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Investigation of the scale factor between full scale ladle furnace process and water models

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Abstract

The ladle furnace process is an important process in the steel manufacturing industry. The purpose of this process is to optimize the composition of the elements in the melt as well as to homogenize the temperature in the liquid.

It is common practice to model this process using smaller water models. In order to accurately scale these models a variety of criteria and scaling factors are needed. The central phenomenon which all else is derived from is the two-phase gas plume dominating the fluid flows. The plume, and its dependant parameters are difficult to define. Which ones ought to be used and how to use them has not been standardized. Concerns have been raised whether the most common method of scaling is even applicable in ladle metallurgy. This report gives an account for studies concerning these variables and their effect on the subject. The objective of this report is to highlight ways to improve these simulations with respect to debated parameters.

The conclusion of this study points out the reasons for why these variables may be of importance for the modeling of the ladle furnace process. It also specifically mentions future work that should be conducted in order to provide deeper knowledge of the different parameters affecting the method of modeling.

Keywords

Ladle furnace, Modified Froude number, Two-phase gas plume, Water model scaling

Sammanfattning

Skänkmetallurgin är en viktigt process inom stålindustrin. Syftet med denna process är att optimera den kemiska sammansättningen i smältan och att homogenisera temperaturen i vättskan.

Det är vanligt att modelera denna process med hjälp av vattenmodeller. För att träffsäkert skala dessa modeller krävs en mängd kriterier och skal-faktorer. Det mest centrala fenomenet, utifrån vilket allt annat kan härledas, är två-fas gasplymen som dominerar flödena i skänken Plymen och dess beroende parametrar är svåra att definera. Vilka som bör användas och hur de används har inte standardiserats. har väckts över om den vanligaste skalningsmetoden ens går att använda i skänkmetallurgi. Denna rapport redogör för studier rörande dessa variabler och deras påverkan på ämnet. Syftet med denna rapport är att belysa olika tillvägagångssätt till att förbättra dessa simulationer med hänsyn till debaterade parametrar.

Slutsatsen för denna studie lyfter fram anledningarna till varför dessa variabler är av vikt för modellering för skänkmetallurgin. Även framtida arbete som bör utföras för att ge djupare förståelse för de olika parametrarna belyses.

Nyckelord

Skänkmetallurgi, Froudes modifierade tal, Två-fas gasplym, Skalning av vattenmodell

Contents

Chapter 1

Introduction

1.1 Background

In order for the Swedish steel manufacturing industry to remain relevant on an international market, high quality and sustainability are two of the most important parameters that have to be taken into consideration. As such it is expedient to try to make the processes involved in the steel-making as efficient as possible. One of these processes is the ladle furnace. Consequently, a constant and homogeneous temperature must be maintained and the chemical composition in the melt is adjusted. This is done in order to create the desired properties, and quality of the steel. In order to achieve a homogeneous composition in the melt, one must stir the liquid steel. The stirring is, by today's standard, done by blowing an inert gas into the vessel. Argon is an example of a commonly used gas for these matters. As the gas rises it mixes the contents in the ladle by bulk convection. The composition in the liquid steel then adjusts as the melt comes in contact with added elements. Furthermore, one must separate the liquid steel from the atmosphere as this exposes the melt to unwanted elements that in turn affect the composition of the liquid steel. This is done by a layer of slag at the surface of the melt [1].

The ladle furnace process requires a significant amount of energy and is thus, costly. Therefore, one must strive to reduce the amount of time required to achieve the desired composition as much as possible. This specific time is called the *mixing time*. Experiments done directly in the ladle furnace are naturally very expensive. Therefore one would want to use less energy demanding and less costly physical models for this process. Due to the similarity in kinematic viscosity between water and liquid steel, a common practice is to use water models. However, these models are usually scaled down versions of their industrial counterparts, which introduces a variety of similarity criteria that have to be met in order for the models to accurately represent reality.

One of these similarity criteria is called the geometric similarity. It simply means that the systems being compared have equal geometric ratios but different sizes. With this relationship one can calculate the scale factor, λ, as:

$$\lambda = \frac{L_m}{L_{f.s.}} \tag{1.1}$$

Where L_m and $L_{f.s.}$ is the liquid depth for the model and the full scale process respectively. The arguably more important criteria is the dynamic similarity between the full scale and the model. In order to calculate this similarity the modified Froude number: Fr_m is used. The relationship is then formulated accordingly:

$$Fr_{m,m} = Fr_{m,f.s.} \tag{1.2}$$

The geometric scale factor has been widely used, together with an exponent, n, to scale different parameters in the modeling process. n has previously been defined in various ways [2, 3, 4], most often based on the similarity equation, Eq. (1.2). Because of these different expressions, exactly which value the exponent n should have is up for debate. Additionally, the question has been raised [5] whether the modified Froude number, in its current state, is applicable in ladle metallurgy at all.

