EXPERIMENTAL STUDY OF LANCE BUBBLING PHENOMENA

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Abstract

The injection of gases in liquids is a widely used process in the industry, especially in chemical reactors and metal converters. Three types of injection exist, bottom injection, side injection and top injection (top submerged lance injection). The last is the one studied in this project.

The von Karman Institute for Fluid Dynamics was requested to do a hydrodynamic study of this type of process and during its first stage it was seen that the bubble formation frequency changes according to the scale of the reactor. This change in frequency with the scale of the reactor is studied in this project.

A new theoretical analytical model is developed. The theoretical results are compared with the experimental ones and with the literature. The influence of the lance submergence depth is quantified. A correlation based on the Strouhal and Weber numbers is found. The constant pressure and constant flow regimes are compared. The pressure signal is correlated to the image visualization, including the coalescence phenomena. Two dimensionless geometrical parameters are found, that model the frequency evolution when the reactor scale is changed.
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Nomenclature

\( \lambda \)  The virtual (added) mass coefficient or the amount of liquid a bubble has to accelerate as a fraction of the bubble volume

\( \mu_{g,l} \)  dynamic viscosity of the gas or liquid phase (kg/m/s)

\( \nu \)  kinematic viscosity (= \( \mu/\rho \))

\( \rho_{g,l} \)  density of the gas or liquid phase (kg/m\(^3\))

\( \sigma \)  surface tension of the liquid phase (N/m)

A  function used to calculate the virtual (added) mass coefficient

B  function used to calculate the virtual (added) mass coefficient

d  lance diameter (m)

D  vessel diameter (m)

\( F_D \)  drag force (N)

\( F_{ST} \)  surface tension

g  gravitational constant (9.81 m/s\(^2\))

H  height of the liquid bath (m)

h  distance from lance tip to bottom of the vessel (m)

I  submergence depth (=H-h)

K  empirical constant used on the detachment criterion

R  radius of the bubble

Re  Reynolds number

U  gas velocity at the nozzle (m/s)

\( V_b \)  bubble volume (m\(^3\))

\( V_c \)  chamber volume (m\(^3\))
1. Introduction

Over the last decades, interest in intensive bath smelting techniques has risen, due to capacity efficiency and environmental issues. The submerged lance technology has been successfully applied for the purpose of smelting and converting copper mattes by Umicore. The von Karman Institute was asked to conduct a hydrodynamic study of the reactor.

The injection of gases in a liquid is always accompanied by the creation of gas bubbles. They can be distinct bubbles at lower injection rates or a continuous stream of gas into the liquid at higher flow rates, for a given orifice design. The last case also shows periodic behavior up until high exit velocities. This periodic creation of gas bubbles at the lance exit results in pressure pulses in the gas supply system and the gas off take system as well as in violent movement of the liquid bath, especially when forming large gas bubbles. Complete insight and control of the operation of the smelter requires in depth knowledge of the frequency related phenomena and especially the accurate prediction of the bubbling formation frequency. If the frequency is the same as the eigen frequency of the reactor, structural damage can occur.

The lack of predictive frequency models for these vessels leaded to the need to extend the models available to be used in the industrial case. Previous studies at VKI with a vessel scaled 3 times down when compared to the one used in this study lead to a model for the prediction of the bubbling frequency. However, comparing these studies with the literature an interesting result can be found, the frequency changes depending on the scale of the reactor. A literature review, presenting important results, models and authors is done in chapter 2 of this thesis. The study of this scale effect will be the main goal of this thesis. Laboratory tests are conducted with a water model in order to assess the applicability of the existing theoretical models to this particular setup. The influence of different parameters on the bubbling frequency is also studied; different water heights, submergence depths, injection chamber volumes, lance diameters and gases are tested. Air and Helium are used in order to assess the influence of different gases but also to allow tests at higher flow rates. The experimental campaign is explained in detail in the chapter 3 of this thesis.

The results are compared to those from previous studies done at VKI and with the literature. Flow visualization is made with a high speed camera in order to assess the bubble formation frequency and to better understand the flow. The results from the frequency measured with the camera and the pressure fluctuations are compared and discussed. A theoretical model is proposed on chapter 4, using the experimental values obtained. The results are presented and discussed in the mentioned section also.
2. Literature review

2.1 Bibliographical survey

The injection of gases into liquids has been studied for over a century as it is a common operation in chemical and metallurgical processing. In the majority of applications, the gas is injected through a nozzle either at the base or side of the vessel and therefore, studies of these configurations have dominated the literature. In contrast, the injection through a top submerged lance has found more applications in the last decades. The commercialisation of top submerged gas injection processes as the Ausmelt and Siromelt processes [Floyd, 1996], for bath smelting has rekindled an interest in this operation.

A substantial number of studies have been made for top submerged lance injection, however most of them lack experimental data. In the last years work has been done to help us understand better, the control parameters of the whole system and to validate theoretical approaches (numerical modelling). Two distinct regimes are identified, the constant flow, which is based on a balance between the buoyancy force acting on the forming and rising bubble and the acceleration of the fluid surrounding the bubble. In the constant pressure regime the flow rate entering in the bubble is not constant anymore, it is time dependent. It is proportional to the velocity of injection in the bubble (at each instant) and is equal to the rate of change of the bubble volume.

Amongst the first to propose models for the bubbling frequency, with and without viscous effects, at constant flow rate and also to solve numerically the system of equations relative to the constant pressure regime, were [Davidson & Schuler, 1960]. Other authors have found empirical correlations for the bubbling frequency [Iguchi et al 1995] and [Iguchi & Chihara, 1997], however most correlations are for the constant flow regime. The most extensive work found in this field is the one by [Neven, 2005], where a comprehensive experimental and numerical study is made. Two experimental setups are taken, water models and high temperature systems. Several parameters are studied in order to assess the most important parameters in this type of injection. The pressure fluctuations measured in the lance are correlated to the bubbling frequency, to confirm this, visualization is made and also the bubble diameter is studied. Different vessel diameters are tested to verify the influence of the vessel walls in the flow and more precisely in the bubbling frequency. The effect of liquid cross flow is also studied, however for the present case it has no practical interest.

