model will provide insight about how casting conditions affect fluid flow, solidification, and heat transfer.
2 Literature Review

DC casting of aluminum was developed by W. T. Ennor more than 60 years ago\(^3\). While DC casting is not particularly new, the technologies, knowledge, and tools being used by industry are continually being developed to improve the process. One area where significant advancement is currently being made is the use of computational modelling to provide insight into the casting process. Since similarities exist between HDC aluminum casting and other casting technologies, this literature review includes work published on modeling, measurement, and validation techniques which have been used for horizontal and vertical casting of steel, aluminium, magnesium, and titanium alloys.

2.1 **Modeling Direct Chill (DC) Casting**

One of the first publications in which a heat transfer model was used to simulate DC casting was by Adenis et al. in 1962, in which a 2-dimensional (2-D) axisymmetric geometry with heat transfer coefficient boundary conditions was used to model steady state magnesium alloy billet casting.\(^4\) Since then a significant amount of work has been completed to improve accuracy, resolution, and robustness of DC casting models. Initially heat conduction models, with enhanced thermal conductivity at temperatures greater than the solidus, were developed to approximate effects of liquid flow.\(^5\) The conduction-only models provided insight into the effects of casting parameters; however, they were limited because convective and turbulent effects were not accurately accounted for. With the advancement of computing technology, coupled thermal-stress\(^4\), thermal-fluid\(^6-13\) and even thermal-fluid-stress models\(^14\) have been developed. Though numerous publications have been produced, the majority have been conducted on Vertical Direct
Chill (VDC) casting of aluminum, due to the fact that this is the most common DC casting technique.\textsuperscript{27}

In order to properly track liquid flow and the corresponding heat transport, it is necessary to develop a coupled thermal-fluid flow DC casting model. This type of model is based on the fundamental governing equations that describe conservation of mass, momentum, and energy, shown for Cartesian coordinates in equations 2-1, 2-2, and 2-3 respectively\textsuperscript{6,10,11,12}

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_i)}{\partial x_i} = 0 \tag{2-1}
\]

\[
\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + S_M \tag{2-2}
\]

\[
\frac{\partial (\rho H)}{\partial t} + \frac{\partial (\rho Hu_i)}{\partial x_j} = -k \frac{\partial^2 T}{\partial x_i^2} + S_E \tag{2-3}
\]

where $\rho$ is the density [kg m\(^{-3}\)], $t$ is the time [s], $u$ is the velocity [m s\(^{-1}\)], $x$ is the length [m], $P$ is the pressure [Pa], $\tau_{ij}$ is the stress tensor [Pa], $S_M$ is a momentum source [kg m\(^{-2}\) s\(^{-2}\)], $H$ is the enthalpy [J kg\(^{-1}\)], $T$ is the temperature [K], $k$ thermal conductivity [W m\(^{-1}\) K\(^{-1}\)] and $S_E$ is an energy source [W m\(^{-3}\)]. For Newtonian fluids, which describe the behaviour of molten metals\textsuperscript{6,10,11,12}, the stress tensor is linearly proportional to the rate of deformation tensor \(\dot{\gamma}\), and viscosity $\mu$ [Pa s] as shown in equation 2-4.

\[
\tau_{ij} = 2\mu \dot{\gamma} = \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \tag{2-4}
\]
In addition, to modeling basic fluid flow and heat transfer, other phenomena need to be accounted for in casting problems, including flow damping within the mushy zone, buoyancy, and possibly, turbulence, depending on the flow behaviour.

**Evolution of Latent Heat**

Evolution of latent heat occurs throughout solidification. It can be accounted for using either a source term or an effective specific heat. The source term approach incorporates an energy source term, $S_E$, into the energy equation (equation 2-3) such as:

$$ S_E = \rho h_{lat} V_c \frac{\partial f_s}{\partial t} $$

[2-5]

The effective specific heat method modified the specific heat, shown in equation, 2-6 so that the latent heat is implicitly included within the enthalpy.

$$ C'_p = C_p - \frac{df_s}{dT} L $$

[2-6]

H. Wei et al. found that the computational time for the effective specific heat method is at least 20 times faster than for source term methods.

**Flow Damping**

Solidification results in a transformation from the liquid phase, in which an infinitesimal shear force causes permanent and continuous deformation, to a solid phase which may deform elastically or plastically. CFD solidification modeling solves the mass, momentum, and energy equations throughout the domain of a casting. Often the solid, mushy, and liquid is treated as a single continuum with varying properties where a transition from fluid to solid behaviour is conducted by dampening the flow to the casting.
velocity. Various approaches have been taken which include: addition of a Darcy momentum source\textsuperscript{7,6,17}, ramping viscosity\textsuperscript{9,10} or a combination of the two.\textsuperscript{12}

The most common method of damping flow passing through a porous media is with a Darcy momentum source term, shown in equation 2-7

\[ S_{\text{Darcy}} = -\frac{\mu}{K}(u - u_{\text{set}}) \]  \hspace{1cm} \text{[2-7]}

where \( \mu \) is the viscosity [Pa s], \( K \) is the permeability [m\textsuperscript{2}], \( u \) is velocity [m s\textsuperscript{-1}], and \( u_{\text{set}} \) is a specified velocity (i.e. casting velocity) [m s\textsuperscript{-1}]. The permeability shown in equation 2-8 may be calculated using the Carman-Kozeny relationship, which has been used to describe how the permeability varies in a dendritic structure,\textsuperscript{18,19}

\[ K = \frac{(1 - f_s)^3 \lambda_2^2}{180 f_s^2} \]  \hspace{1cm} \text{[2-8]}

where \( f_s \) is the fraction solid, and \( \lambda_2 \) is the secondary dendrite arm spacing [m]. At the solidification front where primary dendrite tips are present, the permeability should be calculated using the primary dendrite arm spacing, \( \lambda_I \). However traditionally this effect is neglected and the secondary dendrite arm spacing is used.\textsuperscript{19} Permeability values for a 75 \( \mu \text{m} \) secondary dendrite arm spacing are shown in Figure 2-1. Rappaz et al. has shown that flow is significantly damped at permeability values which are less than the \( 10^{-8} - 10^{-9} \) range.\textsuperscript{19} Observing Figure 2-1, for a 75 \( \mu \text{m} \) secondary dendrite arm spacing, significant damping (i.e. \( K < 10^{-8} \)) occurs at fraction solid greater than 0.05.
Buoyancy

Buoyancy-induced flow occurs due to unstable density gradients which cause cooler, denser liquid to sink and hotter, less dense liquid to rise. During DC casting, significant temperature gradients are present which produce significant density gradients. Various approaches have been adopted for buoyancy-induced flow, which include: not accounting for buoyancy\textsuperscript{13}, applying a Boussinesq momentum source term\textsuperscript{11,12}, or using a ‘full’ buoyancy model. The Boussinesq source term approach approximates buoyancy effects by applying a momentum source term (shown in the right hand term in the Equation 2-9 momentum equation) while assuming a constant density throughout the system,\textsuperscript{20} thus,
where $\beta$ is the volume thermal expansion coefficient [K$^{-1}$]. This approximation is suitable for cases in which the variation of density is linear and produces minimal effects on energy and momentum transport. However, during solidification of aluminum alloys there is a 7-8\% nonlinear variation in density which affects the energy and momentum of the cast material. Taking these considerations into account the Boussinesq method may not be an ideal method of implementing buoyancy effects.

The 'full' buoyancy model evaluates the difference between a reference density ($\rho_{\text{ref}}$) and the current local density, multiplies the difference by gravitational acceleration to create a momentum source term (shown on the right side of the momentum equation below), thus,

$$
\frac{\partial(\rho_{\text{ref}} u_i)}{\partial t} + \frac{\partial(\rho_{\text{ref}} u_j u_j)}{\partial x_j} = \frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} - \rho_{\text{ref}} \beta g (T - T_{\text{ref}}) \quad [2-9]
$$

When using the full buoyancy model, care must be taken to correctly select how the density varies with temperature. Firstly, if the modeling domain is fixed, thermal contraction of the solid cannot be accounted for if mass is to be conserved. Secondly, depending on how the density variation is implemented, buoyancy effects may be adjusted to represent the solidification behaviour.

**Turbulence**

Turbulence, a property of fluid flow rather than the fluid itself, develops due to shear forces. As the kinetic energy of the fluid which is passing by an object increases,
the probability of a random perturbation increases. The perturbations can develop into vortices which increase the dissipative and diffusive behaviour of the fluid. In CFD simulations, a number of options are available to simulate turbulent flow; specifically: Direct Numerical Simulation (DNS), Reynolds Averaged Navier-Stokes (RANS) simulations, and Large Eddy Simulation (LES). However, in terms of CPU run time, only the RANS method is suitable for practical engineering applications. RANS-based CFD simulations introduce turbulence by adding an eddy viscosity, $\mu_T$, to the molecular viscosity and a turbulent conductivity, $k_t$, to the thermal conductivity. Numerous RANS turbulence approximations have been developed which are categorized as either zero-equation models, one-equation models, or two-equation models. Zero-equation models are the simples, they do not require a solution to additional equations and turbulence effects are approximated based on a field variable. One-equation and two-equation models require solution of one or two, additional equations, respectively.

When single-phase CFD turbulence models are applied to solidification problems, care must be taken to prevent enhanced dissipative effects within the solid. A number of approaches have been used to do this. Shyy et al. developed a method to eliminate enhanced heat transfer within the mushy and solid regions, which a number of other authors have since adopted. This method involves modifying the $k-\varepsilon$ turbulence model formulation of eddy viscosity (equation 2-11), by using equation 2-12 to formulate the $C_\mu$ coefficient as opposed to the traditional constant value of 0.09. By modifying the $C_\mu$ coefficient, the eddy viscosity is ramped within the mushy region to zero at a fraction solid equal to 1, effectively eliminating turbulence in the solid and ensuring correct conduction.
\[ \mu_t = \frac{C_p \rho k^2}{\varepsilon} \]  

\[ C_p = 0.09 \left\{ \sqrt{1 - f_s} \right\} \exp \left[ -3.4 \left( 1 + \frac{\rho k_{ke}^2}{\mu \varepsilon} \right)^2 / 50 \right] \]  

[2-11]

[2-12]

Where \( f_s \) is the fraction solid, \( \rho \) is the density [kg m\(^{-3}\)], \( k_{ke} \) is the turbulent kinetic energy [m\(^2\) s\(^{-1}\)], \( \mu \) is the viscosity [Pa s], \( \varepsilon \) is the turbulent eddy diffusivity [m\(^2\) s\(^{-3}\)].

Amin et al.\(^9\) used a zero equation turbulence model, due to its ease of implementation and simple numerical formulation. However turbulence effects are poorly predicted using a zero-equation turbulence models because they are only based on flow variables and do not account for convection or diffusion of turbulent energy.\(^{25}\)

### 2.2 Thermal Boundary Conditions in DC Casting

During DC casting, heat is removed from the ingot/billet via conduction in addition to free and forced convection. Due to the relatively low temperatures, radiation effects are negligible.\(^{27}\) Initial solidification occurs within the primary cooling region where heat is removed using a water cooled mould. After the cast section exits the mould, water jets within the secondary cooling region remove the majority of the thermal energy (~80%).\(^{26}\) Understanding these phenomena and the magnitude of heat flux is important to accurately develop the thermal boundary conditions for primary and secondary cooling.
2.2.1 Primary Cooling

Primary cooling provides the initial heat removal necessary for formation of a solidified shell. A schematic of the primary cooling region is shown in Figure 2-2. As shown, various interfaces between the ingot and mould are present, specifically: the meniscus (in which surface tension causes a small gap to form at the corner), the liquid-mould interface, the solid-mould interface, and the gap. Primary cooling heat transfer data is typically published as heat flux, \( q \), and/or heat transfer coefficients, \( h \), as functions of time, location, and/or temperature. In order to develop a robust model, data for heat transfer as a function of temperature is desirable because it allows the model to be flexible by not being limited to a single set of conditions (i.e. a range of casting speeds and thermal distributions); however, care must be taken because major process changes can affect the interfacial contact.