1.2 Problem

Due to the different opinions about the variables mentioned above it is questionable whether the current way of modeling is the most reliable. If not, how can it be improved and which criteria should be taken into consideration?

1.3 Purpose

The purpose of this work is to make a literature study concerning the dimensionless numbers that have been used to calculate the scale factor between the models and the full scale converter. By doing this we can then investigate how the mixing times are correlated in the experiments and in theory.

1.4 Goal

The goal of this project is to give an accurate explanation of the criteria most often used for water modeling. Furthermore, to give a clear picture of whether the commonly used scaling factors are applicable in all cases and why. Based on these relationships give examples on how experiments testing these factors could be improved.

Our project has not been conducted, or intended, to be harmful towards any instance in any way. All studies have been made in a way that lies within the boundaries of good ethics.

1.5 Methodology

In order to give an answer to our problem we decided to make a thorough literature study about parameters affecting our problem. To find our sources, our arrangement was to search the internet. In order to gain trustworthy sources we decided to use search engines specifically customized for scientific studies, such as Google Scholar and KTH Library. We refer to previous studies that have been made in similar work or work that covers a part of our research. Commonly used keywords were: ladle furnace, water model, defining plume, scale factor, effect of nozzle.

1.6 Related Work

Previous studies of the physical modeling of the ladle furnace process have been made. Back in 2000, D. Mazumdar, H.B. Kim and R.I.L. Guthrie made a report on how to correlate physical water models with the full scale process through calculating a scale factor between the two. After calculating this scale factor they could then determine the value of the different parameters in the model, e.g. flow rate and geometrical size [2].

Mazumdar and Guthrie had previously studied gas injections in the full scale ladle furnace process as well as in water models. This was made in three different ways. The first method was to observe and measure different parameters of the gas in water models. Secondly, a mathematical model was made, i.e. no physical model. Furthermore one would purely chose variables and make assumptions for the variables in the different equations used to calculate desired parameters. Thirdly, a based of a combination of both methods were conducted in order to precipitate the different results of desired parameters while using the same variables for both methods [6].

In a two-part series of studies [7, 8], K. Krishnapisharody and G.A. Irons wrote about the spouts of liquid created by the rising bubble plume. These articles laid the groundwork for what would later [9, 5], by the same authors, become a critique of the use of the modified Froude number in ladle metallurgy. By comparing the numbers' original purpose to that of ladle metallurgy and realizing its shortcomings when modeling the metallurgical process it was stated that a revision was needed. An alternative was proposed; The plume Froude number.

Chapter 2

Parameters for Water Modeling

2.1 The modified Froude number

The modified Froude number is, as the name implies, based on the Froude number. William Froude originally developed this number to describe the resistance of a ships hull against the water passing by it. The Froude number is defined by

$$Fr = \frac{v}{g \cdot y_m} \tag{2.1}$$

where v is velocity of the flow, g is the acceleration of gravity and y_m is the hydraulic deep of the control volume. To better fit the process of blowing gas into a liquid the Froude number was altered. The result was the modified Froude number. It describes the relationship between the injection velocity of a gas and the buoyancy of a liquid. It was initially used to describe the plume of gas injected horizontally into copper converters [10]. The number has since been widely used to describe the two-phase plume responsible for the bulk mixing in the ladle furnaces process and the correlating water models. It is formulated as:

$$Fr_m = \frac{\rho_g}{\rho_l} \cdot \frac{U_0^2}{g \cdot d_0} \tag{2.2}$$

Where ρ_g is the density of the gas, ρ_l the density of the liquid, U_0^2 injection velocity and d_0 is the diameter of the injection apparatus [11].

Another expression for the modified Froude number, suggested specifically for ladle flows has been formulated by D. Mazumdar [4]. By using an idealized expression of the buoyancy force and the dynamic similarity, Mazumdar produced:

$$Fr_m = \frac{U_P^2}{g \cdot L} \tag{2.3}$$

Where U_p is the plume rise velocity and L is the liquid depth. The plume rise velocity was formulated as:

$$U_p \approx Q^{1/3} \cdot L^{1/4} \cdot R^{-1/4} \tag{2.4}$$

This expression for the plume rise velocity originates from unpublished research by the same author in cooperation with R.I.L. Guthrie. It is stated to be consistent with experimental data [4].

2.2 Scale factor

In order to determine the scale factor between the full scale vessel and the water model observations of certain variables must be made. The geometrical scale factor is decided by calculating the factor between the characteristic length of the full scale vessel and the model as shown in equation Eq. (1.1). The characteristic length in ladle furnaces and water models are the liquid depth [11].