Several parameters are changed, the gas flow rate, the fluid nature (water and glycerine are tested), the lance submersion depth, the lance diameter and the vessel diameter. From here it can be concluded that all of these parameters with exception of the fluid nature are control parameters and will affect the bubbling frequency and the behaviour of the flow in general. The bubbling frequency increases with lower submergence depth and with vessel diameter. The lance diameter plays a role for low gas flow rates, after a critical value, the outer diameter of the
lance is always the one affecting the flow, this is in agreement with [Liow, 2000], which concluded the same in his experiments. Having knowledge of the control parameters allows a more focused study on them. In Neven’s work an important behaviour on the bubbling frequency is noticed, it increases with the diameter of the reactor. This scaling effect has not yet been studied and one of the main objectives of this project is to understand and model it. The numerical solutions proposed by Neven are quite similar to the ones from [Davidson & Schuler, 1960], with some adaptations such as the added mass coefficient ($\lambda=0.3$ instead of $\lambda=11/16$) and the detachment criteria ($s=2R(t)$).

As said before, this is the most complete reference found and after it, work can be focused on the control parameters. This was done by [Gosset et al., 2007]. The pressure fluctuations were successfully correlated to the bubbling frequency, visualization of the bubble formation was made in order to better understand it’s growth and to assess the applicability of the detachment criteria previously used by [Neven, 2005]. Visualization of the free bath surface was also made, in this case for design reasons but it can also help us understand the motion of the whole bath, however this will not be one of the objectives of the project. In their campaign [Gosset et al., 2007] changed several parameters, the gas flow rate, the gas nature, the lance submergence depth, the lance diameter and the volume of the injection chamber. In their experiments, the flow rate was varied and Helium was also used, Helium allows reaching higher flow rates without entering the jetting regime. The lance submergence was confirmed as a control parameter, as well as the lance diameter. These results will be confirmed in this study and so far, we can conclude the same behaviour when the lance submergence depth is changed, in both models [Gosset et al., 2007] and the facility I’m working in, which is scaled 3 times from their facility. As for the lance diameter, their results are in agreement with [Neven, 2005]. It is interesting that although they have the same ratio between lance and vessel diameter, the results in bubbling frequency are different and for the bigger facility the frequency is higher. This is in agreement with what has been previously mentioned, there is a scale effect. In my study several lance diameters will also be tested in order to then model this phenomenon. The volume of the injection chamber is also a very interesting parameter, [Gosset et al., 2007] concluded that it influences the pressure fluctuations on the injection system. With a reservoir (volume=28l) inserted in the injection system, the low frequency components disappear for low flow rates. For higher flow rates (5l/s), it is seen that the fluctuations are clear and the signals with and without the chamber are almost the same. This suggests that the constant flow regime dominates for high flow rates. In the experiments already done with my setup I was able to reproduce these results, both with Helium and Air. New changes to the injection system have been proposed and will be undertaken in order to understand it’s influence in the complete system. In my experimental campaign I have showed the influence of the chamber volume, introducing the same chamber used by [Gosset et al., 2007] but also without the chamber. Two different rotameters are being used, one for low flow rates, another for the high ones, the only difference between them being the volume. A clear drop in frequency can be seen when a change is made from the small rotameter to the big one. The overlapping flow rates between these two rotameters is very small and tests have been made for those flow rates, it was found that for the same flow rate the frequency was lower in about 1Hz for the bigger rotameter when compared to the small one. More experiments will be carried out, with more rotameters, in order to try to explain this variation in frequency.
In the numerical part [Gosset et al., 2007] studied the sensitivity of the models to the added mass coefficient (λ) and the bubble detachment criteria. λ is made variable and a function of the Reynolds number and its evolution is fitted in order to provide acceptable predictions for the bubble frequency. The detachment criteria is determined with the experiments, s=R(t) is the one that fits best the experimental data. A simple correlation for the frequency is obtained through the constant flow model. The constant pressure model also gives good predictions when λ is fitted. A dimensionless criterion in terms of Capillary and Bond numbers is proposed for the occurrence of the maximum frequency and it is showed to be in good agreement with the experiments with different lance diameters. These parameters will be studied and with the help of a high speed camera and image post processing adjustments to these parameters will be made in order to find a correlation for the bubbling frequency that includes the scaling effect.

2.1.1 Davidson & Schüler (1960)

These authors were the first to propose models at constant flow rate with and without viscous effects but also to solve numerically the system of equations relative to the constant pressure regime. For the constant flow regime:

\[ F = 0.5797 \left( \frac{\lambda}{ho} \right)^{-0.6} \left( \frac{q}{d} \right)^{1.5} \]  \hspace{1cm} (2.1)

obtained solving analytically equation (2.1) with the added mass coefficient \( \lambda = 11/16 \). They also solved the equation for the constant pressure regime:

\[ \frac{dV_b}{dt} = k \sqrt{\left( P_{tip} - P_{atm} - \rho_l g (L - s) - \frac{4 \sigma}{d_b} \right)} \]  \hspace{1cm} (2.2)

where k is the orifice constant fitted to the experiments with the relation \( k = q / \sqrt{\Delta P} \).