At the corner, between the backing plate and the mould, a small meniscus region is present. It is known that the size and shape of the meniscus is intrinsically transient and its behaviour affects the casting surface morphology. Heat transfer as aluminum solidifies on a chill has been characterized using various test methods including: static casters, cold finger tests, mould simulators, and industrial measurements in conjunction with inverse heat transfer calculations. Typical heat transfer coefficients for aluminum-metal interfaces have been reported in the range of 1000 to 4000 \( \text{W m}^{-2}\text{K}^{-1} \). As cooling occurs, first a mushy-mould interface, and then a solid-mould interface forms causing the heat transfer coefficients to decrease. Thermal contraction then produces an air gap, across which the heat transfer coefficient drops significantly to values of 150 to 200 \( \text{W m}^{-2}\text{K}^{-1} \).
2.2.2 Secondary Cooling

In the secondary cooling region water directly contacts the evolving ingot. Grandfield and McGlade documented approximate values related to the water flow and heat transfer typical for DC casting. Mass flow rates for the water jets are 2 to 4 kg s$^{-1}$ per mm of mould with an impingement velocity of about 2 m s$^{-1}$. The surface temperatures of the ingot at the jet impingement point have been measured between 250-300°C. As shown in Figure 2-3, the ingot temperature decreases significantly prior to and during impingement.

![Diagram of primary cooling region](image-url)
During normal operation, nucleate boiling predominates and the water jet impingement heat transfer coefficients are on the order of 40,000 W m\(^{-2}\) K\(^{-1}\); thus producing heat fluxes between 5 to 6 MW m\(^{-2}\).\(^{27}\) Final water temperature measurements have shown typical temperature rises of 40 to 50°C.\(^{27}\) Grandfield et al. claim that although boiling occurs on the ingot’s surface, the water is sufficiently sub-cooled that most of the bubbles subsequently collapse after detachment.\(^{27}\)

### 2.3 Validation Techniques

Validation is crucial to confirm that a model accurately reflects the physical process. Ideally flow and thermal measurements would be available at any location;
however, this is not possible. Instead measurements should be taken at locations that illustrate certain phenomena, with methods that have minimal effect on the phenomenon of interest. For validation of DC casting models, flow and thermal measurement are desirable but often difficult to obtain.

Flow Measurements

Many techniques have been developed for making flow measurements. Typical techniques include: Pitot tubes, propeller type velocimeters, reaction probes, hot-wire anemometry, karman vortex probes, Partical Image Velocimetry (PIV)\textsuperscript{32}, and Laser Doppler Velocimetry (LDV). However, using these methods with molten aluminum and within the constraints of an industrial DC caster is impossible for all techniques except the reaction probe. Alternate techniques which have potential for DC caster flow measurement include: electromagnetic flow meters and melting probes.\textsuperscript{33} Electromagnetic flow meters measure the potential produced as a conducting liquid flows through a magnetic field. Melting probes originally developed by Argyropoulos et al.\textsuperscript{34, 35} measure the melting rate of spherical samples that have the same chemistry as the melt. Prior calibration experiments provide a relationship between metal velocity and melting time which are then used to correlate the local metal velocity.

Temperature Measurements

Temperature measurement can be made by direct and in direct methods. Direct methods use thermocouples at distinct locations such as the mould, ingot surface, and ingot sub surface (sump and solidified material). Measured mould temperatures, in conjunction with an Inverse Heat Conduction (IHC) model, can provide information
about the heat transfer occurring within the primary cooling region.\textsuperscript{36} Surface temperature measurements provide weak validation data. This is because the surface temperatures, at locations which are accessible, vary little with process changes. Internal temperature measurements like cast-in thermocouples, provide thermal history throughout the casting, however production is lost due to contamination of the ingot.

In direct methods, reviewed by J.F. Granfield\textsuperscript{37}, rely on observations which indicate thermal phenomena, specifically solidification. Sump profile measurements can be made using a number of techniques. Dip-rod tests use a rod to feel/find the sump depth. This type of measurement is not exact because the fraction solid that stops the rod is not clear. The dip-rod method is well suited for casting processes which allow easy access to the sump (i.e. aluminum vertical direct casting), but is more difficult when the access is complicated (i.e. HDC casting). Various doping methods, which include: modification of the liquid composition, radioactive tracers, or the addition of a high concentration of grain refiner can also be used. The results of the doping methods are a boundary within the cast structure which can be correlated with the doping event and prior location. Draining the sump rapidly can also be used to reveal the sump topology, and is well suited for an HDC caster. The resulting profile must be interpreted carefully because it is not clear what fraction solid flows away and what remains, in addition to the fact that further solidification can occur during draining. Grandfield also reviewed some non-destructive, but more complicated, techniques which include using radiation (X-ray / \(\gamma\)-rays) or ultrasound to locate the sump. Microstructural observations can also be used to reveal cooling rates, through secondary dendrite arm spacing (SDAS) correlations.\textsuperscript{18}
3 Scope and Objectives

Alcan currently operates five HDC casters at its plants in Canada and France. As a means to improve the fundamental understanding of HDC casting, and provide insight about process improvements which could be made to the T-ingot casters, a collaborative research project with Alcan's Arvida Research and Development Center and the Department of Materials Engineering was initiated. The objective of the project was to develop and validate a coupled thermal-fluid flow model which would be capable of providing insight about how process conditions (casting temperature, cast velocity, cooling, etc.) would affect T-ingot casting. Lab-scale experiments and industrial measurements at UBC and ALCAN were proposed as a means to provide data for model development and validation.

Development of a HDC model requires careful consideration of the physics occurring within the industrial process so that boundary conditions, material properties, and modelling methodology accurately represent the various phenomena (buoyancy, turbulence, solidification effects). Sensitivity of the model results to numerical effects, modeling methods, and process parameters should also be evaluated so that an appreciation of care required throughout development is known.

In light of the above discussion, sub objectives of the research:

- Develop knowledge of the physics of HDC casting
- Develop and validate (when possible using simplified scenarios) boundary conditions, modelling methods, and material properties that can represent the physics of HDC casting.
• Evaluate how implementation of the boundary conditions, modelling methods, and material properties affects the predicted thermal and fluid flow in HDC T-ingot casting.

• Select an optimal combination of boundary conditions, modelling methods and material properties, by comparing model predictions to measurements made on industrial cast T-ingots.
4 Mathematical Model Development

A mathematical model has been developed to predict the thermal and fluid flow occurring during HDC casting of T-ingot. The commercial computational fluid dynamics (CFD) package, CFX 10.0, has been selected as a computational platform due to its ability to solve coupled thermal-fluid flow simulations and flexibility to include user-defined functions and subroutines. Additionally this software is in use at Alcan, which facilitates easy transfer of the modelling methodologies developed. As part of the development process, an incremental approach was taken in order to produce a model that accurately represents the physics of the process and is robust. This involved developing the geometry, boundary conditions, and methods to describe: latent heat evolution, buoyancy, flow damping, and turbulence. The methodology presented in this chapter represents the best practice determined by comparison to measurements. Results presented in Results and Validation (Chapters 5) compare the best practice predictions to the experimental measurements, while the Sensitivity Analysis (Chapter 6) shows how alternate modelling methodologies affect the predictions.

4.1 Governing Equations

The conservation equations used for the coupled turbulent thermal-fluid flow model which includes buoyancy, turbulence, and solidification effects are shown in equations 4-1, 4-2, and 4-5.

The conservation of mass equation of shown in equation 4-1,
\[ \frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_i)}{\partial x_i} = 0 \quad [4-1] \]

where \( \rho \) is density [kg m\(^{-3}\)], \( t \) is time [s], \( u \) is velocity [m s\(^{-1}\)], \( x \) is distance [m].

The conservation of momentum, represented by equation 4-14, is a balance between changes in momentum or acceleration (left side) with the sum of the negative pressure gradient, viscous forces, and momentum source terms.

\[ \frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = \]

\[ -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \mu_{\text{eff}} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right) + g(\rho - \rho_{\text{ref}}) - \frac{\mu}{K} (u_i - u_{\text{set}}) \quad [4-2] \]

Where \( g(\rho - \rho_{\text{ref}}) \) introduces buoyancy effects, \( \frac{\mu}{K} (u_i - u_{\text{set}}) \) is the Darcy momentum source term that dampens flow in the mushy zone and constrains the velocity of the solidified material. \( P \) is the pressure [N m\(^{-2}\)], \( g \) is the gravitational acceleration, \( u_{\text{set}} \) is the casting velocity, \( \mu_{\text{eff}} \) is equal to the sum of \( \mu + \mu_t \), where \( \mu \) is the dynamic viscosity [Pa s] and \( \mu_t \) is the turbulent viscosity approximated using a modified \( k-\varepsilon \) turbulence model where the turbulence viscosity is

\[ \mu_t = \frac{C_\mu \rho k_{\text{tke}}^2}{\varepsilon} \quad [4-3] \]

in which \( k_{\text{tke}} \) is the turbulent kinetic energy [m\(^2\) s\(^{-2}\)], \( \varepsilon \) is the turbulent eddy dissipation [m\(^2\) s\(^{-2}\)] and \( C_\mu \) is the coefficient calculated according to equation 4-4. Initially, the method proposed by Shyy et al. to calculate \( C_\mu \) (refer to equation 2-12) was evaluated. This method led to significant turbulence in the mushy zone and a more aggressive method of eliminating turbulence was sought. Although physically unrealistic, equation 4-4 satisfies the numerical condition of ramping \( C_\mu \) to 0 near the liquidus temperature.
\[ C_\mu = 0.09(1 - f_s)^{25} \]  \[4-4\]

The conservation of energy represented by equation 4-5, accounts for the heat balance

\[
\frac{\partial (\rho H)}{\partial t} + \frac{\partial (\rho H u_i)}{\partial x_i} = -k_{\text{eff}} \frac{\partial^2 T}{\partial x_i^2}
\]

\[4-5\]

where \( H \) is enthalpy [J kg\(^{-1}\)], \( T \) is temperature [K], and \( k_{\text{eff}} \) is the effective thermal conductivity [W m\(^{-1}\) K\(^{-1}\)]. The effective conductivity is the sum of the materials actual thermal conductivity, \( k \), and a turbulent conductivity enhancement, \( k_{\alpha} \), which is dependent on eddy viscosity. Enthalpy is calculated in CFX using piecewise integration, which is shown below.

\[
H(T) = \sum_i \left( \frac{C_p T_i + C_p T_{i+1}}{2} \right) \times (T_{i+1} - T_i)
\]

\[4-6\]

Since a modified variation of density was used and latent heat was evolved using an effective specific heat method, a density corrected effective specific heat (shown below) was used.

\[
C'_p = \left( C_p - \frac{d f_s}{d T} L \right) \times \left( \frac{\rho}{\rho_{\text{mod}}} \right)
\]

\[4-7\]

Where \( C_p \) is the materials actual specific heat [J kg\(^{-1}\) K\(^{-1}\)], \( d f_s/dT \) is the slope of the fraction solid curve with respect to temperature [K\(^{-1}\)], and \( L \) is the latent heat of fusion [J kg\(^{-1}\)], \( \rho \) is the actual materials density [kg m\(^{-3}\)], and \( \rho_{\text{mod}} \) is the modified density used in the model [kg m\(^{-3}\)].
4.2 Domain

The model domain was selected to ensure that fluid flow and heat transfer in the ingot were adequately described while at the same time minimizing the domain size to minimize computation time. To do this, the domain shown in Figure 4-1 was limited to a half section of the aluminum T-ingot. The tundish was neglected because the fluid flow within it was not expected to impact the T-ingot. Half of a T-ingot was modeled by assuming symmetry along the vertical center plane. The transfer tubes were included to better describe the turbulence at the inlet to the casting. The length of the domain was selected to ensure that the thermal boundary conditions implemented at the outlets \( (dT/dx=0) \) did not influence the thermal/fluid flow predictions in the sump.