When measuring the material transport in the ladle furnace process the modified Froude number has been proven to be the dominant variable [2]. Thus the same variable was observed and was chosen as a starting point in order to recreate the same flow in the model as in the full scale process. In correlation with the equation for Froude's number Kim and Fruehan [3] proposed the relationship

$$\frac{Q_{mod}}{Q_{f.s}} = \lambda^{2.5} \tag{2.5}$$

where Q_{mod} is the gas flow rate in the model, $Q_{f.s}$ is the gas flow rate in the full scale and λ is the geometrical scale factor between the characteristic length of the model and the characteristic length of the full scale vessel. Two other correlations have been made throughout the last decades [4, 2]. The resulting numbers for the exponent n from these two works, $n = 1.5$ and $n = 2.75$, are derived from different relationships to those made by Kim and Fruehan. The precise way they were formulated is not available as they both rely on unpublished research [4, 2]. These three exponents of λ, $n = 1.5, 2.5, 2.75$ were included in the experiments made by Mazumdar and Guthrie

[2]. The relationship between the flow rates of the model and the full scale process is generally formulated as

$$Q_{mod} = \lambda^n Q_{f.s.}$$

2.3 Effects of Slag

As the gas plume rises it pushes some of the liquid to the surface. This can result in the slag being pushed to the side, creating what is called a slag eye. The eye is an important parameter since it exposes the liquid to oxygen and nitrogen, thus changing the composition of the melt in an undesirable way [6]. A bigger slag eye also results in a greater risk of re-oxidation of the melt. As such a higher gas flow is not necessarily preferable even though this would result in a shorter mixing time [12]. Some studies [3, 13] also mention that high gas flow rates are not the most advantageous for mass transfer. M. Ek *et al.* [13] even go so far as to state that a high gas flow rate could lead to the flushing off of non-metallic inclusions from the ladle wall. It is commented that the time needed for proper inclusion removal will always be longer than the time needed for proper mixing.

Slag has, in the last thirty years, usually not been modeled. However, in recent years, more effort has been put into this area. In spite of this, a substance that accurately represents the properties slag and its interactions with the melt remains unresolved [14]. Coconut oil has been used to model the top layer as its kinematic viscosity, at room temperature, roughly equals that of slag, at 1873 Kelvin. The density ratio of water and petroleum roughly equals that of steel and slag [15]. In an experiment testing the inclusion removal rate silicone oil was employed [13].

Investigations on water models show, that in the presence of slag at the top of the liquid, the mixing time increases [16]. In correlation to this, the exponent *n* for the scale factor λ^n appears have a higher value when slag is present as well [3].

2.4 Water model experiments

In order to make a simulation of the lade furnace process water models are often used. In these experiments, water is used to simulate the liquid steel. However,there are different ways to conduct such experiments. A number of different techniques have been used to measure the gas induced liquid flows; electromagnetic flow meter, drag probe, laser doppler velocimetry and a combination of electro-resistivity probe and a laser doppler velocimetry [6].

In an water model experiment made by Zhongqiu LIU, Linmin LI and Baokuan LI, with an oil layer on the surface representing the slag was used. Furthermore they used nitrogen gas to simulate the argon gas and had a temperature of 25^oC and *1 atm* pressure. When the flow rate was steady, *NaCl* was added in order to measure the conductivity changes at a local point in the liquid. One could then determine the mixing time to when the conductivity achieved a desired level of homogeneity. The desired level of concentration homogeneity was calculated with a difference coefficient α as:

$$\alpha = \mid \frac{c_t - c_{inf}}{c_{inf} - c_0} \mid \tag{2.6}$$

where c_t is the concentration at a given time, c_0 is the initial concentration and c_{inf} is the concentration at the time when the difference in concentration barley changes. The criteria of a homogeneous mix was established as $\alpha = 1$%. Other studies have set $\alpha = 5$% [13]. One could then measure the different mixing times, and how they are dependent on different gas flow rates, slag thickness and injection location. Furthermore, one could also determine the mixing time by measuring whenever the pH-value ceased to vary. The results from the experiments indicates an increasing mixing time with injection at the center of the bottom as well as a large difference at different flow rates. However, the mixing time of a non-centered injection does seem to follow a linear decrease in mixing time for increasing gas flow rates [11]. This relationship has been confirmed by [14] as well.