2.1.2 Iguchi et al (1995)

They proposed the following empirical correlation for the bubbling frequency:

\[ F = 92.8 \left( \frac{\rho_l}{\rho} \right)^{\frac{1}{4}} \left( \frac{\rho_g}{\rho_l} \right)^{\frac{1}{3}} \frac{1}{d} \sqrt{\frac{(q^2/g)^{\frac{1}{6}}}{d}} \]  \hspace{1cm} (2.3)
2.1.3 Iguchi & Chihara (1997)

They proposed the following empirical correlation for the bubbling frequency:

$$F = 1.06 \left( \frac{g}{\sigma} \right)^{\frac{1}{4}} \rho_l^{-\frac{1}{5}} \left( \frac{g}{d} \right)^{-\frac{1}{2}} (\rho_g q)^{\frac{1}{2}}$$  \hspace{1cm} (2.4)

2.1.4 Neven (2005)

This is the most complete reference found in the literature. A full investigation of the process is done. Experiments in a water/helium reactor are made and modeling is also undertaken. The modeling is based on the work of Davidson & Schüler (1960) with some adaptations such as for the fraction of entrained liquid ($\lambda = 0.3$ instead of $\lambda = 11/16$) and the detachment criteria ($s=2R(t)$). Concerning the experimental part, a very extensive study was made which gives very useful information for the experimental campaign.

2.1.5 Gosset et al (2007)

This report made at the Von Karman Institute gives useful experimental information. The constant flow model is studied and a new criteria for $\lambda$ is introduced. In this study the added mass coefficient is function of the Reynolds number on the lance, $\lambda(Re)$, a summary of the constant flow model is shown:

$$F = 2.28 \lambda^{-\frac{3}{5}} q^{-\frac{1}{5}}$$  \hspace{1cm} (2.5)

$$\lambda = A Re^{-B}$$  \hspace{1cm} (2.6)

$$A = 2.83 d^{-0.564}$$  \hspace{1cm} (2.7)

$$B = 0.307 d^{-0.1}$$  \hspace{1cm} (2.8)

The detachment criteria used is $s=R(t)$, as it is shown that this is more relevant for the frequency range being studied. In (2.7) and (2.8) $d$ is the lance diameter. The constant pressure regime was also studied, however as this study will focus on the constant flow regime no effort will be putted into it. As it can be seen in figures 2.1 and 2.2 the influence of the added mass coefficient and of the detachment criterion is obvious and these parameters should be studied in order to solve the model. The new form of the added mass coefficient seem so much more meaningful than the previous considerations that can be found in the literature.
Figure 2.1 Influence of the detachment criteria on the bubbling frequency

Figure 2.2 Influence of the added mass coefficient on the bubbling frequency
2.2 Bubble Formation Frequency

Several models have been proposed to model the bubble formation process as was illustrated in section 2.1. The bubbling frequency and the accompanying force equilibrium depend strongly on the injection regime. On the one hand we have a constant pressure regime which can appear at relatively low flow rates and which accounts for the influence of the chamber volume on the equilibrium bubble volume. The pressure inside the chamber is approximately constant and the chamber is large enough to accommodate small variations of injection gas volume. This way the outflow of gas into the bubble does not have to equal the inflow of gas into the chamber at all times and the gas outflow will be determined by an orifice equation. The average outflow of gas of course equals the inflow into the chamber. The constant pressure regime is only applicable to relatively low flow rates. This means that at higher flow rates we always deal with a constant flow regime and the gas chamber volume has no impact on bubble formation frequency. No definition exists of the transition gas flow rate from constant pressure to constant flow for a fixed gas chamber volume. The transition depends somehow on gas chamber volume, orifice geometry and gas discharge dynamics. On the other hand we have a constant flow regime. This regime is characterized by the fact that the outflow of gas into the gas bubble matches exactly the constant inflow of gas into the gas chamber. The chamber is usually so small or gas flow rates so high (see above) that the chamber cannot accommodate any excess of gas during bubble formation. The gas inflow into the gas bubble is therefore constant at all times during bubble formation. The constant flow regime is thus also the regime where the gas chamber volume will not influence the gas discharge dynamics such as bubbling frequency. Both regimes and the relative force equilibrium are treated in sections 2.3.1 and 2.3.2.

2.3 Theoretical models

This section gives insight on the most common theoretical approaches, which correspond to two distinct bubbling regimes. The constant flow regime corresponds to configurations where the gas flow rate injected in the bubble is constant throughout bubble formation. It is usually the case when the gas injection chamber is small and is unable to follow possible pressure variations when the bubble is growing and detaching. The constant pressure regime corresponds to situations where the injection system damps the pressure fluctuations due to bubble formation, involving a variable flow rate in the lance. This usually happens when the volume of the injection system is large and thereby able to handle small variations of pressure. The derivation of these models is presented and discussed. The derivation made is for the most recent and for the one that gives the best results for this setup, the one developed by [Gosset et al., 2007]. Other important models, for bubbling, found in the literature are also reviewed.
2.3.1 Constant flow rate regime

The inviscid version of the constant flow rate model is based on a balance between the buoyancy force acting on the forming and rising bubble and the acceleration of the fluid surrounding the bubble. This volume of liquid pushed by the bubble is considered to be equal to a fraction \( \lambda \). The balance is expressed by:

\[
(\rho_l - \rho_g)V_b g = \frac{d}{dt}(\lambda \rho_l V_b \frac{ds}{dt})
\]  

(2.9)

Figure 2.3 Force balance and detachment criteria

Where \( s \) is the distance between the tip of the lance and the center of the bubble, \( V_b \) is the bubble volume, \( \rho_l \) and \( \rho_g \) are respectively the density of the liquid and of the gas and \( g \) is the gravitational acceleration. Due to the large differences in density between the gas and the liquid, this equation is most of the times written without the density terms.

