A Mathematical and Experimental Study of Inclusion Behavior at a Steel-Slag Interface

Jenny Wikström

Doctoral Thesis

Royal Institute of Technology
School of Industrial Engineering and Management
Department of Materials Science and Engineering
Division of Applied Process Metallurgy
SE-100 44 Stockholm
Sweden
Jenny Wikström. *A Mathematical and Experimental Study of Inclusion Behavior at a Steel-Slag Interface*

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

ISRN KTH/MSE--07/60--SE+APRMETU/AVH  
ISBN 978-91-7178-781-1

© The Author
To my heart’s greatest joy

Patrik and our son Hugo
ABSTRACT

The aim of this thesis work is to increase the knowledge of inclusion behavior at the steel-slag interface by mathematical modeling and in-situ Confocal Scanning Laser Microscope experiments. Mathematical models based on the equation of motion predicting liquid and solid inclusion behavior was first investigated. Four main forces, the buoyancy force, the added mass force, the rebound force and the drag force, act on the inclusion as it crosses the interface. There are three types of behavior an inclusion at the steel-slag interface can adopt. These are a) pass, which means that the inclusion is separated to the slag, b) remain, where the inclusion stays at the interface without being fully transferred to the slag or c) oscillate, and the inclusion rises and descends at the interface until the motion is dampened out by the interfacial forces. The studies showed the importance of accurate experimental physical property data. Application of the models to industrial conditions illustrated that useful plots could be made showing the industry how to optimize their interfacial properties in the ladle and tundish to obtain maximum inclusion separation.

In-situ Confocal Scanning Laser Microscope (CSLM) experiments were carried out in order to study agglomeration of liquid and semi liquid inclusions at the steel-gas and steel-slag interfaces and in the slag. Liquid-liquid inclusion agglomeration at steel-gas and steel-slag interfaces was seen to not occur without using force. However, when already transferred to the slag the inclusions agglomerated freely due to a higher free energy force. Comparison of experimental and theoretical agglomeration force showed good agreement between experiments and theory.

The main conclusion of this work is that inclusion separation is a complex field of study and there exist no model that takes everything into account. Here the tendency for inclusion transfer and how to manipulate the physical properties for inclusion separation together with agglomeration experiments have been studied. For the future maybe coupling of models for computational fluid dynamics, agglomeration, inclusion separation, dissolution and slag entrainment in addition with experimental physical property data can provide a better overview and understanding.

Keywords: mathematical modeling, inclusion separation, tundish, ladle, slag, steel-slag interface, CSLM experiments, agglomeration, physical properties
ACKNOWLEDGMENTS

First, and most of all, I would like to express my sincere gratitude and appreciation to Professor Pär Jönsson, my supervisor throughout this work for his patience, support and positive attitude during my work towards this doctoral thesis.

I also would like to thank Professor Keiji Nakajima for his help, comments and fruitful discussions during the years.

I would like to thank Dr Anders Tilliander for his help during my work especially with respect to the discussions regarding my experimental results.

I would also like to thank Dr Hiroyuki Shibata and Professor Shozo Mizoguchi at Tohoku University for helping me with my experiments and taking good care of me when I visited their laboratory in Sendai.

Dr Robert Eriksson helped me when I started my studies and I wish to thank him for his help and guidance.

I am very thankful to the Swedish Steel Producers Association and STEM for financing my work.

Many thanks to my colleagues and friends at the Department of Material Science and Engineering, especially Line Hallgren (my room mate), Johan Björklund, Niklas Kojola, Maria Swartling, Jesper Janis, Mikael Ersson, Mattias Warne, and Margareta Andersson for all their help and laughs during the years. Not to forget my former colleagues Annie Nordqvist, Jesper Appelberg, Martin Bjurström, Johan Ekengård and Joel Gustafsson who where there for me in the beginning.

Last but not least my parents Monica and Erik, my brother Johan, relatives and four legged friends are greatly acknowledged for their never ending love and for always believing in me.

Stockholm, August 2007
Jenny Wikström
SUPPLEMENTS
This thesis is based on the following supplements:

Supplement 1: “Solid Inclusion Transfer at a Steel-Slag Interface with focus on Tundish Conditions”
J. Wikström, K. Nakajima, R. Eriksson and P. Jönsson

Supplement 2: “A Mathematical Model to Study Liquid Inclusion Behavior at the Steel-Slag Interface”
J. Wikström, K. Nakajima, R. Eriksson and P. Jönsson

Supplement 3: “In-situ Studies of Agglomeration Between Al₂O₃-CaO Inclusions at Metal-Gas, Metal-Slag Interfaces and in the Slag”
J. Wikström, K. Nakajima, H. Shibata, A. Tilliander and P. Jönsson
Submitted to Ironmaking and Steelmaking, Nov. 2007.

Supplement 4: “Application of a Model for Liquid Inclusion Separation at a Steel-Slag Interface for Laboratory and Industrial Situations”
J. Wikström, K. Nakajima, L. Jonsson and P. Jönsson
Part of this work has been presented at the following conference:

“In-situ studies of the agglomeration phenomena for calcium-alumina inclusions at liquid steel-liquid slag interface and in the slag”

J. Wikström, K. Nakajima, A. Tilliander and P. Jönsson

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

1. Literature survey, calculations, major part of the writing.
2. Literature survey, calculations, major part of the writing.
3. Literature survey, experimental work, major part of the writing.
4. Literature survey, calculations, major part of the writing.
# CONTENTS

1 Introduction
   1.1. Project Objectives 3

2 Mathematical Model
   2.1. With steel film formation 10
   2.2. Without steel film formation 13

3 Experimental Study
   3.1. Experimental conditions 15
   3.2. Experimental agglomeration force theory 18
   3.3. Theoretical agglomeration force theory 19

4 Results
   4.1. Mathematical model parameter study 23
       4.1.1. Change of physical property parameters 24
       4.1.2. Change of slag viscosity and overall wettability 26
       4.1.3. Change of inclusion and slag density 27
       4.1.4. Change of sulphur content in the steel melt 29
       4.1.5. Change of oxygen content in the steel melt 30
       4.1.6. Change of temperature in the steel 31
       4.1.7. Change of inclusion initial velocity 32
   4.2. Industrial application of the mathematical model 33
       4.2.1. Solid Al2O3 inclusions in tundish conditions 34
       4.2.2. Liquid 50wt%Al2O3-50wt%CaO inclusions in ladle conditions 36
   4.3. Experiments with CSLM 37
       4.3.1. Agglomeration at steel-gas interface 37
       4.3.2. Agglomeration at steel-slag interface 40
       4.3.3. Agglomeration in the slag 43
       4.3.4. Application of the mathematical model to CSLM experiments 45

5 Summarized Discussion 49

6 Conclusions 53

7 Future Work 55

References 57
Chapter 1

INTRODUCTION

Sweden is a small country on the map and the steel production is low compared to the rest of the world. In addition the steel production at each company is highly specialized in order to remain competitive on the world market. Thus, the focus is to produce high quality special steel that give optimum material properties for each product segment. In order to obtain a high quality steel with the desired material properties, parameters such as temperature and inclusion characteristics are necessary to control during steelmaking. With good inclusion separation, the steel quality increases because the majority of the material properties are improved by lowering the inclusion content in the final product. In addition, the risk of nozzle clogging and unwanted stops in the casting is avoided. Instead, steel plants can increase the production and at the same time get better price for the final product. Studies of inclusion separation from the steel to the slag are therefore of great interest. However, direct observations of the inclusion separation to the slag in the steel plants are impossible because of the glowing liquid steel, the non-transparent slag, the small inclusion sizes (µm) and often a cover powder on top of the slag to protect the steel from reoxidation and temperature drops. Although there are many obstacles, it is an area that has been studied before by other researchers both experimentally and theoretically.

In the experimental studies the problems have been the sampling. It is difficult to get samples representing the steel-slag interface. Solhed et al. [1] developed a sampler for this purpose called the MISS-sampler (Momentary Interfacial Solidification Sampling). The sampling with the MISS-sampler was difficult in the tundish because of the cover powder protecting the steel from reoxidation. In order to do the sampling, the cover powder had to be removed. However, it is difficult to do that without also removing the slag. In the ladle the difficulty was the high radial velocity causing filling problems of the sampler. Beskov et al. [2] sampled steel with another sampler called the RS-sampler (Rapid Solidification-sampling) in the ladle and also took some samples of the slag. However, sampling at the steel-slag interface in the ladles has not yet been successfully done.
Owing to the problems with experimental plant studies, mathematical models describing the separation and growth of inclusions in tundish and ladles were developed. Söder et al. [3] summarized in a table the development and areas of application for different models existing today. Moreover, Jönsson et al. [4] presented a recent summary at the seventh Clean Steel conference that there exists no model which takes all important growth and removal mechanisms into account. Neither do the models account for deposition at the slag interface or the inclusion behavior at the steel/slag interface. Nor do the models take into account the effects of reoxidation on inclusion formation. These models also often assume that when the inclusion has reached the steel-slag interface it will separate to the slag.

Another type of inclusion behavior studies have been done with the Confocal Scanning Laser Microscope (CSLM). Emi et al. [5] originally developed the CSLM technique that enables in-situ studies of phenomena such as phase transformations [6, 7, 8] at steel-gas interface, inclusion agglomeration [9, 10, 11, 12, 13] at steel-gas interface, inclusion behavior at steel-slag interface [14, 15, 16, 17] and dissolution at slag-gas interface [18, 19, 20, 21]. Sridhar et al. [14] were pioneers for in-situ studies of inclusion behavior at the steel-slag interface.

Inclusion removal to the slag is divided into four steps in the ladle. In Figure 1, a schematic illustration of the upper left part of a ladle is seen. First (1.), the inclusion is transported to a turbulent boundary layer by the stirring of the melt. Secondly (2.), the inclusion is transported to the steel-slag interface. Thereafter (3.), separation of inclusion to the slag phase is possible. Finally (4.), dissolution of inclusion in slag phase may occur.
In this work, the focus is on step 3, inclusion behavior at the steel-slag interface. Initially, a mathematical model originally developed by Nakajima et al [22] is used and also further developed. Then inclusion behavior at steel-gas, steel-slag interfaces and in the slag was experimentally observed with a Confocal Scanning Laser Microscope (CSLM) that allows in-situ studies. This information is seen as new valuable information that can be used both for a deeper understanding as well as for improving existing fundamental mathematical models for inclusion growth and removal.

1.1 Project Objectives

The general aim of this Ph. D. work is to increase the knowledge on inclusion behavior at the steel-slag interface by mathematical modeling and in-situ experiments. A mathematical model of inclusion behavior at a steel-slag interface for solid inclusions (S1) has been used as well as extended to include the treatment of liquid inclusions (S2). Initially, a parameter study has been done to see which physical property parameters influence the inclusion separation the most (S1, S2). Also, how the mathematical models can be applied to industrial conditions and what can be done in the industry to improve the inclusion separation (S1, S2). In-situ experiments with the CSLM were made in order to direct observe the inclusion behavior at steel-slag interface (S3). Another reason for the experiments was to find out if it is possible to verify the mathematical models with the experiments (S4).
Thus, the present thesis work is intended to trace the following flow diagram shown in Figure 2.