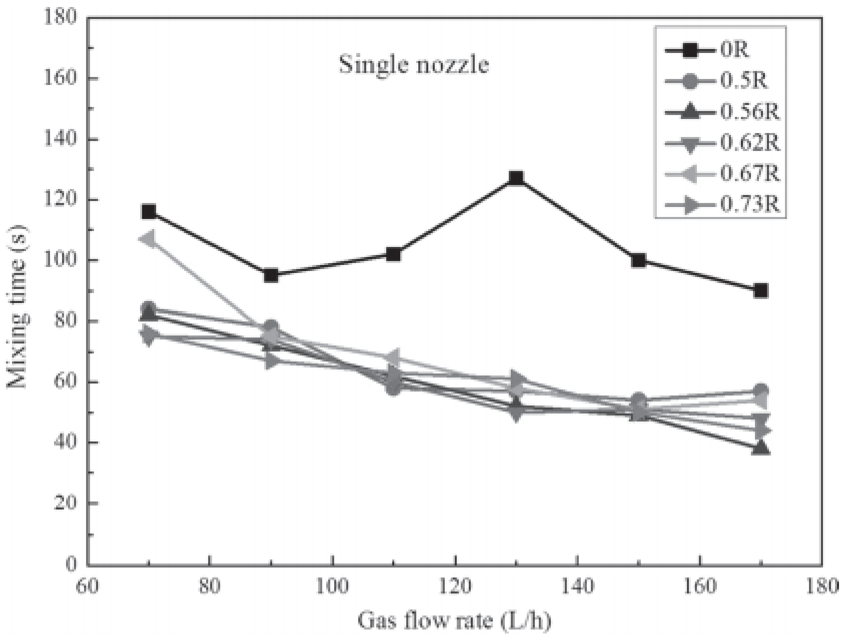

Figure 2.4.1: Different mixing time at different injection location and flow rates [11]

Back in 2000 Mazumdar, H.B Kim and R.I.L Guthrie [2] published a study of the mixing time in the ladle furnace using water models. Furthermore, the experiment was made with different relations in four different vessels A, B, C and D with a variation in the liquid depth and the ladle scale with one vessel A used as a reference. To compare how the different relations differed each vessel was compared to the reference in five different gas flow rates. Water was used as the liquid and air was blown with a vertical lance, simulating the argon gas stirring. In order to determine whenever the liquid had achieved an optimal mixing a probe, sulphuric acid was added to the system. When the concentration between the liquid and the probe ceased to vary one could decide that the mixing was complete. The optimal mixing percentage was assumed to be 95%. The mixing time with respect to the reference vessel A was measured and displayed in Figs: (2.4.2, 2.4.3, 2.4.4).

The mixing time could the be calculated as:

$$\tau_{m,mod} = \lambda^{1/2} \cdot \tau_{m,f.s} \tag{2.7}$$

Where $\tau_{m,mod}$ is the mixing time for the model and $\tau_{m,f.s}$ in the mixing time for the full scale process. The expression requires geometrical and dynamic similarity [2].

The conclusion drawn from the experiments was that there is not an absolute correlation between a specific number on n in λ. For example, a comparison between vessel A and B proved to match well with relation Eq. (2.5). However the comparison between vessel A and D did not prove to deduce the same relationship. From this, it was suggested that while the vessels may be geometrically similar the dynamic similarity does not necessarily correlate. Furthermore, the results from the experiments concluded that the most applicable relation for most cases is $n = 1.5$. However this relation does only appear to apply when the models are dynamically similar rather than geometrical [2].