It is possible to include the viscous and surface tension effects in the balance:

\[
(\rho_l - \rho_g)V_b g = \frac{d}{dt}(\lambda \rho_l V_b \frac{ds}{dt}) + F_D + F_{ST}
\]  

(2.10)

Where \( F_D \) is the drag force on the bubble and \( F_{ST} \) is the surface tension force. This equation cannot be solved analytically, hence, numerical solving is required. The main objective is to keep the model analytical and so equation (2.10) will not be solved.
The gas flow rate $q$ in the bubble is constant in time and so:

$$V_b = q \cdot t \quad (2.11)$$

Combining equation (2.11) and equation (2.9) and integrating two times one reaches:

$$s = \frac{g \cdot t^2}{4\lambda} \quad (2.12)$$

Considering that the bubble detaches when the distance between the bubble center and the tip of the lance is equal to the radius of the bubble, $s = R(t)$. The detachment time can then be computed and the bubbling frequency $F$ is simply the inverse of it:

$$F = 2 \cdot 4^{\frac{3}{5}} \left(\frac{3}{\pi}\right)^{\frac{1}{5}} \left(\frac{1}{\lambda}\right)^{\frac{3}{5}} q^{\frac{1}{5}} = 2.28 \lambda^{-\frac{3}{5}} q^{-\frac{1}{5}} \quad (2.13)$$

Where,

- $F$ – bubbling frequency (Hz)
- $\lambda$ – added mass coefficient
- $q$ – volumetric flow rate (m$^3$/s)

From equation (2.11) we know the volume of the bubble when this time is reached. Combining equations (2.11) and (2.13) the diameter of the bubble can be calculated:

$$D_b = 2^{\frac{3}{5}} \left(\frac{3}{\pi}\right)^{\frac{2}{5}} \left(\frac{1}{\lambda}\right)^{\frac{1}{5}} q^{\frac{2}{5}} \quad (2.14)$$

Although this report doesn’t focus on the dimension of the bubbles this comes as an important result for the study of the general flow. [Neven,(2005)] used a version of this model, however he adopted a different detachment criterion, $s=2 \cdot R(t)$, in his case. It is noticeable that the model can be improved by including other forces in the bubble balance and also a more accurate detachment criterion.

### 2.3.2 Constant pressure regime

In the constant pressure regime, the flow rate entering in the bubble is not constant anymore, it is time dependent. It is instantaneously proportional to the velocity of gas injection in the bubble (gas velocity at the tip of the lance) and is equal to the rate of change of the bubble volume:

$$q(t) = v_{ib}(t) \pi r^2 = \frac{dV_b(t)}{dt} \quad (2.15)$$
Where $v_{ib}$ is the gas injection speed in the bubble, and $r$ is the radius of the lance.

The velocity $v_{ib}$ is driven by the pressure drop produced at the tip of the lance so that:

$$\Delta P_{\text{tip}} = P_{\text{tip}} - P_b = \xi 0.5 \rho_g v_{ib}^2(t) \quad (2.16)$$

Where $\Delta P_{\text{tip}}$ is the singular pressure drop at the tip of the lance, $P_{\text{tip}}$ is the pressure at the lance tip, $P_b$ is the pressure in the bubble and $\xi$ is the coefficient of singular pressure loss for this configuration (this coefficient is empirical as it is nearly impossible to fix it for the configuration of a growing bubble). The relation $v_{ib}(t) = k \sqrt{\Delta P_{\text{tip}}}$ is generally used (with $k$ being experimentally determined).

It is possible to relate the pressure in the bubble to the upstream conditions and so:

$$P_b = P_{\text{atm}} + \rho_l g(L - s(t)) + \frac{4\sigma}{D_b(t)} \quad (2.17)$$

Where $P_{\text{atm}}$ is the atmospheric pressure, $L$ is the lance submergence depth and $\sigma$ the surface tension. This leads to the velocity at the tip of the lance:

$$v_{ib}(t) = \sqrt{\frac{1}{\xi 0.5 \rho_g} \left( P_{\text{tip}} - P_{\text{atm}} - \rho_l g(L - s(t)) - \frac{4\sigma}{D_b(t)} \right)} \quad (2.18)$$

One can relate the injection velocity in the bubble to the instantaneous flow rate and also to the rate of growth of the bubble. Combining equations (2.1), (2.7) and (2.10):

$$\frac{\pi}{2} D_b^2(t) \frac{dD_b}{dt} = \pi \frac{d^2}{4} \sqrt{\frac{1}{\xi 0.5 \rho_g} \left( P_{\text{tip}} - P_{\text{atm}} - \rho_l g(L - s(t)) - \frac{4\sigma}{D_b(t)} \right)} \quad (2.19)$$

$$\frac{g}{\lambda} = \frac{3}{D_b(t)} \frac{dD_b}{dt} + \frac{d^2 s}{dt^2} \quad (2.20)$$

Although in the industry the conditions leading to a constant pressure regime are easily met (presence of a large reservoir before the injector), this model suffers a low popularity because it requires solving numerically a set of equations. An improved version of this model may include viscosity and surface tension forces in the balance. It is also worth noting that this approach usually considers $P_{\text{tip}}$ directly, when actually the pressure drop from the reservoir till the lance tip could be evaluated instead. As in the previous regime, a detachment criterion should also be adopted.
2.4 Transition to Jetting Behavior

Non-ferrous processes are usually characterized by low pressure injection of gasses in the bath. All processes are thus operating in the bubbling regime creating large gas bubbles in the bath which can interact with each other or with the reactor lining. Evidence of this is plentiful due to measurements of pressure pulses in the gas supply system ([Ashman et al., 1981] [Gray et al, 1984] [Hoefele and Brimacombe, 1979]). Ferrous processes on the contrary show jetting behavior because they operate at much higher pressures. The transition from bubbling to jetting behavior is important because it induces changes in pressure, penetration depth of the gas, interaction with the wall, recirculating flow patterns, mixing energy, contact interface between liquid and gas, etc . . .