![Figure 4-1: Model domain used to simulate T-ingot HDC casting including geometry and surface mesh](image-url)
One mesh was used for all of the simulations, with exception of the mesh sensitivity study, to provide consistency in model resolution. Details of the baseline mesh, used to represent the domain, are shown in the table below.

Table 4-1: Baseline mesh information

<table>
<thead>
<tr>
<th>Element Type</th>
<th>Tetrahedral</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Element Edge Length</td>
<td>15 mm</td>
</tr>
<tr>
<td>Number of Elements</td>
<td>235008</td>
</tr>
<tr>
<td>Number of Nodes</td>
<td>44279</td>
</tr>
<tr>
<td>Maximum Element Edge Length Ratio</td>
<td>7.86</td>
</tr>
</tbody>
</table>

4.3 Thermophysical Properties of Aluminum

The properties required for the HDC simulation include: density, latent heat, viscosity, specific heat, and thermal conductivity. In order to most accurately characterize the behaviour of the material, knowledge of the thermophysical properties is required over the range of temperatures experienced in the process. In some cases data for the entire temperature range is available, while in other cases properties must be approximated. For example, at temperatures between the liquidus and solidus, properties were often approximated using a weighted average of the solidus and liquidus properties based on fraction solid thus

\[ \rho_{\text{mesh}} = f_s \rho_{\text{solidus}} + (1 - f_s) \rho_{\text{liquidus}} \]  

Knowledge of the true thermo-physical properties is being emphasized because in a number of cases alternate properties are used in conjunction with calculated corrections. The alternate properties and correction methods are employed to better describe the physics of the process and improve solver robustness. At Alcan’s Alma HDC casting
facility, T-ingot is produced from aluminum alloy A356 and commercial purity aluminum. The thermophysical properties for both of these aluminum alloys will now be summarized.

### 4.3.1 Foundry Alloy

Foundry alloy in this thesis refers to aluminum alloy A356, which is used in a number of shape casting applications which include: automotive wheels, engine blocks and engine heads. Where possible data for A356 were used; however, a complete property data set for European alloy LM25, which has a similar composition to A356, was found in the literature and used in cases where A356 data were not available. Table 4-2 compares the composition ranges of A356 and LM25. The main differences are the magnesium (Mg) range and the maximum allowable iron (Fe); however the main addition, silicon (Si) is the same.

**Table 4-2: Composition ranges of A356 and LM25 alloys (wt%).**

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Si</th>
<th>Fe*</th>
<th>Cu</th>
<th>Mn</th>
<th>Mg</th>
<th>Ni*</th>
<th>Zn*</th>
<th>Sn*</th>
<th>Ti*</th>
<th>Pb*</th>
</tr>
</thead>
<tbody>
<tr>
<td>A356</td>
<td>6.5 - 7.5</td>
<td>0.2</td>
<td>0.2</td>
<td>0.1</td>
<td>0.25 - 0.45</td>
<td>...</td>
<td>0.1</td>
<td>...</td>
<td>0.2</td>
<td>...</td>
</tr>
<tr>
<td>LM25</td>
<td>6.5 - 7.5</td>
<td>0.5</td>
<td>0.2</td>
<td>0.1</td>
<td>0.2 - 0.6</td>
<td>0.1</td>
<td>0.1</td>
<td>0.05</td>
<td>0.2</td>
<td>0.1</td>
</tr>
</tbody>
</table>

* maximum allowable amount

Thompson et al. measured the variation of A356 fraction solid with temperature for a cooling rate of 0.52 [K s$^{-1}$]. This data, as well as, LM25 are plotted in Figure 4-2. The LM25 fraction solid behaviour used was in the model, in which the solidus and liquidus temperatures were taken as 523°C and 612°C, respectively.
Figure 4-2: Fraction solid of A356\textsuperscript{43} and LM25\textsuperscript{41} as a function of temperature.

The thermo-physical properties of the foundry aluminum properties used in the model are shown in Figures 4-3, 4-4, 4-5, and 4-6 while tabular thermophysical data can be found in Appendix A.

Figure 4-3: Specific heat (Cp) in addition to latent heat and density corrected effective specific heat (eff\,Cp) as a function of temperature for foundry aluminum.
Figure 4-4: Viscosity of foundry aluminum as a function of temperature.

Figure 4-5: Thermal conductivity of foundry aluminum as a function of temperature.
4.3.2 Commercial Purity Aluminum

Aluminum produced electrolytically in a Hall Héroult cell is cast for re-melt and identified as commercially pure Al. A complete data set for pure aluminum was reported by Mills\textsuperscript{41}. In this thesis commercial purity aluminum was assumed to have the same properties that Mills documented, except with linear solidification occurring between 661\degree C and 636\degree C. Figures 4-7, 4-8, 4-9, and 4-10 show the variation of specific heat, viscosity, thermal conductivity, and density as a function of temperature for commercial purity aluminum while tabular thermophysical data can be found in Appendix B.
Figure 4-7: Specific heat (Cp) in addition to latent heat and density corrected effective specific heat (eff Cp) as a function of temperature for commercial purity aluminum.

Figure 4-8: Viscosity of commercial purity aluminum as a function of temperature.
Figure 4-9: Thermal conductivity of commercial purity aluminum as a function of temperature.

Figure 4-10: Density of commercial purity aluminum and modified density variations as a function of temperature.
4.4 **Boundary Conditions**

Boundary conditions are important in CFD analysis because they constrain the problem so that a solution can be determined. Care was taken to ensure that the boundary conditions represent the physics of the process in order to produce accurate results. In the cases where assumptions are made, it is important that the effects and significance of the assumptions are understood. Flow and thermal boundary conditions used for the HDC model as well as the necessary assumptions are described in the following sections.

### 4.4.1 Flow Boundary Conditions

A cross section of the HDC process (Figure 4-11) illustrates the location and type of fluid flow boundary applied to the HDC ingot.

![Fluid flow boundary conditions](image)

**Figure 4-11: Fluid flow boundary conditions.**

Surfaces of the model where liquid metal contacts solid components have a no-slip boundary condition which fixes the fluid velocity to the wall velocity (i.e. the velocity of the liquid metal along the surfaces of the transfer tubes and the backing plate is set to 0 m
Mushy or solidified aluminum that is in contact with a solid component or exposed to air/water is assumed to have a free-slip boundary condition which does not introduce shear and fixes the velocity normal to the face to zero. The surfaces of the model where free-slip occurs include those in the primary mould cooling region, the air gap, and the secondary water cooling region. A free-slip boundary condition was applied to the primary mould cooling region because it allows the velocity of the surface material to ramp to the casting velocity, thus improving solver robustness by not over constraining the problem. The no-slip condition existing between the liquid metal and the mould was neglected because during steady state operation the portion of the primary cooling region exhibiting the condition is very small and has little effect on the flow behaviour. However if significant process changes were made which increased the liquid-mould interfacial area, a no-slip boundary condition would be required to accurately reproduce the impact of shearing along this surface. The outlet boundary was constrained by fixing the velocity normal to the surface to the casting speed (baseline casting speed was 0.00175 m s\(^{-1}\)). Using the mass flow exiting the outlet, a uniform velocity which conserved mass was applied normal to the inlet faces. Specification of a uniform inlet velocity was based on an assumption that no pressure difference exists between the transfer tubes. Fixing the inlet velocity promotes uniform feeding, however if this model is used to study blockage of the transfer tubes due to freezing or chemical reaction, then a pressure boundary condition should be applied, or else the tundish should be included in the domain.
4.4.2 Thermal Boundary Conditions

Thermal boundary conditions were developed to describe the heat transfer phenomena occurring in each region. A uniform casting metal temperature of 682 K for A356 was specified at the inlet surface. Effective heat transfer coefficients were developed for the transfer tubes and backing plate based on the cumulative thermal resistances assuming 1-D heat transfer, refer to in Equation 4-9.

\[
\frac{1}{h_{\text{eff}}} = \frac{1}{h_{\text{in}}} + \frac{x}{k} + \frac{1}{h_{\text{out}}} \tag{4-9}
\]

Where \( h_{\text{in}} \) and \( h_{\text{out}} \) are the internal and external heat transfer coefficient respectively [W m\(^{-2}\) K\(^{-1}\)], \( x \) is the thickness of the material separating the cast material from the surrounding environments [m], and \( k \) is the thermal conductivity [W m\(^{-1}\) K\(^{-1}\)]. The effective heat transfer coefficients for the transfer tubes and backing plate were 11.4 and 5 W m\(^{-2}\) K respectively. The far field temperatures for the transfer tubes and backing plate were taken as 300°C and 100°C, respectively, based on recommendations from Alcan.

Heat transfer within the primary cooling region is being characterized concurrently with model development in a parallel project by Mr. Massimo DiCiano using an inverse heat transfer technique. Complete description of the primary cooling characterization using this technique may be found in Massimo DiCiano’s M.A.Sc. thesis which is soon to be published.\(^{45}\) Since the characterization study was being conducted at the same time as the development of the HDC model, a preliminary effective heat transfer coefficient has been assumed and is shown for A356 in Figure 4-12, which ramps from 4000 to 50 W m\(^{-2}\) K\(^{-1}\) based on a weighted average of fraction solid.

32
The variation of the primary mould cooling region boundary condition is related to the evolution of interfacial contact resistance. At high temperatures, when liquid is present, good contact exists between the mould and aluminum resulting in a high heat transfer coefficient. As solidification and thermal contraction progress, the contact deteriorates to the point where an air gap may form, leading to increased resistance. Within the primary mould cooling region, a constant far-field temperature of 50°C was assumed based on the approximate temperature of the mould.

Within the secondary water cooling region, water jets emanating from the mould impinge on the surface of the emerging ingot. A highly complex non-linear variation in heat transfer occurs due to the local flow conditions (impingement, free flow) and corresponding boiling water heat transfer behaviour. A schematic showing the various
regions occurring locally at the bottom of the ingot is shown in Figure 4-13. Added complexities arise on the vertical surfaces of the ingot due to gravitational effect which cause the size and location of free flowing region to change; as shown schematically in Figure 4-14.