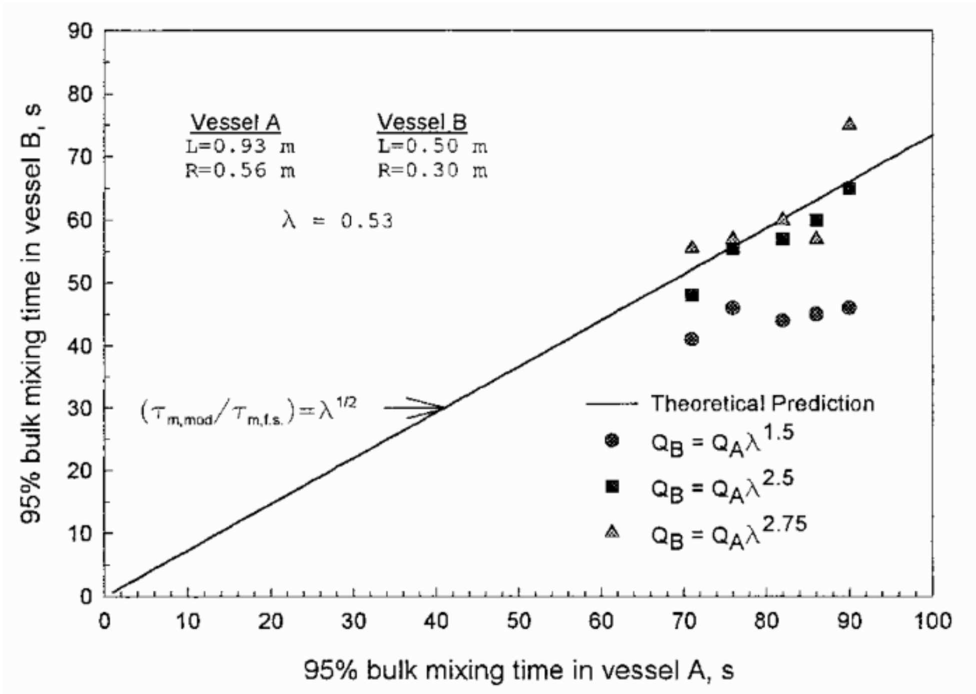

Figure 2.4.2: Vessel B compared to pilot vessel A [2]

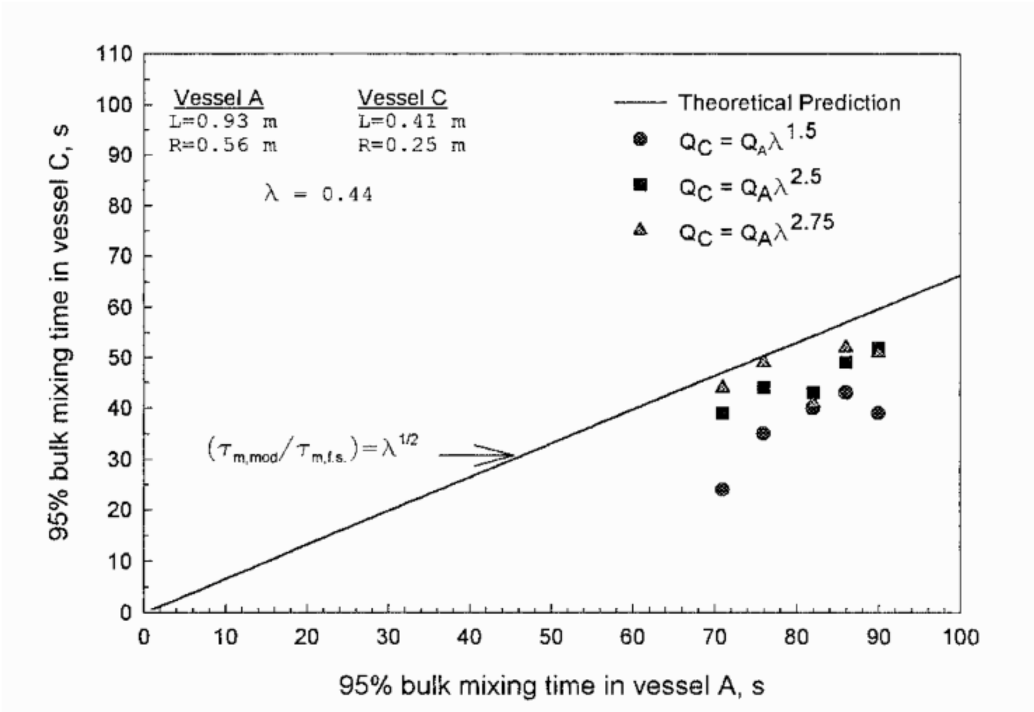

Figure 2.4.3: Vessel C compared to pilot vessel A [2]