![Flow Diagram](image)

**Figure 2.** The flow sheet of the aim and content of this thesis.

As shown in Figure 2, the main focus of the thesis is to increase the knowledge of inclusion behavior at the steel-slag interface. It has been studied for solid and liquid inclusions by mathematical modeling (S1, S2). Industrial ladle and tundish conditions were then applied to the mathematical models (S1, S2, S4). Though, before the application of the industrial conditions to the models an investigation of the physical property parameters in the models had to be conducted (S1, S2, S3, S4). The mathematical modeling was then compared for solid and liquid inclusions (S2). Experiments with the CSLM microscope were also made to investigate liquid inclusion behavior (S3). The liquid inclusion agglomeration was studied at steel-gas, steel-slag interfaces and in the slag. From the liquid inclusion experiments, agglomeration/capillary attraction force was estimated and calculated using estimated physical property parameters and a model developed by Nakajima et al [10].
Present work is aimed to give the industry information of the importance of physical properties of metal, slag and inclusion but also to make suggestions on how to improve the quality of the steel. Furthermore, the author realizes that the doctoral work is not complete unless experiments in the industry or with industrial steel and with various slags are made. This to verify that the inclusion removal is improved by a slag with lower viscosity or a higher overall wettability in order to optimize the steel production and get a more stable casting without clogging in the submerged entry nozzle.
Introduction
Chapter 2

MATHEMATICAL MODEL

Nakajima and Okamura\(^{[22]}\) developed a model for solid inclusion removal at a steel-slag interface. The development of a model for liquid inclusion separation to a slag is similar to the model for solid inclusions\(^{[23]}\). In order to obtain optimal inclusion removal there are some basic criteria that needs to be fulfilled as described in figure 1. However, this study only deals with the separation of an inclusion located just at the steel-slag interface to the slag. Thus, it does not consider dissolution of the inclusion in the slag nor creation of new inclusions due to reoxidation. The mathematical model used in this study is described in detail in supplement 1, but here a review will be presented.

Four forces act on the inclusion as it crosses the interface, besides the force caused by gravity, \(F_a\). These are the buoyancy force, \(F_b\), the drag force, \(F_d\), the added mass force, \(F_f\), and the rebound force, \(F_r\). A comprehensive description of these forces is given in supplement 1 and supplement 2. There are also two types of inclusion transfer situations proposed in the models: with steel film formation and without steel film formation. For liquid and solid inclusions, the inclusion radius (\(R_I\)), the metal, slag and inclusion density (\(\rho_M\), \(\rho_S\), \(\rho_I\)), the metal and slag viscosity (\(\mu_M\), \(\mu_S\)), the metal, slag and inclusion surface tensions (\(\sigma_M\), \(\sigma_S\), \(\sigma_I\)), and the interfacial tensions between metal and slag, metal and inclusion and between inclusion and slag (\(\sigma_{MS}\), \(\sigma_{MI}\), \(\sigma_{IS}\)) are important parameters. In the case of liquid inclusions the inclusion viscosity (\(\mu_I\)) is also an important parameter.

As with all mathematical modeling there are assumptions limiting the model. Before summarizing the equations governing the inclusion transfer across the steel-slag interface, some general assumptions are first outlined:

- The inclusion is spherical with constant volume.
Mathematical Model

- No chemical reactions occur between the phases.
- All fluids are incompressible and isothermal.
- A liquid slag phase.
- A flat interface between steel and slag.
- Uniform interfacial tensions along the interface
- If \( \text{Re} \geq 1 \) a steel film is formed around the inclusion
- Creeping flow around the inclusion

A steel film of initial thickness \(( S_0 )\) is assumed to be formed between the inclusion and the slag if the inclusion Reynolds number is larger than unity \(( \text{Re} \geq 1 )\), where \( \text{Re} \) is defined as:

\[
\text{Re} = \frac{2 \rho_M u_\infty R_i}{\mu_M} \tag{1}
\]

where \( u_\infty \) is the terminal or initial velocity of the inclusion given as:

\[
u_\infty = \frac{2}{3} R_i^2 (\rho_M - \rho_i) \frac{g}{\mu_M} \left( \frac{1 + \kappa}{2 + 3\kappa} \right) \quad \text{for a liquid inclusion} \tag{2}
\]

where \( g \) is the gravity and the viscosity ratio \( \kappa = \frac{\mu_i}{\mu_M} \).

For solid inclusions, the terminal velocity is defined as:

\[
u_\infty = \frac{2}{9} R_i^2 (\rho_M - \rho_i) \frac{g}{\mu_M} \tag{3}
\]

which is obtained from equation (2) by letting the parameter \( \kappa \to \infty \) due to the high solid inclusion viscosity compared with the viscosity of the metal.

After some time the steel film thickness \(( S )\) will have decreased due to drainage of the steel film. During this time, \( t \), the inclusion will have moved a distance \(( Z )\) from
its original position \((Z_0)\) experiencing a velocity \((u_I)\). The drainage of the steel film is illustrated in Figure 3.

\[ \text{Figure 3. A schematic description of the inclusion separation at the steel-slag interface in the case where a steel film is formed.} \]

In the case where no steel film is formed between the inclusion and the slag, \(Re<1\), the inclusion will be in direct contact with the slag at the interface, outlined in Figure 4. In this case the inclusion will also be assumed to have reached the interface with the terminal velocity, \(u_\infty\), given in equation (2) or equation (3) depending on if the inclusion is solid or liquid.

\[ \text{Figure 4. A schematic description of inclusion separation in the case where no steel film is formed between the inclusion and the slag.} \]
In both cases, the inclusion is assumed to be fully separated to the slag when the inclusion has traveled the distance of the inclusion diameter \(d_i\) from its initial position.

The model also proposes three types of behavior that the inclusion can adopt: remain, ii) oscillate or iii) pass, illustrated in Figure 5, depending on the interfacial properties of the system and the size of the inclusion.

![Figure 5](image)

**Figure 5.** Three types of inclusion behavior at the steel-slag interface.

In the pass mode, the inclusion is completely separated to the slag, which is the most favorable mode of inclusion behavior. If the inclusion instead are classified as being in the remain mode, the inclusion stays at the interface not being able to be completely transferred to the slag. The last type of inclusion behavior is the oscillating mode, where the inclusion rises to a maximum position from where it descends to a position just above the original position. Thereafter, the inclusion rises again. This continues until the oscillation is completely dampened out and the inclusion has come to an equilibrium position.

### 2.1 With steel film formation

Together with the above assumptions, the equations of motion describing the separation of liquid and solid inclusions in the case where a steel film is formed at the steel-slag interface can be written in dimensionless form as shown below. Note, that the differences between the equations for liquid and solid inclusions are marked with a rectangular box. Then for liquid inclusions the inclusion transfer to
the slag is expressed as:

\[
\frac{d^2 Z^*}{dt^2} = 2\left(\rho_M - \rho_t\right) - 3C \cdot D(Z^*, S^*) - \frac{2}{F} \left[ G(Z^*, S^*) \right] \frac{dZ^*}{dt} - \frac{6A}{E} \frac{dZ^*}{dt^2} \tag{4}
\]

For solid inclusions the same equation can be set up by letting \( \kappa \rightarrow \infty \) in equation (4). Then one obtains:

\[
\frac{d^2 Z^*}{dt^2} = 2\frac{\rho_M - \rho_t}{\rho_M + 2\rho_t} - 3\frac{C}{R^2} \cdot D(Z^*, S^*) - \frac{2}{F} \left[ G'(Z^*, S^*) \right] \frac{dZ^*}{dt} - \frac{9}{E} \frac{dZ^*}{dt^2} \tag{5}
\]

Here \( Z^* \) is the dimensionless displacement, \( S^* \) is the dimensionless steel film thickness, \( t^* \) is the dimensionless time. The displacement \( Z \) and the steel film thickness were made dimensionless by multiplying both with \( 1/R \) and the time, \( t \), and the velocity, \( dZ/dt \), by multiplying them with \( \sqrt{g/R} \) and \( 1/\sqrt{gR} \) respectively. The first term on the right side of equations (4) and (5) corresponds to the buoyancy force, the second and third term to the rebound force and the last term to the drag force.

Also A, B, C, D(Z^*, S^*), E, F, G(Z^*, S^*) and G'(Z^*, S^*) are defined as:

\[
A = \frac{2 + 3\kappa}{2(1 + \kappa)} \tag{6}
\]

\[
B = \frac{\kappa}{2(1 + \kappa)} \tag{7}
\]

\[
C = \frac{\sigma_{MS}}{R^2 g(\rho_M + 2\rho_t)} \tag{8}
\]

\[
D(Z^*, S^*) = \frac{2 + S^* - Z^* (S^* + Z^*)}{(1 + S^*)^3} \tag{9}
\]
Mathematical Model

\( E = \frac{\sqrt{R_i g (\rho_M + 2\rho_t)}}{\mu_M} \) \quad (10)

\( F = \frac{\sqrt{R_i g (\rho_M + 2\rho_t)}}{\mu_S} \) \quad (11)

\[ G(Z^*, S^*) = \left( \frac{A}{1 + 2S^*} - \frac{3B}{1 + 4S^*} \right) \left[ 1 - \left( \frac{1 - Z^*}{1 + S^*} \right)^3 \right] \] \quad (12)

\[ G'(Z^*, S^*) = \frac{3}{2} \left( \frac{1}{1 + 2S^*} - \frac{1}{1 + 4S^*} \right) \left[ 1 - \left( \frac{1 - Z^*}{1 + S^*} \right)^3 \right] \] \quad (13)

The drainage of the steel film for a liquid inclusion is expressed as:

\[ \frac{dS^*}{dt^*} = Q \frac{dZ^*}{dt^*} \left( 2S^* + Z^* \right) - \frac{S^*}{2S^* + Z^*} \frac{dZ^*}{dt^*} \] \quad (14)

where

\[ Q = \frac{1 + 2\kappa}{2(1 + \kappa)} \] \quad (15)

The drainage of the steel film for a solid inclusion equation (14) becomes:

\[ \frac{dS^*}{dt^*} = Q \frac{dZ^*}{dt^*} \left( 2S^* + Z^* \right) - \frac{S^*}{2S^* + Z^*} \frac{dZ^*}{dt^*} \] \quad (16)

by letting the viscosity ratio \( \kappa \rightarrow \infty \).
2.2 Without steel film formation