**Figure 4-13:** Schematic of secondary water cooling jet impingement occurring on the bottom surface.

**Figure 4-14:** Schematic of secondary water cooling impingent, flow, and ejection on a T-ingot.
Temperature and spatially dependent heat transfer coefficient boundary conditions were developed by Alcan to account for the impingement, free flow, and drop off regions of the secondary cooling zone. The heat transfer coefficient variation was defined for each flow region using a series of lines defined by 4 points that described convection, nucleate boiling, and transition boiling, as shown in Figure 4-15. The points \((T_i, h_i)\) were formulated based on the flow regime and water flow rate \([\text{1 min}^{-1} \text{ per mm of mould}]\). For the bottom and vertical surfaces, the drop-off region was defined based on plant observations. The transition in heat transfer coefficient which occurs between the impingement, free flow, and drop-off regions was calculated as a blend of the two corresponding regions to ensure a smooth variation of heat transfer coefficient. The specific details of these boundary conditions are considered proprietary and will not be discussed.

![Figure 4-15: Idealized description of boiling water heat transfer behaviour using linear variation between 4 points: 1) Onset of convection, 2) Onset of nucleate boiling, 3) Critical heat transfer / temperature, 4) Onset of film boiling](image-url)
Figure 4-16 shows how the heat transfer coefficient varies as a function of location during steady state operation. The heat transfer coefficient evolves through combined effects of temperature and location. An obvious effect is the decrease in bottom heat transfer coefficient at \(~0.55\text{m}\) due to drop-off.

![Heat Transfer Coefficient Graph](image)

**Figure 4-16: Heat transfer coefficients occurring during steady state operation. Top, bottom, and side sample locations illustrated in top right domain diagram.**

### 4.5 Evolution of Latent Heat

Latent heat is released throughout solidification. Two numerical methods were considered to account for the release of latent heat: an effective specific heat method and an energy source term method. With the HDC model, evolution of latent heat was accounted for using an effective specific heat method because it reduces computation
This technique involves modifying the specific heat used in the model to yield the correct variation in enthalpy over the phase change temperature interval. Enthalpy is calculated using a piecewise integration of the specific heat relationship up to the local temperature because the variation of specific heat with temperature cannot be described analytically. The enthalpy maybe calculated using equation 4-10

\[
H(T) = \sum_{i} \left( \frac{C_p, i + C_p, i+1}{2} \right) \times (T_{i+1} - T_i)
\]

[4-10]

where \( T_N = T \), \( T_I = T_{ref} \). During the solidification interval, an effective specific heat \( (C_p') \) can be defined thus;

\[
C_p' = C_p - \frac{df}{dT} \times L
\]

[4-11]

where \( C_p \) is the materials specific heat \([\text{J kg}^{-1} \text{ K}^{-1}]\), \( \frac{df}{dT} \) is the slope of the fraction solid curve with respect to temperature \([\text{K}^{-1}]\), and \( L \) is the latent heat of fusion \([\text{J kg}^{-1}]\). The variation of effective specific heat as a function of temperature is input into CFX in tabular form. The resulting enthalpy, calculated by CFX, is shown in Figure 4-17 for A356. In CFX, the number of points used to describe the thermo-physical properties must be specified. It is critical that a sufficient number of points are used to accurately resolve the highly non-linear effective specific heat.
4.6 Flow Damping

As liquid metal solidifies, there is a transition from free flowing liquid to a rigid solid. The transition occurs due an increase in flow damping as fraction solid increases, until a fully damped rigid solid is present. Flow damping was achieved within the mushy zone and solid using a Darcy-type source term. The Darcy momentum source term, $S_{Darcy}$, shown in equation 4-12 was implemented in CFX. The permeability, $K$, was calculated using equation 4-13. A secondary dendrite arm spacing of 50 μm was used, which corresponds to observed values.
\[ S_{\text{Darcy}} = -\frac{\mu}{K} (u - u_{\text{set}}) \]  

\[ K = \frac{(1 - f_s)^3 \lambda_2^2}{180 f_s^2} \]

Where \( \mu \) is the viscosity \([\text{Pa s}]\), \( u \) is the local velocity \([\text{m s}^{-1}]\), \( u_{\text{set}} \) is the casting velocity \([\text{m s}^{-1}]\), \( K \) is the permeability \([\text{m}^2]\), \( \lambda_2 \) is the secondary dendrite arm spacing \([\text{m}]\), and \( f_s \) is the fraction solid. A minimum fraction solid value of \(10^{-9}\) was set for temperatures above the liquidus to allow permeability to be calculated. Additionally the maximum value of \( \mu/K \) (Darcy source term coefficient) in the Darcy source term was limited to \(10^6 \text{ kg m}^{-3} \text{s}^{-1}\). Based on a sensitivity study it was found that a momentum source term of \(10^6 \text{ kg m}^{-3} \text{s}^{-1}\) provides sufficient damping but does not hinder convergence.

### 4.7 Buoyancy

Natural convection, or buoyancy driven flow, occurs within the HDC process due to unstable density gradients. Buoyancy was implemented using a ‘full’ buoyancy model where the variation of density is included within the conservation equations (mass, momentum, energy) and a buoyancy force based on density difference is applied in the momentum equation thus

\[ \frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = \frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_i} + g(\rho - \rho_{\text{ref}}) \]  

Thus, as temperature decreases the mass of the aluminum within a given volume increases due to thermal contraction. However since a fixed domain is being used, this is only valid in the liquid/mush region where fluid flow can occur to compensate for contraction. Below a specific fraction liquid, feeding stops and an increase in density
should not occur. Based on a sensitivity analysis and sump profile measurements it was decided that a full buoyancy model in which density varies at temperatures above the liquidus, but is constant at temperature below the liquidus, produced the most accurate predictions. Complete description of predicted flow and thermal behaviours of all the buoyancy methods evaluated can be found within the buoyancy sensitivity analysis section 6.1.1. Since a constant density was used at all temperatures below the liquidus, the specific heat was modified to correct the enthalpy balance. Modification of the specific heat ($C_p$) to correct for the modified density variation was done by multiplying the specific heat by the ratio of the materials density to the modified density as shown in equation 4-15.

$$C_{p_{\text{corr}}} = C_p \times \left( \frac{\rho}{\rho_{\text{modified}}} \right)$$

[4-15]

### 4.8 Solver Control

An approximate solution to the governing equations is produced using the CFX solver. One of the challenges with CFD modelling is judging the numerical accuracy of the solutions. In this work, this was done by evaluating the residuals, which are a measure of the difference between the left and right sides of the governing equations. Within CFX residuals are calculated locally, normalized using a sophisticated technique that depends on the current solution range and output as root mean square and maximum values. Within the CFX reference literature, guidelines for judging a solution’s numerical accuracy based on the maximum residual are presented. For residuals greater that $5 \times 10^{-4}$ convergence is poor and qualitative data is largely unreliable, $5 \times 10^{-4}$ provides
loose convergence, $10^{-4}$ provides good convergence and is suitable for most engineering applications, while $5 \times 10^{-5}$ is tight convergence\textsuperscript{46}.

With CFX both steady-state and transient simulations include time within the governing equations. For the steady-state cases, time is not tracked but instead a dummy timestep is used to help control how the solver converges upon the solution\textsuperscript{46}. Since the initial conditions are usually far from the steady state solution, it is advantageous to use a large timestep size to get a rough solution and then use a smaller timestep size to hone in on the exact solution. In some problems, the solution may be intrinsically transient which makes it difficult or impossible to achieve steady-state convergence. In such cases the solver is first run in steady state mode to obtain a non-converged steady-state solution, then that solution is used as the initial condition for a transient quasi-steady-state solution which usually achieves suitable convergence. Within this thesis, suitable convergence was considered to have maximum mass, momentum, and energy residuals falling below $10^{-4}$.

4.9 Model Development Case Studies

In order to assess CFX and verify the basic modelling methodologies used in the 3-dimensional T-ingot model, a series of case studies on simplified problems were examined. These case studies include the Stefan problem, and a 1-dimensional heat conduction problem with flow.
4.9.1 Case Study 1 - The Stefan Problem

The Stefan problem describes growth of a solidification front in a material solidifying at a specified temperature.\cite{47} The analytical solution for this problem, given in equations 4-16 and 4-17, defines the solidification thickness (or location of the solidification front) on an isothermal flat surface, when all of the liquid is at the melting temperature, as a function of time.

\[ S = 2γ \sqrt{α_s t} \quad [4-16] \]

\[ ye^{\frac{γ}{γ}} erfγ = \frac{(T_M - T_0)C_s}{H\sqrt{π}} \quad [4-17] \]

where \( S \) is the location of the solid-liquid interface, \( H \) is the latent heat, \( T_M \) is the temperature of melting, \( T_0 \) is the temperature of the boundary, \( C_s \) is the specific heat, and \( α_s \) is the thermal diffusivity.

A simple model for pure aluminum with geometry and boundary conditions consistent with the Stefan problem was developed in CFX. The location of the liquid / solid interface predicted by CFX and calculated using the analytical solution are compared in Figure 4-18. Observing that there is little difference between CFX’s predictions and the Stefan problem provides confidence that the effective specific heat method evolves latent heat correctly.
Figure 4-18: Location of the liquid / solid interface predicted by CFX and calculated using an analytical solution to the Stefan problem.

4.9.2 Case Study 2 - Conduction with Flow

To assess the impact of turbulence on heat transfer occurring by conduction and bulk flow, a model of heat transfer occurring in a moving fluid between two parallel plates, shown schematically in Figure 4-19, was developed. One plate was hot while the other was cold and the inlet fluid temperature was set to the mean temperature of the plates. Plug flow (i.e. no velocity gradient) existed. This was accomplished in two ways; either free-slip wall boundary conditions or no-slip wall boundary conditions in which the wall velocity matched the fluid velocity. The temperature distribution between the plates was evaluated at a downstream location that exhibited a non-linear thermal gradient (i.e. steady-state thermal profile not established).
The temperature distributions from the different model runs are presented in Figure 4-20. The results from the laminar model, which are assumed to be correct, are compared to results produced using \( k-e \) turbulence models and different wall boundary conditions. As can be seen, conductive heat transfer (i.e. in solidified material) is incorrectly modeled if the standard turbulence model is active. As a result, for heat conduction to be accurately modeled in solidified material, the eddy viscosity needs to be set to zero (Turbulent Free-slip (Zero turbulence) case). In addition to dampening the effect of turbulence on heat transfer by setting the eddy viscosity to zero, an effective thermal conductivity may also be defined to zero turbulent conduction. Both of these techniques were evaluated and produced the same results; however the zero eddy viscosity method was more numerically stable.

Figure 4-19: Conduction with bulk flow case study.

Figure 4-20: Temperature distribution between plates for different modeling methods.
5 Results and Validation

Results produced by the baseline model described in Chapter 4 are presented prior to discussion of validation. Measurements, made on pure and foundry alloy at various casting speeds, are compared to model predictions in the validation section.

5.1 Results

A considerable amount of information is produced by the steady state 3-dimensional coupled thermal - fluid flow model. Interpreting the results requires qualitative and quantitative analysis of pertinent field variables. One of the key solution variables necessary to understanding how the HDC process behaves is temperature. The steady-state temperature distribution over the surface of the domain is presented in Figure 5-1. The variation of temperature on the symmetry plane shows the complete temperature range shown; from the hot fluid in the transfer tubes to the cool solidified face. The thermal distribution over the faces of the transfer tubes and backing plate are relatively uniform. A significant thermal gradient is observed between the primary and secondary cooling regions due to the intense surface cooling caused by the water jets. After water jet impingement (further along the surface in the casting direction), limited reheating is observed. Reheating is caused by the reduction in heat transfer due to a change in the boiling behaviour (i.e. a change from jet impingement boiling to flow boiling), in combination with the ingots large thermal mass.
Figure 5-1: Steady state temperature distribution over the surface of the domain.