One of the first to investigate the transition region between bubbling and jetting was [Leibson et al.,1956]. They defined the onset of jetting as a rapid sequential formation of large, irregular bubbles that coalesce and shatter immediately after detachment and estimated that this would occur from Reynolds numbers exceeding 2000. This regime is known as discrete jetting because reasonably discrete bubbles can be observed. A further increase of gas flow rate ultimately leads to a steady cone of gas entering the liquid. This steady jetting behavior was observed to start around Reynolds numbers exceeding 20000. Reynolds numbers between 2000 and 20000 determine thus the transition region between separate bubbles and a steady jet of gas. [Hoefele and Brimacombe, 1979] have performed such pressure pulse measurements on water models as well as on an industrial scale Pierce Smith Converter combined with cinematographic measurements of penetration angle and depth of the gas jet with the water model. This led to the development of a jetting behavior diagram based on the modified Froude number and the gas to liquid density ratio. The map allows determining the conditions where transition occurs from the bubbling to the jetting regime. It shows that the higher the gas to liquid density ratio is, the lower the Froude number has to be for jetting to occur.

[Ozawa et al,1983] and [Ozawa and Mori, 1983] have confirmed for low density liquids the necessity of choked flow conditions in the tuyere for jetting to start. Choked flow occurs when the velocity of the gas approaches transonic conditions and no pressure increase will lead to a subsequent velocity increase of the gas. When the gas approaches sonic velocity further increases in inlet pressure will lead to compression of the gas and thus higher gas densities but will not result in higher gas velocities. It means that increasing the pressure will result in a heavier gas to be injected in the liquid. [Hoefele and Brimacombe, 1979] have shown before that a heavier gas will more easily cause jetting to occur. All research of jetting transition with pressure pulse traces shows that discrete pressure pulses are observed for the bubbling regime while they vanish gradually when increasing the gas flow rate and the injection conditions approach jetting behavior.

2.5 Pressure influence on bubbling

This section attempts to identify the different ways pressure phenomena interacts with gas injection to influence the bubble frequencies. Pressure variations can be perceived globally such
as the pressure pulsations in the gas phase due to bubble detachment but can also be perceived locally such as the pressure onto the reactor lining around the orifice when gas bubbles make contact with the wall. Pressure will intervene in bubble formation at a submerged orifice in three different ways. First of all, there is the pressure in the gas chamber. Large chambers will show relatively slow pressure build-up at constant chamber inlet flow rates. Prior to bubble formation pressure build-up is observed inside the chamber until the pressure is large enough to overcome hydrostatic pressure and the energy becomes available to expand the bubble nucleus to a fully spherical bubble. The sudden formation of this gas bubble gives rise to a pressure drop inside the gas chamber resulting in a variable gas inflow into the bubble. This regime is referred to as a constant pressure regime because overall pressure variations in the chamber are limited. In the extreme case (infinite gas chamber) gas pressure stays practically constant. Secondly, the static system pressure will affect bubble sizes and frequencies. An elevated or reduced system pressure above the bath will influence bubble formation significantly [Iguchi & Chihara 1998]. [La Nauze, 1972] and [La Nauze and Harris, 1974] have examined bubble formation at elevated systems pressures and concluded that higher system pressures systematically reduced the volume of the bubbles thus resulting in increased bubbling frequencies. These higher bubbling frequencies in turn lead to reduced time delays between individual bubbles and can affect coalescence behavior. [La Nauze and Harris, 1974] show that bubble volume decreases at high injection flow rates due to large static system pressures. At increased pressures transition to double bubbling occurs for smaller gas flow rates. A third pressure-related phenomena are the local pressure variations around the orifice and around the growing bubble which can also interact with the formation process and influence bubble size and frequency. When large bubbles are created, whether through bubble formation at the orifice, or through jet break-up, there is a risk that the bubble will make contact with the lining. Back attack occurs at relatively high flow rates where the gas enters the liquid under conditions of choking flow. The subsequent supersonic expansion of the gas in the liquid and the accompanying drag from the viscous liquid can lead to a momentary flow reversal, called back-attack. This phenomenon has been described by [Ozawa et al,1983] and [Ozawa and Mori, 1983] and can be detrimental to the refractory’s around the orifice. Since these phenomena relate to high flow rates they are usually not relevant for non-ferrous processes where only sub-sonic injection is used. The back-attack phenomena is identified as a major source of refractory wear. Pressure measurements just outside of the nozzle performed by [Wei et al., 1999] have contributed to assess the influence of injection parameters (such as gas flow rate, injection angle and gauge pressure) on the rate of erosion and wear of the lining. Pressure phenomena will also intervene with bubble formation and growth when injecting reactive species. Absorption of gas components into the bath gives rise to pressure oscillations. These oscillations typically occur at high frequencies but can, in certain cases, interact with bubbling frequencies. [Elperin and Fominykh, 1997] modeled these pressure oscillations for absorption of a soluble gas jet and mapped the pressure pulsation regimes according to gas mass flux and concentration of the soluble species. Further away from the orifice pressure variations can occur in the liquid when a large rising bubble induces a wake effect. Pressure will locally be lower than the pressure in the surrounding liquid and a suction effect will be created which can influence the formation of the next bubble when the first one is close enough to the nozzle exit.
2.6 Characterization of the bubble shape