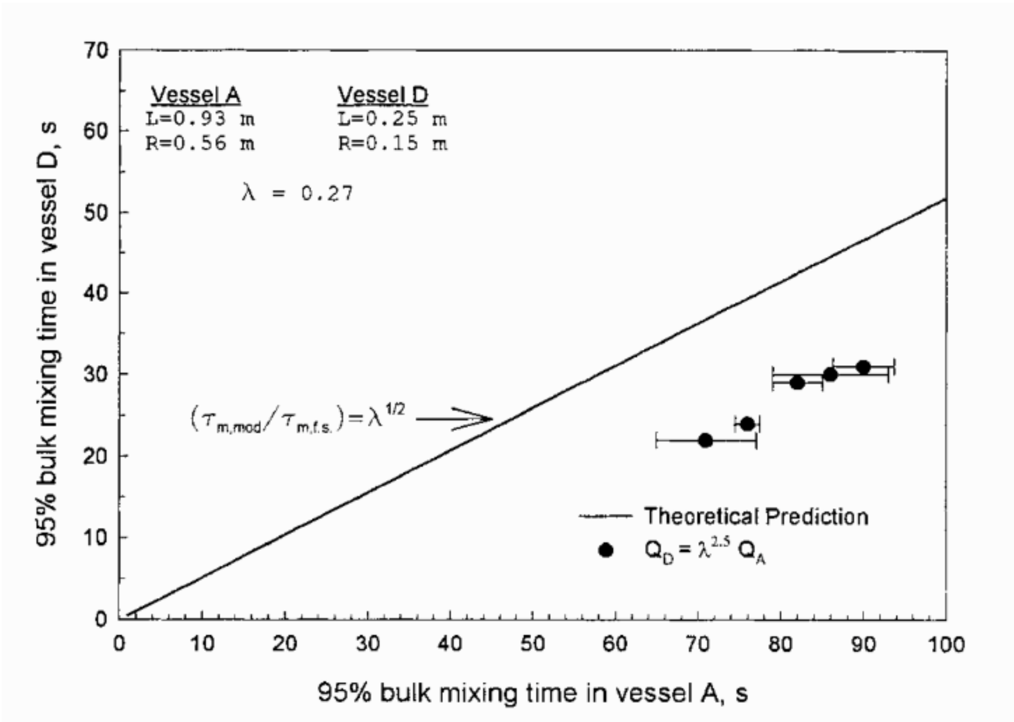

Figure 2.4.4: Vessel D compared to pilot vessel A [2]

2.5 Plume and Bubbles

There have been several ways to characterize the rising gas plume throughout different studies. For instance it has been said [17] to have four regions, mentioned from injection orifice to surface of the liquid: 1. Primary bubble, 2. Free bubble, 3. Plume, 4. Spout. The kinetic energy is reported to be the highest in the primary bubble region, and decays rapidly in the free bubble region. A different study [18] reports the plume to be divided into three regions, namely: Momentum, Transition and Buoyancy. The report goes on to state that the beginning and end of these regions are hard to define, citing the so called penetration depth as a parameter that can help determine this. The penetration depth is said to be where the momentum region transitions into the buoyancy region. It is determined by measuring the void fraction above the injection. However, because the velocity of the injected gas and the buoyancy of the liquid are aligned, exactly which value for the void fraction that is used differs [18]. The fact that penetration depth is defined by void fraction and not velocity, prompted criticism of the use of the parameter altogether [5]. The issue of how and where momentum dissipates is stated to remain unaddressed, as void fraction above the nozzle will be high regardless of velocity. Experiments conducted by [19] indicate that when the liquid height is high enough for the plume to become a bubble column, mixing times start to increase.

The issue of which kind of gas injection apparatus should be used has also been discussed [14, 5]. In most water model experiments a nozzle is used, but the industry standard is to employ a porous plug. The two devices are claimed to not produce the same bubble sizes, with the porous plug creating smaller bubbles than the nozzle. This is somewhat disputed however, with [6] stating that bubble sizes in the fully developed region are more determined by the thermo-physical properties rather than the inlet operating variables. In [14] this is also addressed, as it is mentioned that the thermal expansion of bubbles is quite large, because of the temperature difference between gas and steel, in the industry but negligible in water models. Thus the orifice used for injection is said to have insignificant effect. It has been reported that a porous plug provides an increased mass transfer when compared to a nozzle [14].

2.6 Plume Froude number

The modified Froude number, formulated as Eq. (2.2), is commonly used to calculate the two-phase flow in ladle metallurgy. However, Krishnapisharody and Irons argued against the use of this number [5]. They state that the physical meaning of the modified Froude number was appropriate and meaningful in it's early uses. However, the use of the number in vertical jets are said to have fundamental issues. Firstly, it is pointed out that the importance of the initial momentum is diminished simply by the fact that the trajectory of the jet and the buoyancy force are aligned. Considering the relatively slow injection velocities of the gas in metallurgical ladles, as well as their average height of around 3m, the velocity of the plume is said to be dictated more by the buoyancy force than injection speed. The fact that the modified Froude number incorporates the nozzle diameter is also called into question. It is stated that the width of the injection apparatus has negligible effect on flow characteristics [14, 11]. This would render this an unsuitable parameter to base a similarity criterion on. Krishnapisharody and Irons also point out that standard operating procedure in the industry is to use porous plugs, not nozzles, for which the measurement of its diameter itself is somewhat arbitrary. They question if one is supposed to measure the diameter of the pores, the sum of their diameters, or the diameter of the plug as a whole. This in turn would make measuring the injection velocity more difficult [5].