In order to understand the internal variation of structure/temperature, Figure 5-2 presents a translucent temperature distribution of the surfaces and isothermal surfaces which represent the liquidus (start of solidification) and solidus (end of solidification) are shown. From this the regions of liquid, mush, and solid are defined. Looking closely at intersection of the liquidus and backing plate along the bottom of the ingot, it can be seen that the height of the liquidus wavers in height across the width. This effect is due to localized heating of hot liquid entering the sump from the transfer tubes.
Figure 5-2: Translucent temperature distribution over the domain, with solidus (yellow) and liquidus (orange) isotherm surfaces.

While 3-dimensional images provide a qualitative evaluation of the results, more detailed quantitative information can be extracted. Figure 5-3 shows the variation of the isotherms representing the liquidus, 15% solid, 30% solid and solidus sump profiles extracted from the symmetry plane.
Figure 5-3: Isotherms representing the liquidus, 15% solid, 30% solid, and solidus on the symmetry plane. Top right shows the 3D domain and the symmetry plane sump profiles.

Besides thermal predictions, knowledge of the flow behaviour is important because it provides insight about how feeding and advection on heat occur. Figure 5-4, shows the symmetry plane isotherms and velocity vectors. Liquid aluminum passes through the transfer tubes to feed the sump. As the hot aluminum enters the sump, buoyancy and impingement on the solidification front direct the flow upward. After the hot liquid reaches the top, heat is extracted causing an increase in density, which drives the now cooler liquid down. This process produces a ‘clockwise’ current, which flows up the backing plate and down the solidification front. In addition it can be seen that the flow is significantly damped before 15% solid, is reached.
Velocity

Figure 5-4: Symmetry plane isotherms representing liquidus (red), 15% solid (green), 30% solid (light blue), and solidus (dark blue); in addition to velocity vectors which are coloured and sized based on velocity.

To give a more complete representation of flow behaviour, streamlines (which represent the path and velocity the liquid would follow) can be used. Figure 5-5 shows the liquidus, 30% solid, and solidus isotherm surfaces, in addition to streamlines which start at the inlets. As liquid exits the transfer tubes it flows upwards to the top of the ingot and then loops down. Some of this liquid will flow out to feed the wing region. Within the solid region, the streamlines run straight in the casting direction.
Figure 5-5: Translucent temperature distribution over the domain, with solidus (yellow), 30% solid (grey) and liquidus (orange) isosurfaces, in addition to streamlines coloured based on velocity which start at the inlets.

5.2 Validation

Various measurements and observations were used to evaluate the accuracy of the model and to provide overall validation. Additionally, the validation task provides insight into the inaccuracies that might exist. Sump depth measurements, SDAS measurements, and macroscopic examination were conducted on industrially cast material for comparison with the models predictions.

5.2.1 Sump Depth

The first method used to assess the HDC T-ingot model was comparison with measured sump profiles. End-of-cast sump profiles from foundry and pure aluminum castings were measured and compared to predicted isothermal surfaces. The procedure used to obtain the end of cast sumps involved sequentially lowering the metal head in the
tundish, stopping extraction and cooling, and opening the drain holes located at the bottom of the tundish. During drainage both solidification and remelting may occur, and non-coherent mushy material may slump. An example of an empty sump is shown in Figure 5-6. As can be seen, the transfer tubes did not completely drain likely due to slumped mushy material. Although the drained sump does not represent the exact steady state profile, it provides useful information on the near steady state profile. The sump measurements were conducted by Alcan on several different planes across the width. Figure 5-7 shows the locations of the 5 planes used for the foundry alloy ingots. For reference the solidus and liquidus symmetry plane sump profiles are shown in blue and red respectively.

![Figure 5-6: Photograph of an end of cast ingot (viewed in the casting direction).](image)
Figure 5-7: Location of foundry alloy sump profile measurement planes. Solidus (blue) and liquidus (red) sump isotherm profiles shown are shown on the symmetry plane.

**Foundry Alloy Sump Depth**

Sump measurements of the foundry alloy (A356) were conducted by Alcan on three cast ingots produced using a proprietary inlet geometry that will not be discussed here. The model domain was adjusted for this technology and run to steady state using the standard casting practice described in Chapter 4. Figures 5-8 to 5-12 compare the predicted sump depths to the measured depths for each measurement plane. Standard deviations for each height-width location were calculated based on the measurements from 3 ingots and are shown as error bars at each point. The predicted sump profiles were taken at the intersection of the measurement plane and steady state 30% solid isotherm surface. Selection of this location was based a profile that best fit the data. Considering that steady state predictions are being compared with ingot sump profiles measured after draining, the predictions fit the results reasonably well. It is interesting to note that larger standard deviations were present in the data above the maximum sump depth, relative to the data below. This is likely due to differences related to material
ripping from the top face, as apposed to slumping on the bottom face. Discussion about how sump profiles could have evolved throughout draining is discussed in the Transient Evolution of the Sump Profiles section.

Figure 5-8: Comparison of predicted sump profile with measured sump data for A356 at the 0 mm plane (symmetry plane).
Figure 5-9: Comparison of predicted sump profile with measured sump data for A356 at the 100 mm plane.

Figure 5-10: Comparison of predicted sump profile with measured sump data for A356 at the 200 mm plane.
Figure 5-11: Comparison of predicted sump profile with measured sump data for A356 at the 295 mm plane.

Figure 5-12: Comparison of predicted sump profile with measured sump data for A356 at the 365 mm plane.
**Pure Aluminum Sump Depth**

Sump measurements were made by Alcan on commercial purity aluminum T-ingots, cast using 3 different casting velocities; 0.002, 0.0025, and 0.0032 (m s\(^{-1}\)), referred to as casting practices 1, 2, and 3 respectfully. Measurements were made only on the top sump profile (i.e. sump face above the maximum depth) and on one ingot at each casting speed; thus standard deviations for the data points were not calculated. Figures 5-13 and 5-14 compare the predicted sump profile for casting practice 1 to measured sump, while Figures 5-15 to 5-17 are for casting practice 2, and Figures 5-18 to 5-20 are for casting practice 3. The predicted sump profiles were taken as the intersection of the plane and 50% solid isotherm surface. Evaluating the measured data and predicted sump profiles it can be seen that the fit is quite good at three casting speeds. This shows that the model is flexible enough to model reasonable changes in casting speed.
Figure 5-13: Comparison of predicted sump profile to measured profile for commercial purity aluminum at the 0 mm plane (symmetry plane) using casting practice 1.

Figure 5-14: Comparison of predicted sump profile to measured profile for commercial purity aluminum at the 332 mm plane using casting practice 1.

Figure 5-15: Comparison of predicted sump profile to measured profile for commercial purity aluminum at the 71 mm plane using casting practice 2.
Figure 5-16: Comparison of predicted sump profile to measured profile for commercial purity aluminum at the 150 mm plane using casting practice 2.

Figure 5-17: Comparison of predicted sump profile to measured profile for commercial purity aluminum at the 261 mm plane using casting practice 2.
Figure 5-18: Comparison of predicted sump profile to measured profile for commercial purity aluminum at the 0 mm plane (symmetry plane) using casting practice 3.

Figure 5-19: Comparison of predicted sump profile to measured profile for commercial purity aluminum at the 100 mm plane using casting practice 3.
Transient Evolution of the Sump Profiles

In an effort to assess the change in sump profile at the end of cast, the time required to drain the liquid metal was estimated. Numerical integration of Bernoulli’s equation developed in terms of discharge rate (seen in equation 5-1) and the tundish geometry was used.

\[ Q = CA\sqrt{2g(H - H_o)} \]  \[5-1\]

where \( Q \) is the discharge rate \([m^3 \text{ s}^{-1}]\), \( C \) is an orifice coefficient equal to 0.65 based on recommendations from Alcan personnel, \( A \) is the orifice area \( [m^2] \), \( g \) is the gravitational acceleration \([9.8 \text{ m s}^{-2}]\), \( H \) is the instantaneous surface height, and \( H_o \) is the orifice height. Using this method the predicted drain time was estimated to be 20 s. The predictions
were confirmed with thermal data from a thermocouple submerged in the tundish. The volume of liquid metal in the sump was neglected in this analysis due to the difficulty associated with describing the variation of volume with height. The liquid sump region represents an additional 20% of metal to be drained.

To understand how the sump may evolve during the 20 s required to drain it, the HDC model was run in transient mode without any metal loss. In one case, extraction was stopped, there was no change to the cooling conditions (Vcast=0; Full Cooling). While in the second case, extraction was stopped and cooling in the primary and secondary cooling regions was terminated (Vcast=0; Adiabatic). In reality the heat transfer conditions would evolve throughout the shut down; however using these limiting cases should provide estimates of the maximum change expected in the sump profile. The liquidus, 30% solid, and solidus isotherm profiles for the transient cases at the end of 20 seconds are compared to the steady state profiles in Figures 5-21 to 5-23. Observing these figures, a number of observations can be made. Comparing the adiabatic and full cooling simulations, the upper and central portions of the sump profiles are similar, while the lower portion shows a large difference particularly near the secondary water jet impingement location which is around 50 mm. Comparing the upper sump profile of transient simulations to the steady state simulation shows a relatively consistent inward (i.e. sump shrinking) shift of the sump profiles. It is not clear why the sump profiles are predicted to evolve in the manner shown; however it is hypothesized that buoyancy and a lack of advection are contributing to the counter-intuitive effects.
Figure 5-21: Maximum change in liquidus symmetry plane sump profile after 20s when casting is stopped and adiabatic (blue) or full cooling (red) thermal boundary conditions are applied, relative to steady state casting conditions (green).

Figure 5-22: Maximum change in 30% f_s symmetry plane sump profile after 20s when casting is stopped and adiabatic (blue) or full cooling (red) thermal boundary conditions are applied, relative to steady state casting conditions (green).
Figure 5-23: Maximum change in solidus symmetry plane sump profile after 20s when casting is stopped and adiabatic (blue) or full cooling (red) thermal boundary conditions are applied, relative to steady state casting conditions (green).

It should be noted that this transient analysis neglects the free surface (air-liquid aluminum) that evolves during the draining operation, as well as slumping of the low fraction solid mushy material. The minimum fraction solid that will exhibit enough strength/coherency to maintain its position is not known, but would likely occur within the 15-100 percent solid range. One conclusion which can be made is that the upper surface of the cast sump profile more accurately represents the steady state profile, while the bottom profile is less representative of the steady state profile due to mushy material slumping as the sump drains.
5.2.2 Secondary Dendrite Arm Spacing

Secondary Dendrite Arm Spacing (SDAS) measurements were conducted on samples cut from an industrially cast A356 T-ingot. Two locations (shown in Figure 5-24) were evaluated: location A provided information about fast (near surface) solidification, and location B represented slow (center) solidification occurring in the process. SDAS measurements were conducted by removing, mounting, grinding and polishing (up to 1μm) the A356 samples using traditional metallographic sample preparation techniques. Micrograph images of known magnification were taken and the SDAS was determined by measuring the length of at least 4 consecutive secondary dendrite arms at various locations until a total of at least 100 arms had been measured. The length of all the measurements was then divided by the number of arm spacings to provide an average SDAS. Figure 5-25 shows an example of the center A356 microstructure with two measurement locations and the number of arm spacings measured.