A gas bubble in a liquid, especially when the liquid is in motion, will be subjected to deformation under influence of the stresses on the interfacial area between liquid and gas. Surface tension usually urges the gas bubble to assume the spherical shape but velocity gradients in the liquid, the proximity of solid boundaries or gas momentum can alter the shape of the gas bubble. Most work in literature assumes a spherical bubble shape. Not only is it convenient to consider gas bubbles as spherical but most experiments have shown that the spherical assumption is a good approximation of the actual shapes observed. Under influence of external forces the bubbles can elongate and become ellipsoid while large bubbles tend to assume a spherical cap shape when rising to the surface of the bath. A graphical correlation based on three well-known dimensionless groups has been established by [Grace et al., 1973] for bubbles freely rising in an infinite medium. The correlation in figure 2.4 is drawn in terms of the Eotvos number, $Eo$, the Morton number, $M$, and the Reynolds number, $Re$

\[
Mo = \frac{(\rho_l - \rho_g) g \mu^4}{\rho_l^2 \sigma^3}
\]

\[
Eo = \frac{(\rho_l - \rho_g) g D_b^2}{\sigma}
\]

\[
Re = \frac{Ud}{V_g}
\]

where $D_b$ is the equivalent diameter of the bubble, $\sigma$ the surface tension of the liquid, $\nu$ the kinematic viscosity of the liquid and $U$ the relative velocity between the gas bubble and the liquid. A large Eotvos number ($Eo > 40$) usually characterizes large gas bubbles. The graph shows therefore that smaller gas bubbles maintain a roughly spherical shape over a much larger range of Reynolds numbers. The shape of larger gas bubbles will thus more easily be affected by turbulent flow. For theoretical convenience gas bubbles which do not have a spherical shape are assigned an equivalent sphere based on volume, area, projected area or projected diameter. An equivalent sphere is a sphere with the same value of one of the above parameters. Consequently a shape factor is defined to measure the degree of deviation from the spherical shape. The shape factor is the ratio of one of the other parameters of the equivalent sphere to the value of that parameter for the actual bubble shape. This terminology will prove its value when discussing bubbles in confined geometries where gas bubbles are deformed by the presence of walls. With exception of a sphere, three bubble shapes have been investigated in previous work. Larger gas bubbles rising in a bath will assume the spherical cap shape. Another shape that is frequently considered is the ellipsoid. When injecting gas at high gas flow rates through e.g. a bottom orifice and with high exit velocities, the gas can possess considerable momentum and cause the bubble at the orifice to elongate vertically and to become an ellipsoid. It is as if the gas pushes the bubble upwards from the inside.
2.7 Previous Experimental work

2.7.1 Neven (2005)

This is the most complete reference found concerning top submerged lance injection. The study of several parameters is studied, the liquid properties, the gas properties, the wall effect, the lance submergence depth and the lance diameter. Other non frequency related phenomena are also studied, reading of this work is recommended due to its extensive amount of valuable information about this type of flow.
2.7.1.1 Lance Submergence Depth

Lance submergence depth can vary during operation of an industrial Isasmelt reactor. During smelting feed is continuously added to the bath and the bath level continuously increases. The operator will periodically adjust the lance height to maintain an average lance submergence depth. This means that, however limited, the submergence depth varies. There are two sources of influence from hydrostatic pressure to be expected. First, there is the reduction in gas volume due to the fact that the gas exits the lance at a higher hydrostatic pressure. Since submergence depth is limited, hydrostatic pressure is small. Secondly, the height of the liquid level above the lance exit intervenes in the force equilibrium for the constant pressure regime through its impact on the pressure difference in the orifice equation, although the difference in depths examined here is so small that no remarkable influence is expected. Figure 2.4 shows indeed no significant difference between frequencies at different depths ranging from 20 cm to 50 cm. A lance with diameter of 5 cm and equipped with swirlers is used here. Only at low submergence depths a considerable increase in bubbling frequency is observed. These low submergence depths cause the gas to escape before the bubble equilibrium volume is reached. This is referred to as 'bad coupling' between gas jet and bath. Part of the gas volume escapes through a channel directly to the surface. The effective gas volume available for bubble formation is much lower since part of it escapes alongside the lance. The lower effective gas flow rate causes frequencies to rise significantly. General accordance between experimental results and calculated frequencies using both flow regime models is found. At lower gas flow rates we clearly see the evolution of the bubbling frequency according to the constant pressure regime force equilibrium. At approximately $6 - 7 \times 10^{-3}$ m$^3$/sec, the flow regime changes and the frequencies exhibit behavior consistent with a constant flow regime. Frequencies are somewhat higher than predicted since turbulence and flow patterns cause premature detachment from the lance exit thus resulting in slightly higher frequencies. The range of flow rates used throughout his thesis is roughly situated in a transition zone between both flow regimes. The added mass
coefficient determining the virtual mass has been reduced compared to the theoretical values of 11/16 or 0.5 which were applicable to laminar flow. The added mass coefficient used in these calculations is an empirically determined value of 0.3 and is lower than the values given in the literature for injection in an infinite medium. The limited influence of lance submergence depth has been confirmed during operation of the industrial reactor. Frequencies do not change significantly when altering the lance submergence depth.

2.7.1.2 Lance diameter

This series of experiments was performed to investigate the influence of the lance diameter on the bubbling frequency. A larger lance diameter is expected to promote a smooth detachment of the gas bubbles at lower gas flow rates. A larger lance diameter will thus result in higher frequencies at the lowest flow rates examined here. Increasing the gas flow rate leads to larger bubbles and the volume of the lance end protruding into the gas bubble will subsequently become less important compared to the gas bubble volume. Detachment isn't influenced by the lance diameter anymore since surface tension becomes rapidly negligible and inertia and buoyancy remain the only influential forces in the equilibrium. Another aspect is the increased chamber volume. A larger chamber volume is expected to result in larger gas bubbles. It is therefore expected that the bubbles created with a larger lance (without swirlers) will also be larger. However, the measurements show no significant difference between both series. This means that surface tension does not intervene in the bubble formation process and that the lance diameter is no major obstacle for smooth bubble formation and detachment at these particular flow rates and lance diameters. The general conclusion is that these two influences occur only at even lower gas flow rates, way below the flow rates that apply to the Isasmelt submerged injection conditions.