Krishnapisharody and Irons go on to state that the modified Froude number involves redundant dependencies. Because of this, there is no fundamental basis for the usage of the modified Froude number in rising plumes [5]. Therefore, an alternative to the modified Froude number, called the *plume Froude number*, was formulated as:

$$Fr_p = \frac{\overline{U}_l^2}{\overline{\alpha} g H} \tag{2.8}$$

$\overline{U}_l$ is the area-averaged vertical velocity over a plume cross-section, $\overline{\alpha}$ the cross-sectional area-averaged void fraction in the plume, g is the gravitational acceleration, and H is the bath height. Krishnapisharody and Irons previously proved [9] that only the non-dimensionalized gas flow rate and axial height are required to characterize free-rising plumes. This became the basis for the *plume Froude number*.

Chapter 3

Results

3.1 Usage of the geometrical scale factor

In order to regulate the gas flow rate in the water model and measure a corresponding mixing time, a scale factor Eq. (1.1) has been used [11, 2, 3]. This geometrical scale factor is then used to calculate an in-scale appropriate rate of the gas flow in the experiment or in the full scale process. The exponent n of the scale factor can be calculated by using Eqs. (1.2), (1.1) and, depending on if one takes the injection or plume rise velocity into account, Eqs. (2.3) [4] or (2.2) [11]. Frequently used values are 1.5, 2.5 and 2.75 [2]. However, the values for the exponent are empirical. Furthermore, two of the numbers; 1.5 and 2.75, have been used in several experiments but the origins of the values have not been published [4, 2].

The value of the exponent of λ^n has been noted to vary depending on several factors. One of these factors could be slag. However, there are sources [2, 19] that disregard the effects of slag or report [14] that they have been disregarded previously.

Efforts to simulate a layer of slag in the water models have been attempted using substances such as coconut oil and petroleum. This has proven to increase the exponent for the scale factor [3]. However, since these are only rough approximations a substance that can more accurately model industrial slag is needed in order to make a more lifelike simulation.

As shown in Figs. (2.4.2, 2.4.3, 2.4.4) water models were constructed and compared to each other using one water model as a reference system for the other systems [2].

As a foundation, the theoretical relationship between mixing times, which depends on geometrical, and dynamic similarity between two systems, was chosen. Different proposed exponents were then tested in order to see which one was the most fitting with respect to mixing time ratio. As shown, every experiment does not seem to favor the same relationship. However, these attempts have been made where the gas is injected by a vertical lance instead of a vertical plug or nozzle.

3.2 Modifications of Froude's number

A significant usage of Froude's number can be seen when it comes to modelling the full scale ladle furnace process. The modified Froude number has been used specifically since it represents the ratio of the inertia of the injected gas to the buoyancy force. However, there appears to be different ways of modifing Froude's number. Another version of the modified Froude number has been specifically formulated for ladle flows, Eq. (2.3) [4]. Furthermore, many sources assume that the buoyancy force is a major parameter responsible for mixing phenomena.

While most sources use the modified Froude number Eq. (2.2), which was obtained by non-dimensionalizing the momentum equation, Krishnapisharody and Irons [5] suggest another equation, the plume Froude number Eq. (2.8). It is further claimed that the modified Froude number is not the best method for calculating the dynamic similarity Eq. (1.2) for several reasons, the most prominent being:

1. The momentum of the injected gas dissipates quickly after exiting the injector and thus has an insignificant contribution to the momentum of the plume. Instead it is the buoyancy force that dominates the plume rise velocity.

2. The number uses the diameter of the injection orifice as an important parameter. However, it is very common to use a nozzle in water models, even though the industry standard is to use a porous plug. The different apparatus variants produce different bubbles and the measurement of their diameter differs.

The plume Froude number is formulated with respect to the dependent parameters of the plume i.e. bath height, void fraction, an expression for the plume rise velocity and the acceleration of gravity.

3.3 Characterizing the plume

It appears there are different ways to characterize the plume. One could either look at the kinetic energy at the primary bubbles or the void fraction at the injection point. Furthermore, one could take into account that the kinetic energy decays as the plume rises in the liquid. However, if taking respect to void fraction, the velocity of the plume is the most contributing factor of mixing time. This velocity would then be considered to be most dependent on the buoyancy force of the liquid. Regardless, it seems to be a consensus [17, 18] that the most important area in the plume is at the bottom, where the plume begins. Regardless of the way of characterizing the plume it appears to be agreed that the bath height would prove to be a most significant variable.

Another dispute is whether the type of injection apparatus affects the plume [5, 14]; if a nozzle produces the same result as a porous plug. Additionally, questions have been raised whether the thermal expansion for bubbles in the industry has a more dominating effect than the shape of the injection apparatus [6].