![Figure 5-24: Schematic of sample location and the corresponding average SDAS](image_url)

A - SDAS = 22 μm

B - SDAS = 41 μm
Temperature versus time histories at the SDAS sample locations were extracted from the steady state model by dividing the distance in the casting directing by the casting speed. This manipulation is based on the assumption that, at the temperature range of interest, the material is moving at the casting velocity. Primary phase solidification time was estimated by the time required to cool from the liquidus (613.5°C) to the eutectic start temperature (571.5°C). Using the primary phase solidification time and the following correlation, the SDAS at each location was predicted.
\[ SDAS = 11.84 \times \Delta t_{primary}^{0.32} \quad [5-2]^{48} \]

where SDAS is in \( \mu m \) and \( \Delta t_{primary} \) is the length of time it took for the primary aluminum phase to form [s]. As can be seen in Table 5-1 the predicted and measured SDAS are similar.

Table 5-1: Predicted and measured SDAS of industrially cast A356 T-ingot, at near surface (A) and center (B) locations on the symmetry plane.

<table>
<thead>
<tr>
<th>Location</th>
<th>SDAS [( \mu m )]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>predicted measured</td>
</tr>
<tr>
<td>A</td>
<td>21</td>
</tr>
<tr>
<td>B</td>
<td>53</td>
</tr>
</tbody>
</table>

### 5.2.3 Macrostructure

Post-cast analysis of the macrostructure formed in a T-ingot section of pure aluminum (Figure 5-26) was conducted to provide insight about the solidification processes occurring during the cast. The photograph in Figure 5-27 has been marked to show areas of interest. The lower wing area exhibits a fine grain size. This may be attributed to the solidification behaviour and/or the collection of solidified material that had broken or remelted from the coherent solid and settled on the flat wing. A seam in the microstructure (marked with a thick red dashed line) is observed running across the ingot; it is mostly horizontal in the central part of the ingot and becomes diagonal in the wing region. This seam is the location where the top and bottom solidification fronts meet. Other less obvious seams (marked with a dashed yellow line) are present in the wing region. These seams are the result of the top-side and bottom-side solidification
fronts meeting. Colouration attributed to grain size or orientation differences can be seen near the inlets, which may indicate the dominant directions of flow from the inlets.

Figure 5-26: Post-cast microstructure – pure Al

Figure 5-27: Macrostructure of ingot slice with observed features marked
Comparing the macrostructural observations in Figure 5-27 to the predicted solidus depth (Figure 5-28a; which is shown looking along the casting direction where red is deepest and dark blue is shallow) and streamlines (Figure 5-28b, shown looking along the casting direction where red is high velocity and dark blue is slow velocity), a number of similarities are observable. First, the location of the maximum sump depth follows a path similar to that of the Top-Bottom solidification front intersection line, being horizontal in the central region of the ingot and diagonal (starting at about the second inlet from the outside) out toward the wing region. Also, observing the streamlines, the majority of the flow exiting from the inlet closest to the outside flows diagonally upward, thus bearing a striking resemblance to the dark regions of the macrostructure (flow lines).

Figure 5-28: Images parallel to the casting direction for model predictions of a) solidus isothermal surface coloured based on sump depth (red - deep, dark blue - shallow); b) streamlines from inlets (red - high velocity; dark blue – slow velocity)

5.2.4 Summary of Validation

Validation of a model is critical to assess its ability to produce accurate predictions. To validate the HDC model, multiple conditions (casting speeds, and alloys)
were used to confirm that the model was robust enough to adapt to reasonable process changes. Various techniques (sump drainage, microstructure, and macrostructure) were also used to reveal different information about the process. While the HDC model has been validated reasonably well using different conditions and techniques, further validation could still be conducted. A technique which would provide very useful data would be the use of cast-in thermocouples. Cast-in thermocouples would provide high precision temperature versus location data from steady state industrial conditions, allowing model accuracy to be further evaluated.
6 Sensitivity

Sensitivity analysis was used during the development of the model described in Chapter 4 to assess the impact of changing the methods used to describe certain phenomena such as buoyancy and flow damping. Additionally, the effect of changing numerical and process parameters was also assessed. During development, the results of the sensitivity analysis helped identify robust methods to describe physical phenomena. The analysis presented here has employed the model presented in Chapter 4 as a baseline.

6.1 Effects of Modeling Methodologies

The techniques used to numerically represent physical phenomena including buoyancy, variation of enthalpy, and flow damping were assessed. In this case, different techniques for describing the same phenomena were implemented and the effects on the predictions used to make decisions on methodology.

6.1.1 Buoyancy Method

The method of including buoyancy was evaluated to understand how it affects the fluid flow and thermal predictions. Four cases which used different buoyancy and/or density variations relative to the baseline simulation were compared; these included: a non-buoyant simulation, two full-buoyancy models which had alternate density variation with temperature, and a Boussinesq buoyancy approximation. All of the models, except the one which used the Boussinesq approximation, had density varying as a function of temperature. The non-buoyant and baseline simulations had density varying as a function of temperature above the liquidus, while the full-buoyancy simulations had density...
varying as a function of temperature above 50% solid and the solidus, respectively. Description of the full-buoyancy and Boussinesq buoyancy models can be found within the literature review section.

The predicted isotherm surfaces and streamlines for each case have been overlaid on the geometry in Figures 6-1 to 6-5. The isothermal surfaces represent the solidus, 30% solid, and liquidus sump profiles, while the streamlines represent the path and velocity that massless particles would follow when injected from the inlets. The isotherm profiles representing 30% solid on the symmetry plane are shown in Figure 6-6.

Comparing the streamlines of the non-buoyant simulation (Figure 6-2) to the other simulations with buoyant effects (Figures 6-1, 6-4, 6-3, or 6-5), it can be seen that the streamlines in the former case are more diffuse and lack the prominent upward flow from the transfer tubes to the top surface of the ingot. The non-buoyant model also showed the lowest and deepest symmetry plane sump (Figure 6-6), which is expected because of the influence buoyancy has on cooling the liquid metal in the sump. In Figure 6-6, the full-buoyancy predictions indicate that as the range of density variation is enlarged (i.e. variation in density at temperatures above: the liquidus, 50% solid, and the solidus) the sump profile shifts upward and becomes shallower. This result occurs because buoyancy effects increase as larger density variations are accounted for. Figures 6-1, 6-3, and 6-4 also show the 3-dimensional effects of this within the wing region of the T-ingot (upper left part of the domain). As stronger buoyancy forces are implemented, the solidification front in the lower wing region changes from being parallel to being diagonal with respect to the T-ingot faces (refer to Figure 6-4). The predictions produced
using the Boussinesq buoyancy method are similar to the full-buoyancy prediction that has density variation at temperatures greater than 50% solid but with a shallower sump.

Based on a comparison of the measured and predicted sump profiles, the full-buoyancy model with density variations occurring at temperatures greater than the liquidus was selected to be a suitable buoyancy method. The selection of this method was also influenced by solidification considerations. While the model treats liquid, mush, and solid material as one phase, in reality two phases are present (liquid and solid). If columnar grain growth occurs, such as on the ingot surface, little or no buoyancy is expected in the solid. If equiaxed solidification occurs, buoyancy will affect metal with low fraction solid since a coherent dendritic network has not yet formed. However, this behaviour should cease once Darcy forces become significant (i.e. at 15 to 30% solid).

Figure 6-1: Full-buoyancy with density variation at temperatures greater than the liquidus (identical to baseline case)
Figure 6-2: Non-buoyant with density variation at temperatures greater than the liquidus

Figure 6-3: Full-buoyancy with density variation at temperatures greater than 50% solid
Figure 6-4: Full-buoyancy with density variation at temperatures greater than the solidus, showing a shifted sump profile in the wing region (see arrow)

Figure 6-5: Boussinesq buoyancy model (CFX implementation)
The truncation of the density variation below the liquidus for proper buoyancy description results in a variation of enthalpy in the model. The sensitivity of the model to this density variation was evaluated using non-buoyant conditions to limit variations in flow patterns. All of the models used an effective specific heat, $C_p^*$, which included the release of latent heat during solidification. Three formulations were compared. Case-1 had density varying as a function of temperature above the solidus. Case-2 had density varying as a function of temperature above the liquidus. Case-3 also had density varying as a function of temperature above the liquidus; however, an energy correction was applied. The energy correction multiplies the effective specific heat by the ratio of the
actual density to modified density \((\rho/\rho_{mod})\). This is done to include energy that would otherwise not be accounted for when density variations are truncated.

The isotherms on the symmetry plane representing 30\% solid for each case are compared in Figure 6-7. The largest difference occurs in sump depth predicted, while the isotherms at the top and bottom of the ingot appear to be unaffected. This is due to the difference in thermal gradient (i.e. low vs. high respectively) at these locations. The largest differences are observable between Case-1 and Case-2. Case-2 has the shallowest sump because enthalpy is under estimated at temperatures below the liquidus. Case-3 more closely matched Case-1, because enthalpy was more accurately accounted for due to the correction factor. The difference in the sump profiles predictions for Case-1 and Case-3 are attributed to the additional advection occurring in the mushy zone of the Case-1 simulation due to thermal contraction being accounted for. A drawback of including contraction in the mushy is that numerical difficulties develop. This is due to the Darcy term fixing the advection rate while feeding is required to conserve mass.
Figure 6-7: Isotherms representing the 30% solid profile on the symmetry plane, showing the effect of density variation methods on non-buoyant simulations. Case-1: \( \rho = f(T > T_{soj}) \), Case-2: \( \rho = f(T > T_{liq}) \), Case-3: \( \rho = f(T > T_{liq}) \)-energy corrected

### 6.1.3 Flow Damping

A Darcy momentum source term is applied in the model to dampen flow in the mushy and solid material. As reported in the literature review chapter, the variation of the Darcy term is an inverse function of the SDAS squared. Consequently, finer SDAS causes the Darcy source term to ramp more rapidly as fraction solid increases. The effect of SDAS variation on model predictions was evaluated by varying the SDAS from the baseline value of 0.05 mm to 0.01 mm, 0.1 mm, and 0.5 mm. The results of these runs are compared in Figure 6-8. The liquidus profile changes little with variation of SDAS near the top and bottom of the ingot (which has high thermal gradients). However, the liquidus sump profile at the center of the ingot changes dramatically as the SDAS
increases from 0.1 mm to 0.5 mm. Changing the SDAS from 0.1 mm to 0.5 mm changes the fraction solid value where the $\mu/K$ component (source term coefficient) of the Darcy term reaches the limit of $10^6$ [kg m$^{-3}$ s$^{-1}$] from 0.175 to 0.45 respectively. The same observations can be made for the 30% solid curves, shown in Figure 6-9, but with less prominent effects.