In the case where $\text{Re} < 1$, no steel film is formed around the inclusion and the equations of motion are expressed as shown below. Also in this case, the differences between the equation for a liquid inclusion and a solid inclusion are marked with a rectangular box. The equation describing the inclusion transfer to the slag is given as:

\[
\frac{d^2 Z^*}{dt^2} = 2 \frac{\rho_s \cdot J(Z^*) - \rho_I}{\rho_s \cdot J(Z^*) + 2 \rho_I} - 3K(Z^*)H(Z^*) - \frac{6A}{L(Z^*)} I(Z^*) \frac{dZ^*}{dt} 
\]

(17)

for a liquid inclusion. For a solid inclusion $\kappa \rightarrow \infty$ in equation (17) and we get:

\[
\frac{d^2 Z^*}{dt^2} = 2 \frac{\rho_s \cdot J(Z^*) - \rho_I}{\rho_s \cdot J(Z^*) + 2 \rho_I} - 3K(Z^*) \cdot H(Z^*) - \frac{9}{L(Z^*)} \cdot I(Z^*) \frac{dZ^*}{dt}
\]

(18)

where $H(Z^*)$, $I(Z^*)$, $J(Z^*)$, $K(Z^*)$ and $L(Z^*)$ are given as:

\[H(Z^*) = Z^* - 1 - \cos \theta_{\text{MS}}\]

(19)

\[I(Z^*) = \left( \frac{\mu_M}{\mu_S} - 1 \right) Z^{*2} - 2 \left( \frac{\mu_M}{\mu_S} - 1 \right) Z^* + \frac{\mu_M}{\mu_S}\]

(20)

\[J(Z^*) = \frac{1}{4} \left( \frac{\rho_M}{\rho_S} - 1 \right) Z^{*3} - \frac{3}{4} \left( \frac{\rho_M}{\rho_S} - 1 \right) Z^{*2} + \frac{\rho_M}{\rho_S}\]

(21)

\[K(Z^*) = \frac{\sigma_{\text{MS}}}{R_i^2 \left( \rho_s \cdot J(Z^*) + 2 \rho_I \right) g}\]

(22)

\[L(Z^*) = \frac{\sqrt{R_i^2 g \left( \rho_s \cdot J(Z^*) + 2 \rho_I \right)}}{\mu_S}\]

(23)
Here the overall wettability $\cos \theta_{\text{IMS}}$ is defined as:

$$\cos \theta_{\text{IMS}} = \frac{\sigma_{IM} - \sigma_{IS}}{\sigma_{MS}}$$  

(24)

If the overall wettability is larger than zero, ($\cos \theta_{\text{IMS}} > 0$), the system is said to be wetting and if it is less than zero ($\cos \theta_{\text{IMS}} < 0$) the system is non-wetting.
Chapter 3

Experimental Study

Emi et al. [5] originally developed the Confocal Scanning Laser Microscope, CSLM, which enables in-situ observations. In this work the CSLM has been used to study liquid inclusion behavior at the steel-gas, steel-slag interfaces and in the slag. Nakajima and Mizoguchi[10] found that capillary interaction between two inclusions of the same type occurs more or less depending on the interfacial tension, particle size, density and contact angle. Here, the same method for agglomeration force estimation has been used to study the interactions between inclusions at the steel-gas and steel-slag interfaces. The experiments are described more in detail in supplement 3.

3.1 Experimental conditions

A high-carbon calcium-treated steel grade and a transparent slag were used in the experiments. The chemical compositions and liquidus temperatures for the steel and slag are given in Table 1 and Table 2, respectively. The steel samples used with inclusion composition, inclusion morphology (solid or liquid, shape, globularity and size), experimental temperature and collision type are summarized in Table 3.

Table 1. The chemical composition (wt%) and the liquidus temperature (°C) of the steel sample.

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>S-Al</th>
<th>Cu</th>
<th>Ca</th>
<th>O</th>
<th>T_L (°C)[22]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel sample</td>
<td>0.75</td>
<td>0.18</td>
<td>0.48</td>
<td>0.005</td>
<td>0.008</td>
<td>0.001</td>
<td>0.01</td>
<td>0.0002</td>
<td>0.003</td>
<td>1480</td>
</tr>
</tbody>
</table>

Table 2. The chemical composition of the slag (wt%) with its liquidus temperature (°C).

<table>
<thead>
<tr>
<th>Slag</th>
<th>Al_2O_3</th>
<th>CaO</th>
<th>SiO_2</th>
<th>T_L (°C)[23]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real</td>
<td>20.7</td>
<td>36.5</td>
<td>42.8</td>
<td>1409</td>
</tr>
</tbody>
</table>
Table 3. Composition and morphology of inclusions observed at steel-gas and steel-slag interface. The parameter $\eta$ represents a constant which is 50-80°C.

<table>
<thead>
<tr>
<th>Interface</th>
<th>State of particles</th>
<th>Chemical composition (wt%)</th>
<th>Morphology</th>
<th>Experimental temp. (°C)</th>
<th>Collision type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Argon gas/steel</td>
<td>Complex</td>
<td>Al$_2$O$_3$ 57-65, CaO 35-43, SiO$_2$ -</td>
<td>$\text{CaO Al}_2\text{O}_3(S)+L$ Globose with tips</td>
<td>1490+$\eta$ Free</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Liquid</td>
<td>Al$_2$O$_3$ 45-56, CaO 44-55, SiO$_2$ -</td>
<td>L Globose</td>
<td>1489+$\eta$ Free/Forced</td>
<td></td>
</tr>
<tr>
<td>Slag* / steel</td>
<td>Liquid</td>
<td>Al$_2$O$_3$ 45-56, CaO 44-55, SiO$_2$ -</td>
<td>L Globose</td>
<td>1460+$\eta$ Free</td>
<td></td>
</tr>
<tr>
<td>Slag*</td>
<td>Liquid</td>
<td>Al$_2$O$_3$ 20-27, CaO 27-36, SiO$_2$ 44-47</td>
<td>L Globose</td>
<td>1460+$\eta$ Free</td>
<td></td>
</tr>
</tbody>
</table>

* Slag composition: 20.7 wt% Al$_2$O$_3$, 36.5 wt% CaO, 42.8 wt% SiO$_2$

The globularity in Table 3 for a particle, $k$, is defined as:

$$ G_k = \frac{4\pi A_k}{l_k^2} $$  \hspace{1cm} (31)

where $A_k$ is the area and $l_k$ is the perimeter of particle $k$ ($k$ = 1, 2) determined from the experimental data. If the globularity is close to unity, $G_k = 1$, the particle is completely spherical. The radius of the particle is defined as:

$$ R_k = \sqrt[3]{\frac{A_k}{\pi}} $$  \hspace{1cm} (32)

Prior to the experiments, some sample preparation needed to be made. The steel was cut and rounded into discs of 4.3 mm in diameter and 2 mm in height. They were then mirror polished and before placed into an alumina crucible with inner diameter of 4.5 mm. The slag was also cut and rounded in the same manner as the steel and mirror polished. It was discovered by try and error during the steel-slag experiments that the thickness of the slag samples needed to be 2 mm in order to get a flat slag interface on top of the steel sample. Otherwise, the slag started to wet the alumina crucible leaving the steel surface free from slag.

Two types of experiments were conducted, illustrated in Figure 6. In a), the steel was melted in an argon gas surrounding and the inclusion behavior at liquid steel-
argon gas interface could be studied. By using a transparent slag b), the inclusion behavior at liquid steel-liquid gas interface could be investigated. In the later experiment setup it was important that the slag was completely liquid before the steel started to melt in order to observe interfacial phenomena such as float out, agglomeration at the interface and separation to the slag. Therefore, the slag liquidus temperature had to be less than the steel liquidus temperature. Furthermore, the slag had to be transparent in order to observe the inclusion behavior, therefore addition of SiO$_2$ to the slag. Another requirement of the slag was that it should be able to wet the inclusions in the steel, which is why Al$_2$O$_3$ and CaO were added.

![Figure 6. Schematic image of the two types of experiments with the CSLM. In a) a steel sample placed in an alumina crucible with argon gas surrounding and b) with a slag disc on top of the steel sample.](image)

The temperature during the experiments was controlled by a thermocouple attached to the sample holder at the bottom of the alumina crucible. Then, the samples were heated with 100°C per minute until the temperature was 50°C below the observation temperature. After that the heating rate and holding temperature was manually controlled until the sample started melting.

The images were monitored and recorded on a video tape at the interval of 30 frames per second. Since the movement and position of each inclusion was observed, the velocity and the acceleration could be determined from the experimental data.
3.2 Experimental agglomeration force theory

The capillary attractive force acting on the inclusions from the experiments, were evaluated from the experimental images. By using the images and assuming that the inclusions are spherical, the acceleration and mass of the inclusions could be estimated.

From the second order equation given below, the movement of the particles can be described:

\[ L(t) = b_1 t^2 + b_2 t + b_3 \]  \hspace{1cm} (33)

where \( b_1, b_2 \) and \( b_3 \) are curve fitting constants and \( t \) is the time.

The acceleration of the particle can be derived from equation (27) above as:

\[ \frac{d^2 L(T)}{dt^2} = 2b_1 \]  \hspace{1cm} (34)

The mass of particle, \( k \), is given as:

\[ m_k = \frac{4\pi R_k^3}{3} \rho_k \]  \hspace{1cm} (35)

where \( \rho_k \) is the density of inclusion \( k \).

Due to the fact that the inclusion particles are moving towards each other, a correction term \( a_k \) is introduced as:

\[ a_k = \frac{m_k}{\sum_i m_i} a \]  \hspace{1cm} (36)
where \(a\) is the acceleration of the particle. Then, the capillary attraction force, \(F\), is described as:

\[
F = m_k \cdot a_k
\]  

(37)

### 3.3 Theoretical agglomeration force theory

A theoretical model describing the capillary interaction between two particles was developed by Nakajima and Mizoguchi[10]. The model evaluates the acceleration of the particles during interaction. Theoretically, the model is based on two spherical particles existing at a two-phase interface that is deformed by the particles due to the capillary effect causing the interaction. A schematic illustration is seen in Figure 7 of the capillary interaction between two spherical particles.

![Figure 7. Schematic figure of the capillary meniscus when the two spherical inclusions experience attraction.](image)

In Figure 7, \(R\) is the radius of the particle, \(r\) is the capillary meniscus radius, \(L\) is the distance between the particles, \(h\) is the elevation of the meniscus, \(b\) is the immersion depth, \(\psi\) is the slope of the meniscus and \(\alpha\) is the three phase contact angle.