![Figure 2.6. influence of lance diameter on bubbling frequency.](image)

Figure 2.6 presents the frequencies for two lance diameters. First, any influence of the lance diameter is expected to occur at lower gas flow rates since at high gas flow rates the chamber
volume does not impact bubbling. At higher gas flow rates any set-up reflects a constant flow regime. Second, using a smaller lance diameter increases the exit velocities and leads to a higher Reynolds number. Larger exit velocities ultimately lead to a jetting regime which is not the regime under investigation in these experiments. Although the exit velocities and Reynolds numbers are still below the transition regime ($v_{exit} < 2 \text{ m/sec and } Re < 1000$), visual observation confirmed the occurrence of jetting conditions. No steady discrete bubbling regime was achieved at higher flow rates for the small diameter lance.

### 2.7.2 Gosset et al (2007)

It has been shown before the existence of some influence caused by the relation between diameter of the vessel (D) and of the lance (d). In this case, several lance diameters were tested on a 0.24 m diameter vessel. The results show that only when the ratio $D/d=27$ the frequency drops around 1 Hz (for the higher flow rates), otherwise, for the other ratios tested the values are quite close. The values are then compared to the ones found by [Neven, 2005], it is curious to see that for the same ratio $D/d=8$ the frequency changes more than 1 Hz. These results should be analyzed carefully, the fact that different lance diameters are used can influence the bubbling behavior in the low flow rates, also [Neven, 2005] shows that no wall effect is present for a D=0.40 m but for D=0.18 m still exists, which leads to the question, is there still a wall effect for D=0.24 m? The diameter chosen for the vessel should allow a study free of wall effects, but of course the lance diameter should also be taken into account. [Neven, 2005] used d=0.05 m and [Gosset et al., 2007] d=0.03 m. The difference in the low flow rates that is noticed in figure 2.5 is most probably related to the lance diameter than to wall effects, it shows for Re=500 that the values of the frequency lower as the Reynolds increases, unfortunately no higher flow rates were tested and no conclusion can be taken.

![Frequency comparison for different D/d](image)

Figure 2.7. Frequency comparison for different D/d

Another parameter tested was the lance submergence depth ($l$). The submergence depth is the portion of lance inside the bath, $l=H-h$ where, $H$ is the bath height and $h$ the distance between
the tip of the lance and the bottom of the vessel. Until now it was not clear which of these parameters influences the bubbling frequency. [Gosset et al., 2007] show that \( l \) is the control parameter, keeping \( l \) constant and changing \( H \) and \( h \), the same frequency is obtained.

![Figure 2.8. Frequency behavior for constant submergence depth (\( l \))](image)

Figure 2.8. Frequency behavior for constant submergence depth (\( l \))
3. Experimental campaign

3.1 P3 facility

The facility used is located on the industrial flows laboratory of the Von Karman Institute (VKI). It is a water model three times bigger than the one used in the previous experiments at the VKI (P1). The facility reproduces the shape of the industrial reactor, cylindrical, with a square shaped box surrounding it, so that visualization is possible without image distortion. A picture and a scheme of the facility are shown below:

![Figure 3.1 Picture of the P3 facility](image1)

![Figure 3.2 corresponding sketch](image2)

A high speed camera is used to record the flow at the same time as the pressure fluctuations on the lance are measured. This will be used to try and correlate the pressure signal with what happens in the flow. The lance submergence depth (l) has been shown before, [Gosset et al (2007)], to be a control parameter for the bubbling frequency on the P1 facility. The same behavior is expected and tests will be made to confirm it. The adjustable parameters are the bath height, H and the distance between the tip of the lance and the bottom of the vessel, h. Two lances are used, one with a diameter of 27 mm and another with 9 mm. This last one was used in the P1 facility and it will allow a good comparison between the two models. The 27 mm lance is centered in the cylindrical vessel, the 9 mm lance had to be moved and therefore it will be about 5 cm deviated. In such a large vessel, this small distance is not expected to influence the behavior of the flow. Wall effects are negligible. To study the effect of the volume of the
injection system on the bubbling frequency, a 28 l chamber is introduced in the injection system and it’s volume is changed. A sketch of the complete system is shown next:

![Diagram of the injection system](image)

Figure 3.3. Injection system of the P3 facility

The injection system without the chamber will be the nominal case. Another change made in the system is the introduction of a sonic hole at the top of the lance. The results will then be compared with the ones found with the rotameters.

The gas injected in the lance can be helium or air. Due to the limited amount of helium available, tests were first performed with air and then with helium. A comparison between the two is made. The injection is made from the VKI 7 bar compressed air network or from a 200 bars helium bottle.

The pressure pulses created by the bubble release at the tip of the lance are measured at the top of the lance with a static pressure tap of 1 mm diameter. The tap is connected to a pressure transducer and an output voltage is acquired on a PC with a Testpoint card. This type of pressure transducer is able to resolve pressure fluctuations provided they are not too high ($F << kHz$) when a suiting tubing system is used. (as small as possible).

### 3.2 Measurement chain

In this section more information is given about the devices and parameters used for the data acquisition. Pressure taps are made in the rotameters and on the lance in order to measure the pressure in both locations. The pressure variations in the lance will be post processed in order to achieve the bubbling frequency. The pressure in the lance depends mainly on the submergence depth of the lance: the gas has to overcome at least the hydrostatic pressure to be released from the lance tip. After calibration of the pressure transducer, the output voltage of the probe
gives the pressure at the top of the lance. The signal is first low passed and then acquired on a PC. The number of samples is high enough to ensure a good frequency resolution.

**Rotameters**

The rotameters are used to quantify the gas flow rate introduced in the bath. Two sets of rotameters are used; the first ones are the models Rota G2.2500 and G1.250. The second set is composed by Yokogawa’s Rota G154 and G263. The working conditions of these are: maximum pressure 8 bar and temperature ranging from 10ºC-80ºC. All the rotameters are graded until 20 cm and the smallest scale available is the mm.