![Figure 6-8](image)

**Figure 6-8:** Isotherms representing the liquidus profile on the symmetry plane for SDAS of 0.01, 0.05, 0.1, 0.5 mm

![Figure 6-9](image)

**Figure 6-9:** Isotherms representing the 30% solid profile on the symmetry plane for SDAS of 0.01, 0.05, 0.1, and 0.5 mm

78
As described in chapter 4, limiting the Darcy momentum source term coefficient to a maximum value can improve convergence. Within the CFX literature, a momentum source term coefficient value of $10^5 \text{ [kg m}^{-3}\text{ s}^{-1}]$ is considered to be sufficient to produce adequate damping.\(^{49}\) An additional sensitivity analysis was conducted to assess the impact of the maximum value which the Darcy source term coefficient could reach. Observing Figures 6-10 and 6-11 it can be seen that the liquidus sump profile changes considerably as the maximum value of the Darcy source term coefficient is changed. Low maximum Darcy source term coefficient values ($10^4$ and $10^5 \text{ kg m}^{-3}\text{ s}^{-1}$) result in significant shift in the profile because the maximum damping forces achieved are insufficient to counteract buoyancy, and the corresponding solid velocity is not set accurately. To better highlight this result, Figure 6-12 shows the predicted solidus isotherm (white line) and casting direction velocity contours of solidified material (where the casting speed was 0.00175 m s\(^{-1}\) and the contours were clipped approximately 3\% above and below, 0.0018 m s\(^{-1}\) and 0.0017 m s\(^{-1}\), respectively). Ideally all of the domain which is solid (i.e. to the right of the solidus) should be moving at the casting velocity. Areas in the solid that are shaded black highlight the material whose velocity has not been set to within 3\% of the intended casting velocity. It can be seen that as the maximum value of the Darcy source term coefficient is increased (top to bottom) the velocity in the solid progressively approaches the casting speed. However as the Darcy source term coefficient was increased from $10^6$ to $10^7 \text{ kg m}^{-3}\text{ s}^{-1}$ convergence was lost since the maximum residuals no longer dropped below $10^{-4}$.\(^{314}\)
Figure 6-10: Isotherms representing the liquidus profile on the symmetry plane for Darcy source term coefficient cut off at $10^4$, $10^5$, $10^6$, and $10^7$ kg m$^{-3}$ s$^{-1}$

Figure 6-11: Isotherms representing the 30% solid profile on the symmetry plane for Darcy source term coefficient cut off at $10^4$, $10^5$, $10^6$, and $10^7$ kg m$^{-3}$ s$^{-1}$
Figure 6-12: Solidus isotherm (white line) and clipped casting direction velocity contours of solidified material for models where the Darcy momentum source term coefficient has been cut off at: a) $10^4$, b) $10^5$, c) $10^6$, and d) $10^7$ kg m$^{-3}$ s$^{-1}$. The intended casting speed was 0.00175 m s$^{-1}$ and the contours were clipped approximately 3% above and below, 0.0018 m s$^{-1}$ and 0.0017 m s$^{-1}$, respectively.
6.2 Numerical Sensitivity

The sensitivity of the model predictions to variations in numerical parameters such as domain length and mesh size have also been evaluated. For these cases, the same modeling methodology and boundary conditions as the baseline model were employed.

6.2.1 Domain Length

The length of the domain was varied to confirm that the thermal boundary condition \((dT/dz=0)\) that is automatically applied at the outlets does not influence the sump predictions. Figure 6-13 compares the temperature versus distance extracted along a sample line whose location is shown on the inset figure as the top right, for models with different domain lengths (0.6 m and 1 m, measured from backing plate to the outlet). The simulation with a shorter domain predicts the same temperature variation as the long domain model for most of the compared length. Near the outlet of the short domain case a small variation is observed at the region close (~0.05 m) to its outlet; however because the sump region is the location of interest the small domain is suitable for all of the cases presented in this thesis.
6.2.2 Mesh Size

Simulations with varying mesh size were assessed by comparing computational requirements and solution results. The domain was meshed with tetrahedral elements of varying size by specifying different maximum edge lengths. Table 6-1 lists the mesh statistics (maximum edge length, number of elements, nodes, maximum edge-length ratio) and approximate computational times for the cases analysed.

Table 6-1: Mesh and computational data

<table>
<thead>
<tr>
<th></th>
<th>Coarse</th>
<th>Medium</th>
<th>Fine</th>
<th>Finer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Edge Length [mm]</td>
<td>20</td>
<td>15</td>
<td>10</td>
<td>7</td>
</tr>
<tr>
<td>Number of Nodes</td>
<td>26799</td>
<td>44279</td>
<td>122071</td>
<td>341527</td>
</tr>
<tr>
<td>Number of Tetrahedral Elements</td>
<td>137770</td>
<td>235008</td>
<td>674341</td>
<td>1917128</td>
</tr>
<tr>
<td>Max Edge Length Ratio</td>
<td>8.26</td>
<td>7.86</td>
<td>6.15</td>
<td>7.89</td>
</tr>
<tr>
<td>Computation Time [hrs]</td>
<td>25</td>
<td>42</td>
<td>102</td>
<td>187</td>
</tr>
</tbody>
</table>

(2.8 GHz Intel Xeon processor)
Figure 6-14 shows the effect of mesh size on the symmetry plane temperature distribution in each case. The 20 mm mesh exhibits the same temperature trends and features as the 7 mm mesh; except numerical noise attributed to the coarse mesh causes a rough temperature distribution. Small variations or sensitivities are observed between the results from the 15, 10, and 7 mm mesh cases. Considering the improvement of resolution, accuracy, and increased computational time associated with using a finer mesh; it was decided that the 15 mm mesh was a reasonable compromise. To help rationalize this decision the computation time for all of the models presented in this thesis (~30) was estimated. The computation time of 30 simulations using the 15 mm mesh, on a 2.8 GHz Intel Xeon processor, would be 67 days, while the 7 mm mesh would be 254 days.
The cases examined use a uniform maximum edge length throughout the domain. One technique used for mesh optimization is to refine the mesh in regions with high gradients and coarsen the mesh in regions of low gradients. This technique leads to a
mesh that is optimized for a specific set of casting conditions. As casting conditions change, the mesh needs to evolve due to changes in the solution gradients. Employing this technique results in additional uncertainty pertaining to whether all of the simulations have equal quality mesh.

6.3 Process Parameters

One obvious use for the model is to predict how changes in process parameters affect the fluid flow and heat transfer in HDC T-ingot casting. Numerous process parameters could be investigated, but in some cases boundary conditions would have to be revised to accurately represent the changes. Alternately, reasonable changes in parameters such as casting speed or casting temperature can be made without extensive modification to the boundary conditions.

6.3.1 Casting Temperature

The effect of casting temperature was evaluated by changing the temperature in 10°C intervals between 660°C and 690°C. Figure 6-15 shows isotherm profiles corresponding to 30% solid for each case. Changing the casting temperature resulted in little change to the sump profile. Close review of the region in close proximity to the mould, shown in Figure 6-15-b and c, shows a small expansion of the sump with increase in casting temperature.
Figure 6-15: Isotherms representing the 30% solid profile on the symmetry plane for casting temperatures of 660°C, 670°C, 680°C, and 690°C. a) Full plot of isotherms, b) Local (top of ingot) plot of isotherm, c) Local (bottom of ingot) plot isotherm
6.3.2 Casting Speed

The effect of casting speed was evaluated from 0.00125 m s\(^{-1}\) to 0.002 m s\(^{-1}\) in intervals of 0.00025 m/s from the base model described in Chapter 4. The liquidus and 30% solid isotherm profile on the symmetry plane are plotted in Figures 6-16 and 6-17 respectively for each casting case. As can be seen the casting speed has a significant effect on the sump profile. The maximum depths of the liquidus and 30% solid isotherms were extracted and plotted as a function of casting speed in Figure 6-18. The linear trend agrees with previous findings documented by Grandfield et al.\(^{27}\)

![Graph showing sump depth as a function of casting speed]

*Figure 6-16: Isotherms representing the liquidus isotherm on the Symmetry plane for casting speeds of 0.00125, 0.0015, 0.00175, and 0.002 m s\(^{-1}\)*
Figure 6-17: Isotherms representing 30% solid on the symmetry plane for casting speeds of 0.00125, 0.0015, 0.00175, and 0.002 m s$^{-1}$.

Figure 6-18: Maximum depth of the 30% solid and liquidus isotherms occurring on the symmetry plane for casting speeds of 0.00125, 0.0015, 0.00175, and 0.002 m s$^{-1}$, with corresponding linear trend lines.
6.4 Summary of Sensitivity

To briefly summarize the sensitivity of the modelling methodologies and process parameters, the variation in a single quantity was assessed. While a single measurement does not represent all of the complex changes occurring over the domain, it does give an overview of model sensitivity. The single quantity used to compare sensitivity was the percentage change of the maximum 30% solid sump depth relative to the baseline model. Table 6-2, summarizes the effects of modelling methodologies and process parameters on the maximum 30% solid sump depth.

Table 6-2: Single parameter summary of sensitivity

<table>
<thead>
<tr>
<th>Change from Baseline</th>
<th>Change Relative to Baseline</th>
<th>Modeling Methodology</th>
<th>Change Relative to Baseline</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Buoyancy Method</td>
<td></td>
</tr>
<tr>
<td>Buoyancy Method</td>
<td></td>
<td>Full: $\rho = f(T &gt; T_{50%soi})$</td>
<td>-0.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Full: $\rho = f(T &gt; T_{sol})$</td>
<td>-1.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Non-Buoyant</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Boussinesq</td>
<td>-5.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SDAS [mm]</td>
<td>0.01</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td>-1.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>7.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Darcy Coefficient Cut-off [kg m$^{-3}$ s$^{-1}$]</td>
<td>10000</td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1000000</td>
<td>5.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10000000</td>
<td>-2.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy Method*</td>
<td></td>
<td>$Cp^* - \rho = f(T &gt; T_{liq})$</td>
<td>-3.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$Cp^* - \rho = f(T &gt; T_{sol})$</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Casting Temperature [$^\circ$C]</td>
<td>660</td>
<td>-1.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>670</td>
<td>-0.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>690</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Casting Speed [m s$^{-1}$]</td>
<td>0.00125</td>
<td>-28.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.0015</td>
<td>-13.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.002</td>
<td>13.6</td>
<td></td>
</tr>
</tbody>
</table>

* percent change of the maximum 30% solid sump depth relative to the baseline model
* Non-buoyant simulations used, thus Corrected $Cp^* - \rho = f(T > T_{liq})$ was used for comparison
Reviewing the modelling methodology results, it can be seen that all of the parameter changes produced less than a 10% shift in the maximum 30% solid sump profile. While this shows that a single parameter change has a relatively small effect, it should be noted that if multiple changes were implemented a compounding effect could cause larger changes.

Process parameters (casting temperature and casting speed) were increased and decreased to illustrate the sensitivity of the process to changes in parameters. As was noted previously (section 6.3.1 & 6.3.2), the process has little sensitivity to casting temperature and a significant sensitivity to the casting speed.
7 Summary and Conclusion

A methodical approach has been taken to develop and validate a steady state coupled fluid flow / heat transfer model of the HDC casting process using the commercial CFD package, Ansys CFX 10.0. Casting practices for aluminum alloy A356 and pure aluminum were simulated using the same model; however slight changes were made so that the properties and behaviour of the metals were represented accurately.

The model is a single continuum in which only cast aluminum is considered and liquid/solid differentiation is based on temperature dependent properties. Effects of turbulence, buoyancy, and solidification were included. Turbulence was accounted for using a modified $k$-$\varepsilon$ turbulence model with elimination of turbulence effects in the solid. Buoyancy was implemented through a ‘full’ buoyancy model in which density variation was accounted for at temperatures above the liquidus. Solidification effects were introduced by describing the evolution of latent heat and flow damping. Latent heat was evolved using an effective specific heat method, while the fluid flow was damped in the mush and solid using a Darcy momentum source term.