The capillary interaction energy between two spherical particles is expressed as:

\[
\Delta W = -\pi \sigma \sum_{k=1}^{2} (Q_k h_k - Q_\infty h_\infty)(1 + O(q^2 R_k^2))
\]  

(38)

where \(k\), represents the particles 1 and 2, \(\sigma\) is the surface tension of the metal or the interfacial tension between metal and inclusion when operating at the steel-slag interface, \(R_k\) is the particle radius and \(O(\infty)\) is the zero-order function of
Experiments

approximation. Furthermore, $q$ is the capillary length defined as:

$$q = \sqrt{\frac{(\rho_I - \rho_{II})g}{\sigma}}$$  \hspace{1cm} (39)

where $I$ and $II$ represents the two phases, $\rho$ is the density and $g$ is the constant of gravity.

$Q_k$ is called the capillary charge described by:

$$Q_k = \frac{1}{2} q^2 \left[ b_k^2 \left( R_k - \frac{1}{3} b_k \right) - \frac{4}{3} D_k R_k^3 - r_k^3 h_k \right]$$  \hspace{1cm} (40)

where $b_k$ is the immersion depth, $r_k$ is the capillary meniscus radius and $h_k$ is the elevation of the meniscus expressed as:

$$b_k = R_k \left( 1 + \cos(\alpha_k + \psi_k) \right)$$  \hspace{1cm} (41)

$\psi_k$ is the slope of the meniscus

$$\psi_k = \sin^{-1} \left( \frac{Q_k}{r_k} \right)$$  \hspace{1cm} (42)

$$r_k = \frac{1}{2} \left( R_k \sin \alpha_k + \sqrt{R_k^2 \sin^2 \alpha_k + 4Q_k R_k \cos \alpha_k} \right)$$  \hspace{1cm} (43)

$$h_k = Q_k \left( \tau_k + 2 \ln(1 - \exp(-2\tau_k)) \right) - (Q_1 + Q_2) \ln(\sigma_q a) +$$

$$+ (Q_1 - Q_2) \left( A - (-1)^k \sum_{n=1}^{\infty} \frac{2 \exp(-n \tau_j) \sinh n \tau_j}{n \sinh n(\tau_1 + \tau_2)} \right)$$  \hspace{1cm} (44)

$j$ and $k = 1, 2, j \neq k, qR_k < 1 \mbox{, } \alpha_k$ is the three phase contact angle and $\sigma_e = 1.78$ is the Euler-Masceroni constant. $A, \tau_i, c$ and $D_k$ are constants used to simplify equation (38) given by:
Chapter 3

\[ A = \sum_{n=1}^{\infty} \frac{1}{n} \sinh n(\tau_1 - \tau_2) / n \sinh n(\tau_1 + \tau_2) \]  \hspace{1cm} (45)

\[ \tau_k = \ln \left( \frac{c}{r_k} + \frac{c^2}{r_k^2 + 1} \right) \]  \hspace{1cm} (46)

\[ c^2 = \frac{(L^2 - (r_1 + r_2)^2)(L^2 - (r_1 - r_2)^2)}{(2L)^2} \]  \hspace{1cm} (47)

\[ D_k = \frac{\rho_k - \rho_n}{\rho_1 - \rho_n} \]  \hspace{1cm} (48)

and \( L \) is the distance between the particles.

If \( L \to \infty \) then:

\[ Q_{ke} = \frac{1}{6} q^2 R_k^3 \left( 2 - 4D_k + 3 \cos \alpha_k - \cos^3 \alpha_k \right) \]  \hspace{1cm} (49)

and

\[ h_{ke} = r_{ke} \sin \psi_{ke} \ln \frac{4}{\sigma e q r_{ke} (1 + \cos \psi_{ke})} \]  \hspace{1cm} (50)

For different values of \( L \), the capillary force

\[ F = \frac{d(\Delta W)}{dL} = -\sigma \sum_{k=1}^{3} \frac{2 \pi r_k \sin \psi_k}{2} \frac{dh_k}{dL} \]  \hspace{1cm} (51)
However, $2\pi r_k$ is the perimeter of the contact line which implies that the application of equivalent radius $R_k$ to particles with lower shape parameter, $G_k$, will cause serious error. To avoid this an effective radius, $R_{k,\text{eff}}$, is introduced based on the perimeter, $l_k$, of the particles as:

$$R_{k,\text{eff}} = \frac{l_k}{2\pi} = \frac{R_k}{\sqrt{G_k}} \quad (52)$$
Chapter 4

RESULTS

In this chapter some of the most important results will be discussed. First, the mathematical model and the parameter study with the change of slag viscosity, overall wettability, inclusion and slag density, sulfur, oxygen, temperature and initial velocity is outlined. Then, the application of the mathematical models to industrial tundish and ladle conditions, change of slag and the application to other inclusions than pure solid alumina inclusions and liquid 50wt%Al₂O₃-50wt%CaO inclusions will be discussed. Finally, the in-situ Confocal Scanning Laser Microscope (CSLM) experiments of liquid inclusions at steel-gas, steel-slag interfaces and in the slag are illustrated together with agglomeration force calculations. At last the application of the mathematical model to the CSLM experiments is overviewed.

4.1 Mathematical model parameter study (S1,S2,S3,S4)

As mentioned in Chapter 2 the mathematical model proposes three types of inclusion behavior, i) remain-the inclusion stays at the interface without being fully separated, ii) oscillate-the inclusion oscillates at the interface with the risk of returning down to the steel melt and iii) pass-the inclusion separates to the slag. In the mathematical model, the physical property parameters are the viscosity and density of the slag, steel and inclusion. Also the interfacial tensions between slag-inclusion, inclusion-metal and metal-slag are important parameters in the model. However, these parameters are not easy to find experimental data for in the literature and needs to be estimated.

Nakajima have earlier developed models for estimating viscosity\cite{24}, density\cite{25}, surface tension\cite{26} and interfacial tension\cite{27}. The parameters $(\rho_S, \rho_I, \mu_S, \mu_I, \sigma_{MS}, \sigma_S, \sigma_I, \sigma_{MS}, \sigma_{MI}, \sigma_{IS})$ were estimated with Nakajima’s models. In the case of a liquid inclusion, no data for the interfacial tension between inclusion and slag was found in the literature. Therefore, the same interaction parameter for the solid alumina inclusion was used to estimate the interfacial tension between liquid inclusion and liquid slag. In Supplement 2, it was investigated how the interaction parameter was affected by inclusion type and slags with varying basicity (Al₂O₃/CaO). It was seen
that the larger slag basicity the larger the interaction parameter is. Also, the interaction parameter varied little with slag basicity. From the study it was concluded that the interfacial tension between the liquid 50wt%Al₂O₃-50wt%CaO inclusion and the slag would be less than for the alumina inclusion because of the smaller surface tension for the liquid 50wt%Al₂O₃-50wt%CaO inclusion than the solid alumina inclusion. So, if the interaction parameter for the alumina inclusion is used as an approximation for the liquid 50wt%Al₂O₃-50wt%CaO inclusion, then the actual overall wettability and the interaction parameter would be slightly larger.

In this section, the effect of changing the physical property parameters, change of slag viscosity and overall wettability, change of inclusion and slag density, change of sulfur and oxygen content in the steel, change of temperature and velocity will be overviewed and discussed.

4.1.1 Change of physical property parameters (S1,S2)

The physical property parameters ($\rho_M$, $\rho_S$, $\rho_I$, $\mu_M$, $\mu_S$, $\mu_I$, $\sigma_M$, $\sigma_S$, $\sigma_I$, $\sigma_{MS}$, $\sigma_{MI}$, $\sigma_{IS}$) in the model were changed, one at a time between -40% to +40%, to find out which of the parameters affect the inclusion behavior the most. The steel was pure iron containing 0.005 mass% S and 0.0025 mass% O. The slag composition was chosen to be (44.1 mass%)SiO₂-(6.6 mass%)Al₂O₃-(4.3 mass%)CaF₂-(2.6 mass%)MgO-(34.6 mass%)CaO-(7.8 mass%)Na₂O.

Table 4 shows the initial conditions in the calculations. In Figure 8, the percentage displacement ($\Delta Z$) from the original position of a 20 µm solid alumina and a 20 µm liquid 50wt%Al₂O₃-50wt%CaO inclusion as a function of the change of each parameter is illustrated.

Table 4. The initial conditions for the parameters in the parameter study.

<table>
<thead>
<tr>
<th>Inclusion</th>
<th>$\sigma_{IS}$ [27] (N/m)</th>
<th>$\sigma_{MS}$ [27] (N/m)</th>
<th>$\sigma_{MI}$ [27] (N/m)</th>
<th>$\rho_{M}$ [22] (kg/m³)</th>
<th>$\rho_{S}$ [25] (kg/m³)</th>
<th>$\rho_{I}$ (kg/m³)</th>
<th>$\mu_{M}$ [22] (Pa.s)</th>
<th>$\mu_{S}$ [24] (Pa.s)</th>
<th>$\mu_{I}$ [24] (Pa.s)</th>
<th>$d_I$ (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al₂O₃</td>
<td>0.440</td>
<td>1.375</td>
<td>1.518</td>
<td>7000</td>
<td>2543</td>
<td>3990</td>
<td>0.006</td>
<td>0.1998</td>
<td>-</td>
<td>20</td>
</tr>
<tr>
<td>50wt %Al₂O₃-50wt%CaO</td>
<td>0.508*</td>
<td>1.375</td>
<td>1.336</td>
<td>7000</td>
<td>2543</td>
<td>2814</td>
<td>0.006</td>
<td>0.1998</td>
<td>0.118</td>
<td>20,100</td>
</tr>
</tbody>
</table>

* The interaction parameter $\phi_{IS}$ for the 50wt%Al₂O₃-50wt%CaO inclusion is given the value 0.5.
Figure 8. The percentage change of inclusion displacement as a function of the change of each parameter in percent of a 20 $\mu$m solid Al$_2$O$_3$ inclusion (dotted line) and a 20 $\mu$m liquid 50wt%Al$_2$O$_3$-50wt%CaO inclusion (solid line).

It is seen that for the 20 $\mu$m inclusion, the slag viscosity and the interfacial tensions are the most important parameters. The interfacial tensions can together form another physical property called the overall wettability, $\cos \theta_{\text{IMS}}$ defined in equation (24). Also it is seen that the slag viscosity affects the solid inclusion more than for the liquid 50wt%Al$_2$O$_3$-50wt%CaO inclusion.

Figure 9 shows the effect of the parameters when the inclusion is a 100 $\mu$m 50wt%Al$_2$O$_3$-50wt%CaO inclusion but with the same conditions as in Figure 8.
Figure 9. The percentage change of inclusion displacement as a function of the change of each parameter (%) of a 100 µm liquid 50wt%Al₂O₃-50wt%CaO inclusion.

For the 100 µm inclusion also the inclusion and slag density starts to affect the inclusion separation besides the slag viscosity and the interfacial tensions.