Chapter 4

Discussion

4.1 Defining the plume velocity

It seems reasonable to assume that the plume is the major factor contributing to the mixing of the liquid. However, as can be seen from previously conducted studies [5, 14, 2, 6], it seems unclear exactly how the plume rise velocity should be defined when using the injection velocity as a starting point. In addition to this, the values used for the exponent of the scale factor become unreliable simply from the fact that the inventors cite unpublished research as sources for vital parts of the numbers origin. Some of the numbers have been shown to fit reasonably well in specific situations, by the inventors themselves. However, the presence of three different values does not strengthen the scaling-method's legitimacy, as this would indicate that it is not a general method for scaling in its current state. It has been noted that one should also consider that the modified Froude number was initially designed to describe horizontal gas injection, not vertical. As such, penetration depth and injection velocity were more defining factors in early applications.

Considering the factors that have been reported to influence the fluid flow, a revision of the way water models are scaled becomes ever more necessary. It does seem reasonable to consider the rising plume as more dependent on the buoyancy force than injection velocity, since that force expresses itself in every part of the liquid, not just at the injection apparatus. Krishnapisharody and Irons [5] mentioned that this is even more logical if the vessel has a large height, and the injection speeds are relatively low, which is the case in the industry. As such there will be a large distance between the surface and the injection point, over which injection speed can dissipate, and over which the buoyancy has influence.

Simply increasing the gas flow rate in order to decrease mixing times and make the modified Froude number more accurate, because of its dependence on the injection velocity, is inadvisable however. As mentioned previously by other studies [16, 13, 12, 3], a high gas flow rate would not be exclusively beneficial for the ladle furnace process. The size of the slag eye is an important factor to consider, as well as being careful to avoid splashing, which is already common practice. When one also considers that inclusion removal does not benefit from high flow rates, it becomes even more apparent that increasing the gas flow rates is not feasible. As such the ladle furnace process in its current state must work with relatively low gas flow rates.

4.2 Simplification of Models

Considering the studies regarding the area, it is noteworthy that a majority of water model experiments [2, 11, 3, 14, 16] do not employ a porous plug. There does not seem to be a logical reason to make such a simplification and it seems to be rare to motivate the given choice of injection orifice. With risk of arguing with hyperbole, it is quite reasonable to make the simplification of using water models instead of only running industrial trials because of the obvious economic and energy benefits. However, using a nozzle in these water models instead of a porous plug does not seem to have notable benefits compared to any associated drawbacks.

It has been standard practice to use the modified Froude number Eq. (2.2) and the similarity equation Eq. (1.2) in studies and experiments concerning the ladle furnace process. However, discrepancies with it's applicability have been noted in several works [3, 5, 14, 18]

One aspect that neither the modified Froude number, nor the suggested plume Froude number, take into account is the presence, or absence, of a slag layer. However, slag supposedly [3] does have an effect on the exponent n of the scale factor λ by increasing the value needed to accurately scale the gas flow rate. This would make it a parameter that must be taken into consideration when scaling the model.

4.3 Benefits, Ethics and Sustainability

We believe that this report will provide a useful foundation for continued research in water-modeling since it highlights the current complications of scaling the process. With greater understanding of how to model the ladle furnace process, it could potentially lead to a more energy- and cost efficient usage of the process. This could prove to be beneficial for both the environment and the industry, by achieving a more sustainable steel production process.

4.4 Analysis of sources

The credibility of the sources in the literature study has been taken into consideration when gathering information. The articles used for the literature study are published by scientific journals. This would prove to indicate unbiased source of information. Rather, if one would gather the same information from studies published by individual companies, content that could be non-favorable for the company could possibly be left out. Furthermore, a scientific paper promotes new findings, regardless the positive or negative nature och the discovery. Concluding, even though some sources appear to disagree on some subjects, they would be rated as unbiased.

Chapter 5

Conclusion and Future Work

It appears that there are different opinions about which parameters should be taken into consideration when modeling the ladle furnace process. As such, there does not seem to exist a definitive way to scale the water models. It appears that the most important thing to notice is the velocity of the plume and how to define it. While there are different definitions of that variable, further research should be made in order to give a correct explanation. After doing this one would be able to define a more applicable scaling criteria.

It is also be important to pay attention to building models that represent reality as well as possible. Therefore, an incorporation of a substance simulating slag in the model should not be neglected.

5.1 Future Work

More studies should be made in order to achieve a greater understanding on which parameter affects the plume rise velocity the most. This could be made by conducting water model experiments based on the newly defined plume Froude number, together with a more industrial-like injection apparatus, and comparing them to experiments using the modified Froude number. Thus, further research regarding the thermal expansion of the bubbles created from a porous plug compared to those of a nozzle should be conducted. Additionally, further research on an adequate substance used to model slag in these models should be made.

Chapter 6

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