The model was validated by comparing predictions with measurements / observations made on industrial cast T-ingots. Drained sump profiles of A356 and pure aluminum T-ingots were mapped and compared to the model predictions. In all 4 cases (one A356 and three pure aluminum at different casting speeds) the predicted sump profiles matched the measured profiles reasonably well. The variations observed were expected since steady state predictions were compared to drained and solidified sumps that evolved throughout the draining process. SDAS measurements were performed on microstructural samples that were removed from an A356 T-ingot at the symmetry plane.
near surface and center. Using thermal predictions, an SDAS was estimated using a
correlation based on the time for the primary phase to solidify. The measured and
predicted SDAS matched closely. The macrostructure of a pure aluminum ingot revealed
unique solidification features. Striking similarities could be seen between model results
(fluid flow streamlines and thermal isosurfaces) and these macrostructure features.

Throughout the development of the model, the sensitivity of model predictions to
process and numeric parameters was evaluated. A final comprehensive sensitivity
analysis was conducted using the baseline model (described in Chapter 4). Three areas
were analysed including: modelling methodologies, numeric changes, and process
parameters. The modelling methodologies evaluated included buoyancy, flow damping,
and thermal energy correction, while numerical changes looked at mesh size and domain
length effects. The process parameters that were evaluated included casting temperature
and casting velocity.

Modelling T-ingot HDC casting has been a success. The model is robust and
capable of accurately predicting the thermal and flow fields of industrially cast pure and
foundry alloy aluminum T-ingot using various casting speeds. Recently, knowledge
gained from the model has allowed Alcan to significantly increase their maximum casting
speed. Further analysis using the model should lead to other advancements.
8 Further Work

Further work which warrants investigation includes validation, model development, and model usage activities. Further validation experiments using cast-in thermocouples are suggested to provide precise steady state temperature data versus location. This data could be used to confirm the sump location and thermal behaviour. Flow field validation could be conducted through melting experiments using the techniques described in the literature review. Implementing either of these techniques on an industrial HDC casting would not be easy; however, the data that could be collected would very useful.

Now that the HDC T-ingot model has been developed and validated, it can be used as a tool to provide further insight into how the HDC process works. A transient analysis of the start-up would provide insight about how steady state operation is achieved. Also if a coupled or un-coupled, finite element thermal-stress model were developed then deformation or hot-tearing could also be analysed.
References


20 ANSYS CFX-10.0 documentation, “Theory - Basic Solver Capability Theory - Buoyancy”

21 ANSYS CFX-10.0 documentation, “Modelling - Basic Capabilities Modelling - Physical Models”


24 S. Chakraborty, N. Chakraborty, P. Kumar and P. Dutta, “Studies on turbulent momentum, heat, and species transport during binary alloy solidification in a


44 Chen X. Grant, “Feeding Blockage of Aluminum Horizontal Continuous Casting”, International Conference of Aluminum Alloys 10, Vancouver, 2006


46 ANSYS CFX 10.0 documentation, “Modelling, Advice on Flow Modelling, Monitoring and Obtaining Convergence, Residual Type and Target".


49 ANSYS CFX-10.0 Documentation, “Modelling / Basic Capabilities Modelling / Physical Models – General Momentum Source”. 
## Appendix A

### Foundry Aluminum Data – data developed from 41

<table>
<thead>
<tr>
<th>Temperature °C</th>
<th>Fraction Solid</th>
<th>Density kg m(^{-3})</th>
<th>Modified Density kg m(^{-3})</th>
<th>Specific Heat J kg(^{-1}) K(^{-1})</th>
<th>Effective Specific Heat, density corrected J kg(^{-1}) K(^{-1})</th>
<th>Thermal Conductivity W m(^{-1}) K(^{-1})</th>
<th>Viscosity m Pa s</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>1</td>
<td>2680</td>
<td>2406</td>
<td>880</td>
<td>941.5159</td>
<td>163</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>1</td>
<td>2662</td>
<td>2406</td>
<td>921</td>
<td>985.382</td>
<td>165</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>1</td>
<td>2641</td>
<td>2406</td>
<td>967</td>
<td>1034.598</td>
<td>162</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>1</td>
<td>2620</td>
<td>2406</td>
<td>1011</td>
<td>1081.673</td>
<td>155</td>
<td></td>
</tr>
<tr>
<td>380</td>
<td>1</td>
<td>2602</td>
<td>2406</td>
<td>1046</td>
<td>1119.12</td>
<td>153</td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>1</td>
<td>2600</td>
<td>2406</td>
<td>1055</td>
<td>1174.755</td>
<td>153</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>1</td>
<td>2578</td>
<td>2406</td>
<td>1098</td>
<td>1172.747</td>
<td>145</td>
<td></td>
</tr>
<tr>
<td>550</td>
<td>1</td>
<td>2578</td>
<td>2406</td>
<td>1120</td>
<td>2697.51</td>
<td>145</td>
<td></td>
</tr>
<tr>
<td>565</td>
<td>0.95</td>
<td>2569</td>
<td>2406</td>
<td>1126</td>
<td>12645.09</td>
<td>141</td>
<td></td>
</tr>
<tr>
<td>567</td>
<td>0.9</td>
<td>2561</td>
<td>2406</td>
<td>1127</td>
<td>46910.35</td>
<td>137</td>
<td></td>
</tr>
<tr>
<td>568</td>
<td>0.8</td>
<td>2544</td>
<td>2406</td>
<td>1128</td>
<td>46847.77</td>
<td>129</td>
<td></td>
</tr>
<tr>
<td>569</td>
<td>0.7</td>
<td>2526</td>
<td>2406</td>
<td>1130</td>
<td>46785</td>
<td>121</td>
<td></td>
</tr>
<tr>
<td>570</td>
<td>0.6</td>
<td>2509</td>
<td>2406</td>
<td>1131</td>
<td>46722.42</td>
<td>113</td>
<td></td>
</tr>
<tr>
<td>571</td>
<td>0.5</td>
<td>2492</td>
<td>2406</td>
<td>1132</td>
<td>8713.005</td>
<td>105</td>
<td></td>
</tr>
<tr>
<td>577</td>
<td>0.4</td>
<td>2475</td>
<td>2406</td>
<td>1140</td>
<td>4578.265</td>
<td>97</td>
<td></td>
</tr>
<tr>
<td>590</td>
<td>0.3</td>
<td>2458</td>
<td>2406</td>
<td>1158</td>
<td>5524.98</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>600</td>
<td>0.2</td>
<td>2440</td>
<td>2406</td>
<td>1171</td>
<td>7327.915</td>
<td>82</td>
<td></td>
</tr>
<tr>
<td>607</td>
<td>0.1</td>
<td>2423</td>
<td>2406</td>
<td>1181</td>
<td>11936.38</td>
<td>74</td>
<td></td>
</tr>
<tr>
<td>609</td>
<td>0.05</td>
<td>2415</td>
<td>2406</td>
<td>1183</td>
<td>11902.64</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>611</td>
<td>0</td>
<td>2406</td>
<td>2406</td>
<td>1186</td>
<td>1190</td>
<td>66</td>
<td></td>
</tr>
<tr>
<td>614</td>
<td>0</td>
<td>2406</td>
<td>2406</td>
<td>1190</td>
<td>1190</td>
<td>66</td>
<td>1.38</td>
</tr>
<tr>
<td>700</td>
<td>0</td>
<td>2379</td>
<td>2379</td>
<td>1190</td>
<td>1190</td>
<td>68</td>
<td>1.2</td>
</tr>
<tr>
<td>800</td>
<td>0</td>
<td>2352</td>
<td>2352</td>
<td>1190</td>
<td>1190</td>
<td>70</td>
<td>1.1</td>
</tr>
<tr>
<td>900</td>
<td>0</td>
<td>2325</td>
<td>2325</td>
<td>1190</td>
<td>1190</td>
<td>72</td>
<td>1</td>
</tr>
<tr>
<td>1000</td>
<td>0</td>
<td>2300</td>
<td>2300</td>
<td>1190</td>
<td>1190</td>
<td>74</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Latent Heat = 249000 J/kg
Appendix B

Commercially Pure Aluminum Data
data developed from 41

<table>
<thead>
<tr>
<th>Temperature</th>
<th>fs</th>
<th>Density (kg m(^{-3}))</th>
<th>Modified Density (kg m(^{-3}))</th>
<th>Specific Heat (J kg(^{-1}) K(^{-1}))</th>
<th>Effective Specific Heat, density corrected (J kg(^{-1}) K(^{-1}))</th>
<th>Thermal Conductivity (W m(^{-1}) K(^{-1}))</th>
<th>Viscosity (m Pa s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>1</td>
<td>2702</td>
<td>2380</td>
<td>905</td>
<td>1027</td>
<td>237</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>1</td>
<td>2685</td>
<td>2380</td>
<td>945</td>
<td>1021</td>
<td>240</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>1</td>
<td>2662</td>
<td>2380</td>
<td>990</td>
<td>1012</td>
<td>238</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>1</td>
<td>2640</td>
<td>2380</td>
<td>1030</td>
<td>1004</td>
<td>233</td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>1</td>
<td>2617</td>
<td>2380</td>
<td>1070</td>
<td>995</td>
<td>228</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>1</td>
<td>2594</td>
<td>2380</td>
<td>1100</td>
<td>986</td>
<td>222</td>
<td></td>
</tr>
<tr>
<td>600</td>
<td>1</td>
<td>2571</td>
<td>2380</td>
<td>1150</td>
<td>978</td>
<td>215</td>
<td></td>
</tr>
<tr>
<td>634</td>
<td>1</td>
<td>2564</td>
<td>2380</td>
<td>1167</td>
<td>975</td>
<td>211</td>
<td></td>
</tr>
<tr>
<td>635</td>
<td>1</td>
<td>2557</td>
<td>2380</td>
<td>1168</td>
<td>972</td>
<td>207</td>
<td></td>
</tr>
<tr>
<td>636</td>
<td>0.96</td>
<td>2550</td>
<td>2380</td>
<td>1168</td>
<td>18180</td>
<td>202</td>
<td></td>
</tr>
<tr>
<td>659</td>
<td>0.04</td>
<td>2394</td>
<td>2380</td>
<td>1180</td>
<td>17080</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>660</td>
<td>0</td>
<td>2387</td>
<td>2387</td>
<td>1180</td>
<td>1180</td>
<td>95</td>
<td></td>
</tr>
<tr>
<td>661</td>
<td>0</td>
<td>2380</td>
<td>2380</td>
<td>1180</td>
<td>1180</td>
<td>91</td>
<td>1.11</td>
</tr>
<tr>
<td>700</td>
<td>0</td>
<td>2366</td>
<td>2366</td>
<td>1180</td>
<td>1180</td>
<td>92</td>
<td>1.049</td>
</tr>
<tr>
<td>800</td>
<td>0</td>
<td>2331</td>
<td>2331</td>
<td>1180</td>
<td>1180</td>
<td>96</td>
<td>0.93</td>
</tr>
<tr>
<td>900</td>
<td>0</td>
<td>2296</td>
<td>2296</td>
<td>1180</td>
<td>1180</td>
<td>99</td>
<td>0.83*</td>
</tr>
<tr>
<td>1000</td>
<td>0</td>
<td>2261</td>
<td>2261</td>
<td>1180</td>
<td>1180</td>
<td>103</td>
<td>0.76*</td>
</tr>
</tbody>
</table>

* extrapolated

Latent Heat = 395000 J/kg