4.1.2 Change of slag viscosity and overall wettability (S1,S2)

As mentioned above, the slag viscosity and the interfacial tensions are the most important parameters for the inclusion behavior. Therefore, the slag viscosity and the overall wettability were varied in order the get an understanding of how the inclusion separation can be improved and how these parameters affect the inclusion behavior. Figure 10, illustrate the effect of slag viscosity and overall wettability on the behavior for a 20 µm and 100 µm solid Al₂O₃ and a liquid 50wt%Al₂O₃-50wt%CaO inclusion with the calculation conditions in Table 4.
It is seen that the area for pass is small. Furthermore, the slag viscosity has to be low and the overall wettability high in order to obtain inclusion separation. It can also be seen that the “pass” region is larger and at the same time that the “remain” region is smaller for the 100 µm inclusion than for the 20 µm inclusion. Hence, in this case solid inclusion separation is easier to achieve than liquid inclusion separation.

4.1.3 Change of inclusion and slag density (S4)
According to the above parameter study, the inclusion and slag density also affect the inclusion separation for 100 µm inclusions. In Figure 11, the result of the change of inclusion and slag density with varying overall wettability is visualized. Table 5, summarizes the slag, inclusion and steel composition together with the estimated physical properties used in the calculations with the mathematical model described in chapter 2.
Figure 11. The effect of slag (solid line) and inclusion (dotted line) density and overall wettability on the inclusion behavior when the inclusion is 100 µm diameter. Chemical composition of slag, inclusion and steel as well as the corresponding physical properties can be found in Table 5 below. Here $\mu_M$, $\mu_S$, $\mu_I$, $\rho_M$, $\sigma_{MI}$ and $\sigma_{MS}$ are constant and $\sigma_{IS}$ varied.

Table 5. The chemical composition (wt%) of the industrial tool steel grade, slag and inclusion together with its physical properties.

<table>
<thead>
<tr>
<th></th>
<th>Chemical composition (wt%)</th>
<th>Physical properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\text{Al}_2\text{O}_3$</td>
<td>$\sigma$</td>
</tr>
<tr>
<td>Slag 2</td>
<td>15</td>
<td>[26] (N/m)</td>
</tr>
<tr>
<td></td>
<td>$\text{CaO}$</td>
<td>$\rho$</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>[23] (kg/m$^3$)</td>
</tr>
<tr>
<td></td>
<td>$\text{MgO}$</td>
<td>$\mu$</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>[24] (Pas)</td>
</tr>
<tr>
<td></td>
<td>$\text{SiO}_2$</td>
<td>$\sigma_{MS}$</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>[27] (N/m)</td>
</tr>
<tr>
<td>Inclusion1</td>
<td>50</td>
<td>$\sigma_{MI}$</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>[27] (N/m)</td>
</tr>
<tr>
<td></td>
<td>$\text{Al}$</td>
<td>$\sigma_{IS}$</td>
</tr>
<tr>
<td></td>
<td>0.0005</td>
<td>* [27] (N/m)</td>
</tr>
<tr>
<td></td>
<td>$\text{C}$</td>
<td>$\phi_M$</td>
</tr>
<tr>
<td></td>
<td>0.72</td>
<td>[27] (-)</td>
</tr>
<tr>
<td></td>
<td>$\text{Ca}$</td>
<td>$\phi_I$</td>
</tr>
<tr>
<td></td>
<td>0.0001</td>
<td>[27] (-)</td>
</tr>
<tr>
<td></td>
<td>$\text{Cr}$</td>
<td>$\phi_{IS}$</td>
</tr>
<tr>
<td></td>
<td>0.05</td>
<td>* [27] (-)</td>
</tr>
<tr>
<td></td>
<td>$\text{Mn}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\text{O}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.002</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\text{S}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.008</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\text{Si}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td>Steel B</td>
<td>1.571</td>
<td>$\phi_{IS}$</td>
</tr>
<tr>
<td></td>
<td>7000</td>
<td>* [27] (-)</td>
</tr>
</tbody>
</table>

* Assuming the same value of $\phi_{IS}$ as for a solid alumina inclusion

It is observed that the inclusion and slag density has the same effect on the
inclusion transfer. Additionally, the separation is promoted if the slag or inclusion density is high.

4.1.4 Change of sulfur content in the steel melt (S4)

The interfacial tensions are important for the inclusion behavior and transfer to the slag. Also the sulfur content in the steel melt is a serious matter because it influences both the interfacial tension between steel and slag as well as between steel and inclusion. Therefore, the sulfur content was varied for a 20 µm and a 100 µm liquid 50wt%Al₂O₃-50wt%CaO inclusion. This caused the surface tension of the steel (σ_M) to decrease with increasing amount of sulfur resulting in decreasing interfacial tensions between steel-slag and steel-inclusion. It is illustrated in Figure 12 the effect of sulfur content and overall wettability on the inclusion behavior. Also here the same conditions as in Table 5 are used.

![Figure 12.](image.png)

**Figure 12.** The inclusion behavior as the sulfur content and overall wettability changes for a 20 µm and a 100 µm liquid 50wt%Al₂O₃-50wt%CaO inclusion. Here the oxygen content is 0.002wt% and the chemical compositions as well as physical properties for the steel, slag and inclusion are found in Table 5. The interaction parameters are kept constant, φ_{IS}=0.7, φ_{MS}=0.398 and φ_{MI}=0.444. Also μ_M, μ_S, μ_I, ρ_M, ρ_S and ρ_I are constant while σ_{IS}, σ_{MI} and σ_{MS} varied.
It is seen that the 20 \( \mu m \) liquid 50wt\%Al\textsubscript{2}O\textsubscript{3}-50wt\%CaO inclusion separation to the slag only occurs if the overall wettability is equal to unity. For the 100 \( \mu m \) inclusion, transfer to the slag occurs when the overall wettability is high (larger than 0.8) and the sulfur content is low. Hence, in order to obtain good inclusion separation to the slag, the sulfur content should be low.

**4.1.5 Change of oxygen content in the steel melt (S4)**

Oxygen is another parameter affecting the surface tension of the metal. The same type of behavior as with sulfur was observed. That is, the surface tension of the metal and the interfacial tensions between steel-inclusion and steel-slag decreases with increasing oxygen content in the steel. The effect on the inclusion separation to the slag for a 20 \( \mu m \) and a 100 \( \mu m \) liquid 50wt\%Al\textsubscript{2}O\textsubscript{3}-50wt\%CaO inclusion is visualized in Figure 13 by using the calculation conditions in Table 5.

![Figure 13](image-url)

**Figure 13.** The effect of oxygen content in the steel and the overall wettability on the inclusion behavior for a 20 \( \mu m \) and a 100 \( \mu m \) liquid 50wt\%Al\textsubscript{2}O\textsubscript{3}-50wt\%CaO inclusion. Here the sulfur content was 0.008wt\% and the chemical compositions as well as physical properties for the steel, slag and inclusion are found in Table 5. The interaction parameters are kept constant, \( \phi_{IS} = 0.7 \), \( \phi_{MS} = 0.398 \) and \( \phi_{MI} = 0.444 \). Also \( \mu_M, \mu_S, \mu_i, \rho_M, \rho_S \) and \( \rho_i \) are constant while \( \sigma_{IS}, \sigma_{MI} \) and \( \sigma_{MS} \) varied.
It can be observed in Figure 12, that the 20 µm liquid 50wt%Al₂O₃-50wt%CaO inclusion needs an overall wettability equal to unity in order to pass into the slag. Also, the 100 µm inclusion is benefited by low oxygen content in the steel as well as high overall wettability to obtain optimal inclusion transfer to the slag. Hence, the oxygen content in the steel melt should be low to get the best conditions for inclusion separation.

### 4.1.6 Change of temperature in the steel (S4)

In ladle and tundish operations, the steel temperature lies between 1823-1873K. How does the temperature affect the inclusion separation for a 20 µm and a 100 µm liquid 50wt%Al₂O₃-50wt%CaO inclusion? In Figure 14, the effect of temperature as the overall wettability and the slag viscosity changed is illustrated for the calculation conditions in Table 5. Table 6, shows the change of physical properties with temperature for the steel, slag and inclusion found in Table 5.

![Figure 14](image.png)

**Figure 14.** The effect of temperature (1823K thin line, 1873K heavy line) on the inclusion behavior as the slag viscosity and the overall wettability changed for a 20 µm and a 100 µm liquid 50wt%Al₂O₃-50wt%CaO inclusion with steel and slag composition summarized in Table 5.
Table 6. Calculation conditions for 1823K and 1873K:

<table>
<thead>
<tr>
<th>T (K)</th>
<th>μ_M (Pas)</th>
<th>μ_I (Pas)</th>
<th>σ_{MI} (N/m)</th>
<th>φ_{MI}</th>
<th>σ_{MS} (N/m)</th>
<th>φ_{MS}</th>
<th>ρ_M (kg/m³)</th>
<th>ρ_S (kg/m³)</th>
<th>ρ_I (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1823</td>
<td>0.006</td>
<td>0.118</td>
<td>1.311</td>
<td>0.444</td>
<td>1.361</td>
<td>0.398</td>
<td>7000</td>
<td>2660</td>
<td>2814</td>
</tr>
<tr>
<td>1873</td>
<td>0.006</td>
<td>0.093</td>
<td>1.310</td>
<td>0.444</td>
<td>1.361</td>
<td>0.398</td>
<td>7000</td>
<td>2648</td>
<td>2799</td>
</tr>
</tbody>
</table>

It is obvious that the temperature of the steel has little effect on the inclusion behavior and especially the separation to the slag.

4.1.7 Change of inclusion initial velocity (S4)

Inclusion velocity is another parameter affecting the inclusion separation to the slag. The mathematical model assumes that the inclusion reaches the steel-slag interface with the initial velocity, \( u_\infty \), described earlier in equation 2.

However, can the separation be improved if the initial velocity is increased? Figure 15 shows the "pass" region for a liquid 20 µm 50wt%Al₂O₃-50wt%CaO inclusion for different initial velocities (0.0001-4 m/s) as the overall wettability and slag viscosity changes. Note, here we assume no steel film formation even though the initial velocity affects Reynolds number. In this case Reynolds number is equal to unity when the initial velocity is 0.0214 m/s.
Figure 15. The effect of inclusion initial velocity (equation 15) on the separation of inclusions when the slag viscosity and overall wettability varies. Here the chemical composition and physical properties of inclusion, slag and steel is seen in Table 5. $\mu_M$, $\mu_I$, $\rho_M$, $\rho_S$, $\rho_I$, $\sigma_{MI}$ and $\sigma_{MS}$ are constant and $\sigma_{IS}$, $\mu_S$ and $u_\infty$ varied in the calculations of the “pass” area.

It is noticed that the initial velocity does not affect the inclusion transfer much. Hence, initial velocity is more important when it comes to transfer the inclusion to the interface. However already at the interface, the slag viscosity and interfacial tensions have larger effect on the inclusion separation.

4.2 Industrial application of the mathematical model (S1,S2)

The above described models were applied to industrial ladle and tundish conditions in order to perhaps be able to improve the quality of the steels in the industry. Four steel plants and five steel grades were studied, see Table 7. Two different steel plants with respective steel grade, one low carbon steel grade (1) and one stainless steel grade (2), were studied on the solid Al$_2$O$_3$ inclusion behavior. Two other steel plants, one tool steel plant with its steel grade (3) and one wire and bolt steel plant with respective steel grades (4 and 5) were applied to the liquid 50wt%Al$_2$O$_3$-50wt%CaO inclusion. The corresponding slags to the steel grades in Table 7 are seen in Table 8. Note, the first number in the name of the slag is connected to the
Results

Table 7. The chemical composition of the five industrial steel grades (wt%)

<table>
<thead>
<tr>
<th>Steel (wt%)</th>
<th>C</th>
<th>S</th>
<th>Mn</th>
<th>P</th>
<th>Cu</th>
<th>Si</th>
<th>Ca</th>
<th>Ni</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0061</td>
<td>0.01</td>
<td>0.63</td>
<td>0.009</td>
<td>0.005</td>
<td>0.01</td>
<td>1ppm</td>
<td>0.038</td>
<td>1ppm</td>
</tr>
<tr>
<td>2</td>
<td>0.016</td>
<td>7ppm</td>
<td>0.77</td>
<td>0.018</td>
<td>0.15</td>
<td>0.51</td>
<td>27ppm</td>
<td>5.23</td>
<td>25ppm</td>
</tr>
<tr>
<td>3</td>
<td>0.4</td>
<td>0.0014</td>
<td>0.39</td>
<td>0.009</td>
<td>0.13</td>
<td>0.14</td>
<td>0.0002</td>
<td>0.14</td>
<td>0.0001</td>
</tr>
<tr>
<td>4</td>
<td>0.22</td>
<td>0.01</td>
<td>0.9</td>
<td>-</td>
<td>0.08</td>
<td>0.003</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>0.72</td>
<td>0.008</td>
<td>0.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.22</td>
<td>0.0001</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 8. The chemical composition (wt%) of the slags corresponding to the steel grades in Table 7. First number in the name of the slag corresponds to the steel grade it belongs to.

<table>
<thead>
<tr>
<th>Slag (wt%)</th>
<th>CaO</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>MgO</th>
<th>FeO</th>
<th>MnO</th>
<th>K₂O</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>3.4</td>
<td>57</td>
<td>27.9</td>
<td>1.8</td>
<td>6</td>
<td>-</td>
<td>3.9</td>
</tr>
<tr>
<td>1.2</td>
<td>11</td>
<td>47</td>
<td>16.2</td>
<td>3.2</td>
<td>11</td>
<td>11.5</td>
<td>-</td>
</tr>
<tr>
<td>1.3</td>
<td>16.8</td>
<td>54</td>
<td>9.5</td>
<td>3.6</td>
<td>11.5</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>2.1</td>
<td>8.3</td>
<td>42.3</td>
<td>18.4</td>
<td>31</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3.1</td>
<td>48.2</td>
<td>8.9</td>
<td>32.9</td>
<td>10</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4.1</td>
<td>47.5</td>
<td>12.5</td>
<td>30</td>
<td>10</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5.1</td>
<td>40</td>
<td>35</td>
<td>15</td>
<td>10</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

4.2.1 Solid Al₂O₃ inclusions in tundish conditions (S1)

Solid alumina inclusion behavior was applied to steel grade 1 with slags 1.1, 1.2 and 1.3 and steel grade 2 with slag 2.1 respectively, sees Tables 7 and 8. Figure 16 shows the behavior of a solid alumina inclusion at the steel-slag interface for the industrial tundish conditions in Table 9 below for one low carbon steel (1) and one stainless steel (2) found in the tundish with respective slags.
Chapter 4

Figure 16. The behavior of a solid Al₂O₃ inclusion applied to industrial conditions.

Table 9. The estimated physical parameters for the industrial conditions.

<table>
<thead>
<tr>
<th>Slag</th>
<th>1.1</th>
<th>1.2</th>
<th>1.3</th>
<th>2.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>µₛ (Pa·s)</td>
<td>24.59</td>
<td>1.987</td>
<td>2.360</td>
<td>0.407</td>
</tr>
<tr>
<td>ρₛ (kg/m³)</td>
<td>3801</td>
<td>3330</td>
<td>3557</td>
<td>2585</td>
</tr>
<tr>
<td>σₛ (N/m)</td>
<td>0.309</td>
<td>0.420</td>
<td>0.399</td>
<td>0.403</td>
</tr>
<tr>
<td>φₛ [27]</td>
<td>0.232</td>
<td>0.431</td>
<td>0.480</td>
<td>0.644</td>
</tr>
<tr>
<td>φₛ [27]</td>
<td>0.511</td>
<td>0.442</td>
<td>0.419</td>
<td>0.301</td>
</tr>
<tr>
<td>σₛₘₛ (N/m) [27]</td>
<td>0.835</td>
<td>0.686</td>
<td>0.624</td>
<td>0.445</td>
</tr>
<tr>
<td>σₛₘₛ (N/m) [27]</td>
<td>1.241</td>
<td>1.346</td>
<td>1.381</td>
<td>1.760</td>
</tr>
<tr>
<td>cosθₛₘₛ [27]</td>
<td>1.561</td>
<td>1.561</td>
<td>1.561</td>
<td>1.724</td>
</tr>
</tbody>
</table>

* Neglects FeO, MnO and TiO₂ content in the estimation of φₛ and φₛₘₛ
It can be seen from Figure 16, that all of the industrial slags have a high or rather too high viscosity and a positive overall wettability. In addition, this makes the model predict remain behavior of the solid Al$_2$O$_3$ inclusion for both steel grade 1 and steel grade 2 regardless of inclusion size (20 µm or 100 µm). Hence, the slags in the tundish for these two plants need modification to obtain a lower slag viscosity.

4.2.2 Liquid 50wt%Al$_2$O$_3$-50wt%CaO inclusions in ladle conditions (S2)

Liquid 50wt%Al$_2$O$_3$-50wt%CaO inclusion behavior was applied to the tool steel grade (3) and the bolt and wire steel grades (4 and 5) found in the ladle together with the respective slags, see Tables 7 and 8. Figure 17 illustrates the prediction of the liquid 50wt%Al$_2$O$_3$-50wt%CaO inclusion behavior on the industrial conditions with the calculation conditions seen in Table 10.

![Figure 17](image)

**Figure 17.** Estimation relationship between the slag viscosity and wettability for a liquid 50wt%Al$_2$O$_3$-50wt%CaO inclusion applied to the industrial ladle conditions in Table 10.
Chapter 4

Table 10. Estimation of physical property parameters for the industrial conditions.

<table>
<thead>
<tr>
<th>Slags</th>
<th>$\sigma_M$ [26] (N/m)</th>
<th>$\rho_M$ [30] (kg/m$^3$)</th>
<th>$\mu_M$ [31] (Pa.s)</th>
<th>$\sigma_S$ [26] (N/m)</th>
<th>$\rho_S$ [25] (kg/m$^3$)</th>
<th>$\mu_S$ [24] (Pa.s)</th>
<th>$\sigma_I$ [26] (N/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>1.856</td>
<td>7750</td>
<td>0.006</td>
<td>0.546</td>
<td>2772</td>
<td>0.067</td>
<td>0.606</td>
</tr>
<tr>
<td>4.1</td>
<td>1.467</td>
<td>7850</td>
<td>0.006</td>
<td>0.539</td>
<td>2755</td>
<td>0.074</td>
<td>0.606</td>
</tr>
<tr>
<td>5.1</td>
<td>1.571</td>
<td>7840</td>
<td>0.006</td>
<td>0.468</td>
<td>2660</td>
<td>0.197</td>
<td>0.606</td>
</tr>
</tbody>
</table>

In Figure 17 it is visualized that for slags 3.1 and 4.1 both the 20 $\mu$m and 100 $\mu$m liquid 50wt%Al$_2$O$_3$-50wt%CaO inclusion will separate to the slag. However, for slag 5.1, the 20 $\mu$m inclusion stays at the interface and the 100 $\mu$m inclusion is predicted to oscillate at the interface with the risk of reentering the steel bath.

4.3 Experiments with CSLM (S3,S4)

In-situ experiments have been performed with a confocal scanning laser microscope (CSLM). This was done to get a better understanding of the inclusion behavior (both solid and liquid) at the interface. The mathematical model used above to study inclusion behavior only takes into account separation, remain and oscillate. It does not account for agglomeration or dissolution which could be a reason why inclusions are not so frequently found in the final product of the steel despite poor wetting conditions. In this section results of the experiments (agglomeration) will be illustrated and discussed. Also, attractive force calculations of the agglomeration are shown.

4.3.1 Agglomeration at steel-gas interface (S3)

Liquid [45-56wt%]Al$_2$O$_3$-[44-55wt%]CaO-semi liquid [57-65wt%]Al$_2$O$_3$-[35-43wt%]CaO inclusion agglomeration was observed at the steel-slag interface at an observation temperature of 1490°C+$\eta$ for the steel and slag composition summarized in Table 11. Because the thermo element measuring the temperature during the experiment is placed at the bottom of the alumina crucible the actual temperature at the surface of the steel bath is 50-80°C higher. Therefore $\eta$ is added to the experimental temperature as a constant with a value of 50-80°C. The CSLM images visualizing the agglomeration are seen in Figure 19 for a) big inclusions and b) smaller inclusions.
Figure 18. The above sequence of images (a) demonstrates how a semi liquid inclusion (B) agglomerate with the big liquid inclusion (A) at the observation temperature $T=1490°C+\eta$ ($\eta$ is a constant dependent on experimental conditions). In the lower sequence (b) another semi liquid inclusion (C) agglomerate with the smaller liquid inclusion (D) at the observation temperature $T=1490°C+\eta$.

Table 11. The chemical composition of the steel, slag and inclusion (wt%) from the CSLM experiments together with the estimated physical properties.

<table>
<thead>
<tr>
<th>Chemical composition(wt%)</th>
<th>Al$_2$O$_3$</th>
<th>CaO</th>
<th>MgO</th>
<th>SiO$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slag 1</td>
<td>20.7</td>
<td>36.5</td>
<td>-</td>
<td>42.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chemical composition(wt%)</th>
<th>Al</th>
<th>C</th>
<th>Ca</th>
<th>P</th>
<th>Mn</th>
<th>O</th>
<th>S</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel A</td>
<td>0.001</td>
<td>0.75</td>
<td>0.0002</td>
<td>0.005</td>
<td>0.48</td>
<td>0.003</td>
<td>0.008</td>
<td>0.18</td>
</tr>
</tbody>
</table>

It is seen in Figure 18, that the bigger inclusions (a) agglomeration time is shorter than the agglomeration time for the smaller inclusions (b). The reason for this is that the capillary attraction force is larger for the bigger inclusions. This can be seen from experimental and theoretical agglomeration force estimations in Figure 19 below with calculation conditions. Also notice that the smaller semi liquid-liquid inclusion agglomeration (b) is followed by a holding time before the agglomerated inclusion C-D obtains a globular shape.
Calculation conditions:

<table>
<thead>
<tr>
<th>Inclusions</th>
<th>( \rho_i ) (kg/m(^3))</th>
<th>( \rho_M ) (kg/m(^3))</th>
<th>( \alpha_M )</th>
<th>( \sigma_M ) (N/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A, D</td>
<td>2814[25]</td>
<td>7000</td>
<td>55.3</td>
<td>1.522</td>
</tr>
<tr>
<td>B, C</td>
<td>3617[32]</td>
<td>7000</td>
<td>60.8</td>
<td>1.522</td>
</tr>
</tbody>
</table>

**Figure 19.** Comparison between the experimental and theoretical capillary force for the agglomeration between inclusions A and B and inclusions C and D respectively. The pair A-B had repulsive force in the positions 5 and 6 (here shown as absolute values of the attraction force). Also note that the marks 1 to 6 indicates the chronological times of observations.

In Figure 19, it can also be observed that the agglomeration between inclusions A and B, the experimental (stars) and theoretical (solid line) agglomeration force agree to some extent. However, the experimental capillary force is a factor 10 smaller than the theoretical for the agglomeration between A and B. Also the experimental capillary force differs with a factor 10 although the inclusions do not change.
distance between each other much. This can be due to inclusion B moving a more solid tip towards inclusion A. The agglomeration between the liquid inclusions C and D, experimental (plus) and theoretical (dotted line) capillary force differs with a factor of 10 at the most. This is rather good results when comparing experiments with this model. Kojola et al. [33] used the same model on experiments with REM-oxides on Fe20%Cr stainless steel and the experimental and theoretical capillary forces differed with a factor 5-10000 where the best results were obtained from interactions between large inclusions.

4.3.2 Agglomeration at steel-slag interface (S3)

Agglomeration at the steel-slag interface could not be observed for the liquid 50wt%Al₂O₃-50wt%CaO inclusions without using force. In this case, see Figure 20, the experimental observation temperature was raised in order to get inclusion agglomeration. Another reason why the agglomeration is forced is a solid steel front capturing the inclusions H, I and J in a liquid metal pool. However, first the inclusions H and I appears (0.0s) at the steel-slag interface, then after 16.1s another inclusion J appears. In Figure 20, the image shows after 16.7s in order to show the best image of the scene. As the temperature increase in the steel and slag melts, the slag flow (seen as grey waves) is also increased. This forces the inclusions H, I and J towards the solid steel front and towards each other. Finally after 21.6s the inclusions agglomerate to a big liquid inclusion.
Figure 20. The flow from the slag and the small metal pool, force the inclusions H, I and J to agglomerate at experimental temperature $T=1490^\circ C+\eta$. Chemical composition of steel and slag can be found in Table 12.

The capillary force describing the agglomeration between inclusions H, I and J is divided into two parts. One called free agglomeration, which is before inclusion J appears. Then as the temperature rises the agglomeration is described as forced. In Figure 21, the capillary force between inclusions H-I (a), H-J and I-J (b) are visualized together with the calculation conditions.
Results

Calculation conditions:

<table>
<thead>
<tr>
<th>Inclusions</th>
<th>( \rho_{[24]} ) (kg/m(^3))</th>
<th>( \rho_M ) (kg/m(^3))</th>
<th>( \sigma_{MS}^{[31]} ) (N/m)</th>
<th>( \alpha_{IMS} ) (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H, I, J</td>
<td>2814</td>
<td>7000</td>
<td>1.25</td>
<td>44.5</td>
</tr>
</tbody>
</table>

Figure 21. The experimental and theoretical capillary force acting on the inclusions H-I (a), H-J and I-J (b). Note that in a) both free and forced agglomeration occurs and in the free agglomeration case the inclusions are attracted to each other and then they repel before finding a neutral position.

It can be noted that in Figure 21 a), the experimental and theoretical capillary force agrees rather well, as the distance between the inclusions H and I decreases. In the beginning when inclusions H and I are quite far away from each other experiencing both attraction and repulsion, the experimental capillary force is scattered around the theoretical line. As inclusion J appears forcing and affecting inclusions H and I, the experimental capillary force (stars) becomes stronger than the theoretical force (solid line). This phenomena, with stronger capillary force than experimental capillary force, can also be seen in b) for inclusions H and J as well as for I and J. Because the inclusions are forced to agglomerate, the experimental capillary force is larger than the force obtained from the theoretical model which does not take into account an additional force. Also, the attraction force between H-J and I-J is larger than between H-I.

It should be mentioned that attractive or repulsive force strongly depends on the contact angle of particle with steel melt, particle size and shape. Liquid inclusions have weaker attraction force due to the lower contact angle between inclusion and steel than a solid inclusion. It can also be explained by the deformation of the interface. A solid inclusion cannot deform itself, but the liquid steel can causing a high contact angle between inclusion and steel. When the inclusion is liquid, both
the steel surface and the inclusion can deform and create a lower contact angle. This will make the attraction force weaker.

4.3.3 Agglomeration in the slag (S3)

Agglomeration of inclusions present in the slag could also be studied with the CSLM. An illustration of the experiment is seen in Figure 22 together with Light Optical Microscope (LOM) images of the slag and inclusions after the experiments.

![Figure 22](image)

**Figure 22.** a) A LOM image of the steel-slag interface with focus on the steel surface after CSLM experiment, b) Same LOM image area as in a) but with focus on the inclusions in the slag and c) illustrates a schematic image of a) and b).

In Figure 22 a) the focus is at the steel-slag interface where the grain boundary of the steel is seen also here the inclusions are seen as “ghost” or vague spots. Figure 22b) shows a little bit higher up in the slag but still the same grain boundary can be seen, but here the inclusions are clear.

Scanning Electron Microscope (SEM) analysis of the inclusions in the slag showed that the inclusions were (20-27wt%Al₂O₃)-(27-36wt%CaO)-(44-47wt%SiO₂). Figure 23 visualize one of the inclusions (23wt%Al₂O₃-30wt%CaO-47wt%SiO₂) found in the slag together with its size and mapping.
Figure 23. A SEM image of one of the liquid inclusions (23wt%Al₂O₃-30wt%CaO-47wt%SiO₂) found in the slag together with its element mapping.

While the liquid inclusions (50wt%Al₂O₃-50wt%CaO) at the steel-gas and steel-slag interfaces did not agglomerate freely, in the slag the agglomeration of (20-27wt%Al₂O₃)-(27-36wt%CaO)-(44-47wt%SiO₂) inclusions was free. This might be explained by a higher free energy force between the inclusions in the slag. Figure 24, shows the liquid inclusion agglomeration (b-c and e-f) in the slag. Note, the inclusions are seen as “ghosts” because the focus is at the steel-slag interface.
Figure 24. Liquid inclusion agglomeration in the slag. Inclusions b and c agglomerate and also agglomeration of inclusions e and f occurs.

Moreover in the slag, the inclusions agglomerate and experience a holding time before obtaining a globular shape. Thus, a conclusion is that liquid inclusion agglomeration in the slag takes place in a similar manner as the semi liquid-liquid inclusion agglomeration at the steel-gas interface seen in Figure 18 b). From a $\text{Al}_2\text{O}_3-\text{CaO-SiO}_2$ phase diagram$^{[34]}$ it was seen that two liquid phases can coexist at the experimental temperatures of this study. This, together with the very short holding time in the experiments can explain why the inclusions were not seen to dissolve into the slag.

4.3.4 Application of the mathematical model to the CSLM experiments (S4)

An interesting question asked during the writing of this thesis and supplements were: Can the mathematical model be applied to the experiments? Since no experimental physical property parameters of these systems could be found, especially for the interfacial tension between the inclusions and the slag, estimations have been made. Table 12 is a summary of the steel, slag and inclusion compositions as well as the estimated physical properties for the inclusions found at the steel-slag interface and in the slag.
### Table 12. Summary of the chemical composition and physical property parameters of the liquid inclusions, slag and steel from the CSLM experiments at 1500°C.

<table>
<thead>
<tr>
<th></th>
<th>Al₂O₃</th>
<th>CaO</th>
<th>MgO</th>
<th>SiO₂</th>
<th>Chemical composition (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slag 1</td>
<td>20.7</td>
<td>36.5</td>
<td>-</td>
<td>42.8</td>
<td></td>
</tr>
<tr>
<td>Inclusion1</td>
<td>50</td>
<td>50</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Inclusion2</td>
<td>23</td>
<td>30</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Al</td>
<td>C</td>
<td>Ca</td>
<td>P</td>
<td>Mn</td>
<td>O</td>
</tr>
<tr>
<td>Slag 1</td>
<td>0.460</td>
<td>2563</td>
<td>0.676</td>
<td>1.250</td>
<td>0.473</td>
</tr>
<tr>
<td>Inclusion1</td>
<td>0.606</td>
<td>2814</td>
<td>0.118</td>
<td>1.276</td>
<td>0.383</td>
</tr>
<tr>
<td>Inclusion2</td>
<td>0.442</td>
<td>2512</td>
<td>1.090</td>
<td>1.230</td>
<td>0.319</td>
</tr>
<tr>
<td>Steel A</td>
<td>1.522</td>
<td>7000</td>
<td>0.006</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Assuming the same value of φₜ as for a solid alumina inclusion

The estimated physical property parameters were then used to predict the inclusion behavior at the steel-slag interface for both the inclusions that were at the interface but also for the inclusions found in the slag. Figure 25, illustrates the mathematical model prediction of the inclusions at steel-slag interface.
Figure 25. Application of the mathematical model on the liquid Inclusion1 found at the steel-slag interface and liquid Inclusion2 found in the slag from the CSLM experiments at 1823K. o represents Inclusion1 and * Inclusion2 in Table 12. Chemical composition of steel, slag and inclusions as well as physical properties can be found in Table 12. The solid lines representing the areas for the different inclusion behaviors are based on Inclusion1, steel A and slag 1 in Table 12. Here $\phi_{IS}$ varies between that of a solid alumina inclusion and 1, that is why an error bar is seen between two * and two o.

$\mu_M$, $\mu_S$, $\mu_D$, $\rho_M$, $\rho_S$, $\rho_D$, $\sigma_{MI}$ and $\sigma_{MS}$ are constant and $\sigma_{IS}$ varied in the calculations for inclusion1 and inclusion2. For the lines representing the areas of inclusion behavior $\mu_S$ and $\sigma_{IS}$ varied.

Here it can be seen that for the liquid 50wt%Al$_2$O$_3$-50wt%CaO inclusions (Inclusion 1) found at the interface in the experiments (since no separation to the slag was observed), also the mathematical model predicts them to remain at the interface. In this case the model agrees with the experiments. Since the interaction parameter between inclusion and slag used here is predicted for as for a solid Al$_2$O$_3$ the error bars in Figure 26 illustrates the possible inclusion behavior for an interaction parameter between 0.647 and 1. However, for the inclusions (Inclusion
2) found in the slag, the mathematical model also here predicts them to stay at the interface. So, either is the estimation of the physical properties, especially the overall wettability, actually much higher and the inclusions should therefore separate to the slag, or the inclusions found in the slag are coming from slag reacting with the alumina crucible.
Chapter 5

SUMMARIZED DISCUSSION

This work was focused on studying the inclusion transfer just at the steel-slag interface, which is defined as step 3 in Figure 1. Mathematical models describing solid and liquid inclusions behavior at the steel-slag interface have been developed in supplement 1 and supplement 2. A parameter study investigating which of the physical property parameters in the models have the largest effect on the inclusion separation has been conducted. Also the applicability of the theoretical models to industrial tundish and ladle conditions has been illustrated in supplement 1 and supplement 2. In the theoretical study of the parameters effect on the inclusion behavior, it was seen that the slag viscosity and the interfacial tensions between steel-slag, steel-inclusion and slag-inclusion were the most important parameters for 20 µm inclusions. The interfacial tensions can together form another physical property parameter called the overall wettability, which describes if the system is wetting \((\cos \theta_{\text{IMS}}>0)\) or not \((\cos \theta_{\text{IMS}}<0)\). For larger inclusions, also the inclusion and slag density started to affect the inclusion behavior. The comparison between a 100 µm solid Al\(_2\)O\(_3\) inclusion and a 100 µm liquid 50wt%Al\(_2\)O\(_3\)-50wt%CaO inclusion showed that the pass and oscillating areas are bigger for the solid alumina inclusion when using the slag and steel chosen in this study (S2). The difference in inclusion density is probably the reason for this. Also, the difference in the inclusion density between the solid and liquid inclusion results in a higher added mass force. However, according to the parameter study the interfacial tensions and the slag viscosity affects the inclusion transfer for both solid and liquid 20 µm inclusions, so the areas of pass, remain and oscillate would be expected to be the same, but they are not. Instead, the oscillating areas are different, especially when the overall wettability has a positive value. A comparison of the parameter studies for solid Al\(_2\)O\(_3\) and liquid 50wt%Al\(_2\)O\(_3\)-50wt%CaO inclusions showed that although there is a difference between the interfacial tensions, the effect on the overall wettability would be negligible. However, the slag viscosity affects the solid Al\(_2\)O\(_3\) inclusion more than the liquid 50wt%Al\(_2\)O\(_3\)-50wt%CaO inclusion. This might be the reason why there is a shift in the oscillating region between these inclusions. In the comparisons between a solid Al\(_2\)O\(_3\) inclusion and other solid
inclusions and in the case where a liquid 50wt%Al₂O₃-50wt%CaO inclusion and another liquid inclusion are compared, the above discussion is justified. It is seen that only for the 100 µm inclusions there is a difference and this is due to the difference in inclusion density between the solid and liquid inclusions respectively.

Other parameters that are important in steel making are the sulphur and oxygen content in the steel melt, temperature of the steel and inclusion velocity. An investigation on how the inclusion behavior is dependent on the slag viscosity and overall wettability was made in supplement 4. Moreover, the effect of inclusion behavior by varying inclusion and slag density, sulfur and oxygen content, steel temperature and inclusion velocity towards the overall wettability were investigated. It was shown from these parameter studies that a high overall wettability, low slag viscosity as well as low sulfur and oxygen content in the steel were the keys to obtain good inclusion transfer to the slag. Also, the model showed that the larger inclusions had easier to separate to the slag than the smaller inclusions due to a higher buoyancy force. By varying inclusion and slag density it is seen that the inclusion density has larger effect on the inclusion “Pass” region than the slag density. Moreover, the separation is promoted if the slag or inclusion density is close to the density of the steel melt. Further more, the variation of steel temperature did not affect the inclusions transfer to the slag. A reason for this might be that the steel, slag and inclusion were liquid at the temperatures in this study and that the physical property parameters did not change much between 1823-1873K. Changing the initial velocity of the inclusion did not have much effect on the inclusions behavior. Hence, having a low slag viscosity is more important for the inclusion separation than initial inclusion velocity at the steel slag interface.

From the application (in supplement 1 and supplement 2) of the mathematical models to industrial ladle and tundish conditions it was shown that the overall wettability should be high (positive) and the slag viscosity should be low in order to obtain optimal inclusion transfer. Though, the slag viscosity should not be too low because then the risk of slag entrainment to the steel is promoted which will result in more inclusions in the steel.

In-situ experiments with the Confocal Scanning Laser Microscope on a high carbon-calcium treated steel containing Al₂O₃-CaO inclusions at steel-gas and steel-slag interfaces using a 20wt%Al₂O₃-40wt%CaO-40wt%SiO₂ slag was done. Also observations of liquid (20-27wt%Al₂O₃)-(27-36wt%CaO)-(44-47wt%SiO₂) inclusions present in the slag could be made. From the studies of Al₂O₃-CaO inclusions at the steel-gas interface only agglomeration between semi-liquid and
liquid inclusions could be observed. The attraction force is as mentioned before weaker between two liquid inclusions than between two solid inclusions. Attraction or repulsion between two particles is strongly dependent on the contact angle between particle and melt, particle size and shape. Liquid inclusions weaker attraction force is due to the lower contact angle between inclusion and steel compared with a solid inclusion. This can also be explained by interfacial deformation. A solid inclusion cannot deform itself, but the liquid steel can which causes a higher contact angle. If the inclusion is liquid, then both steel and inclusion can deform and create a lower contact angle resulting in a weaker attraction force. Agglomeration between liquid Al$_2$O$_3$-CaO inclusions at the steel-slag interface could be observed when the agglomeration was forced. This was done by increasing the temperature. The increased temperature also increased the slag flow and the inclusions were pushed towards each other and also towards a solid steel front. Comparing the attractive force calculations, both experimentally and theoretically, the agreement was fairly good. The difference between experimental and theoretical was a factor 10. Bigger inclusions were also shown in the calculations to have a higher attraction force than smaller inclusions.

Regarding the liquid inclusions found present in the slag, the agglomeration was free. An explanation to this might be higher free energy force for the inclusions in the slag and the different inclusion composition compared with the inclusions at the steel-slag interface.

Comparing the application of the liquid mathematical model for inclusion behavior to the experiments at the steel-slag interface it showed that the inclusions there would remain at the steel-slag interface which also the experiments show. However, applying the liquid (20-27wt%Al$_2$O$_3$)-(27-36wt%CaO)-(44-47wt%SiO$_2$) inclusions found in the slag to the mathematical model it predicts that these inclusions also will remain at the interface if they were found there. Hence, more investigations of inclusion behavior at the steel-slag interface using the CSLM needs to be done and compared with the model in order to get any certain answers to this. Maybe, the actual overall wettability is much higher for the inclusions found present in the slag than the estimated and used overall wettability in the mathematical model.

Overall in supplements 1, 2, 3 and 4, estimations of physical property data had to be made due to the lack of experimental data in the different models used. Therefore, the calculations regarding inclusion behavior, agglomeration force and industrial applications are only a guide to what happens in reality until experimental data and verification of the models by CSLM experiments can be done.
Discussion
Chapter 6

CONCLUSIONS

In Supplements 1, 2 it was concluded that the inclusion can behave in three ways as it crosses the steel-slag interface. It can pass-fully separate to the slag, remain-stay at the interface not being fully separated to the slag, or oscillate-move up to a maximum position and then descend down before rising up again until the motion is damped out. In the remain and oscillating case, the possibility of inclusions reentering the steel bath by a steel flow parallel to the slag exists. The mathematical model also proposes two ways for the inclusions to separate to the slag, with or without steel film formation. This is controlled by Reynolds number. If it is less than or equal to unity no steel film s formed around the inclusion. If it is larger than unity, a steel film will be formed that the inclusion must pass through before it can separate to the slag.

From the parameter studies in Supplements 1, 2 and 4, it was shown that the most important parameters for the inclusion separation are slag viscosity, interfacial tensions, inclusion and slag density as well as sulfur and oxygen content in the steel. Application of the models to industrial conditions showed the need of valid experimental data for industrial conditions is important in order to obtain predictions of inclusion behavior with the mathematical models that are accurate. The combined effect of slag viscosity and overall wettability (based on the interfacial tensions) showed that the slag viscosity should be low and that the overall should be positive in order to obtain optimal inclusion transfer. Also it was shown that the larger inclusions had a larger area of separation than the smaller inclusions. This is because of the higher buoyancy force that the larger inclusions experience. The results showed that useful plots can be made in order to illustrate the tendency of the inclusion transfer and how to manipulate the physical property parameters in order to increase the inclusion separation for specific industrial conditions.

In Supplement 3, in-situ experiments with a Confocal Scanning Laser Microscope was made with Al$_2$O$_3$-CaO inclusions, a high carbon calcium treated steel and a transparent 20.7wt%Al$_2$O$_3$-36.5wt%CaO-42.8wt%SiO$_2$ slag. Observations of the inclusion agglomeration were made at steel-gas, steel-slag interfaces and also of
inclusions present in the slag. Comparison of the experimental and theoretical attractive force showed that the experiments and theory agree rather well, only a factor 10 different. Also it was visualized that the bigger inclusions had easier to agglomerate and it was also seen by the higher attractive force. Application of the experimental conditions to the mathematical models illustrated in Supplement 4 that the model can be applied to the inclusions found at the steel-slag interface. The results of the application of CSLM experiments to the mathematical models showed a need of more CSLM investigations at steel-slag interface in order to be able to make any finite conclusions. Also here, the need of valid experimental property parameter data was elucidated.
Chapter 7

FUTURE WORK

The inclusion behavior at a steel-slag interface is quite complex as illustrated in Figure 1. This study has focused on the possible inclusion transfer to the slag when an inclusion has reached this position. Even though an increased knowledge regarding this topic has been obtained in this thesis, more questions are still not answered. This requires further studies. Based on the results in this doctoral thesis, the following suggestions for future work are recommended:

- Measurements of interfacial tensions and slag viscosities for industrial slags, steels and inclusions. This will make predictions of inclusion transfer for these specific inclusions and slag systems more reliable and thus more useful for industrial conditions.

- More in-depth verifications of mathematical model predictions using CSLM experimental data, especially from the steel-slag interface.

- Combine the current mathematical model of inclusion transfer at the steel-slag interface with models describing the transport on inclusions to the turbulent boundary layer and the transport of the inclusions through the boundary layer to the steel/slag interface (see Fig. 1). In this manner, a better overall model of the inclusion behavior in the vicinity and at the steel-slag interface would be obtained.
REFERENCES