**Pressure transducer**

Two strain gage pressure transducers are used, the transducers will have adequate membranes when related to the range of pressures needed. When the sonic nozzle is used the membrane of the upstream pressure transducer is changed to one allowing higher pressures. The calibration of the membranes was done using the Dimed DPI 601 Digital pressure indicator.

**Demodulator**

The transducers are then connected to demodulators. Two Validyne CD 15 carrier demodulator are used, after calibration.

**Low Pass Filter**

The demodulators connect to a low pass filter, which is used to avoid noise and undesirable frequencies coming from other sources. The filter is set with a gain of 10 and a cut off frequency of 300 Hz. It is connected to the acquisition board.

**Acquisition Board and PC**

The Keithley KUSB – 3100 board is used and connected to a PC where the data is acquired using the program TestPoint v7. The number of samples is set to 32768 and the sampling frequency, such so that the Nyquist criterion is satisfied, is set to 800 Hz. The resolution is 2,4 mV and the frequency resolution is 0,024 Hz.

**High speed camera**

A high speed camera is used to film the flow. The camera model is Phantom v7, an exposure time of 100 µs and a frame rate of 100 pps are used and the trigger is set to 1072p. This will give 5 seconds of recorded images. The program used to process the movies is the Phantom 630 software. A 1200 W light spot is placed on the other side of the water vessel and the vessel is covered with paper in order to obtain the correct lighting for the high speed camera.
3.3 Measurement techniques

3.3.1 Pressure measurements

The bubbling frequency is obtained from measuring the pressure on top of the lance. A 1 mm pressure tap is used to measure the static pressure, this is done for several reasons, the flow at the tip of the lance is too turbulent and it would be difficult to understand what was being measured. The pressure fluctuations provoked by the detachment of a bubble at the tip are reflected on the top. As a bubble detaches an under pressure is created at the tip of the lance which causes the liquid to enter in the lance. This can be seen if the lance is transparent, as in the case of the 9 mm lance. This pressure variation is high and so the tap on top of the lance is able to measure it. The signal is measured and then acquired on the PC, as explained previously. The pressure signal is then processed, a Fast Fourier Transform (FFT) is applied to the signal and the bubbling frequency can be found.

The pressure signal is shown in figure 3.4 for a flow rate of 1,5 l/s, the lance used in this case was the 27 mm diameter and the gas used is helium. The main difference between the air and helium is in the intensity of the power spectrum, higher for air, which was expected. The resultant FFT is shown in figure 3.5. The post processing of the pressure data is the same for all the measurements. When the chamber is introduced in the injection system, it is not possible to measure the pressure fluctuations and so, flow visualization is used to measure the frequency. Because of the consumption of helium, the measurements were first made with air and then repeated with helium, the measurements were repeated always two times with helium (some measurements needed a 3rd run), while for air, most of them were done three times.
Only the bias error is considered here, which is of the order of magnitude of the frequency resolution ($\delta F = 0.24$ Hz)

### 3.3.2 Flow visualization

The high speed camera is used in order to measure the bubbling frequency and to better understand the flow. The images are taken at the same time as the pressure signal and coupling between the two will be attempted. This is not an easy task though, because the pressure signal has to be in phase with the images taken, which is never the case. The time scales of each signal (pressure and images) have to be adjusted for the coupling to be accurate. The images also allow us to see the differences in the flow when each of the two lances is used. The bubble shape is quite similar, in both cases the bubbles tend to look more like a disk (spherical cap) when they are released. When the flow rate is increased, in the small lance, the gas tends to penetrate more inside the liquid, this can be seen in figure 3.7. This is expected as the momentum with the smaller lance will be higher. [Gosset et al (2007)] studied in more detail the penetration depth of the gas, as well as the bubble diameter, for the 9 mm diameter lance. For more details about these parameters the reading of the cited reference is recommended.

When the chamber is introduced, pressure variations become too small for the bubbling frequency to be calculated, with the pressure signal, and so the frequency is measured through the images. In order to validate these measurements, the same is done when the chamber is not in the injection system.
3.3.3 Test matrix

As previously mentioned, several parameters are changed in order to assess the impact of each in the bubbling frequency. Test matrixes are presented in table 1 and 2 showing the different setup changes made.

<table>
<thead>
<tr>
<th>Gas</th>
<th>Lance diameter (d)</th>
<th>Submergence depth (l)</th>
<th>Chamber volume (Vc)</th>
<th>High speed camera visualization</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>9 mm</td>
<td>27 mm</td>
<td>35 cm</td>
<td>85 cm</td>
</tr>
<tr>
<td>Air</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Helium</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

Table 1. Test matrix when using the rotameters

To verify the precision of the rotameters, tests are done using a sonic hole, in this case by assuring Mach 1 on the throat and measuring the pressure before and after it, one can calculate the flow rate passing through the hole and consequently delivered to the lance. Adjustments have to be made to the setup, the pressure taps are located a few millimeters upstream the hole and on the lance, downwards from the hole. A thermocouple is connected to the upstream part.
also, in order to correct the gas density for the temperature increase as the pressure increases. Few tests are made, two hole diameters are tested, 2 mm and 1.25 mm, however due to time constrains, the measurements for the 2 mm diameter hole are not correct and more measurements are needed, therefore only the results for the 1.25 mm diameter hole will be shown and discussed. Table 2 shows the conditions tested with the sonic hole.

<table>
<thead>
<tr>
<th>Gas</th>
<th>Lance diameter (d)</th>
<th>Submergence depth (l)</th>
<th>High speed camera visualization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Helium</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

Table 2. Test matrix when using the sonic hole

The lance diameter is changed and the bubbling frequency is calculated and compared, these values are also compared with the literature and with the theoretical model. The submergence depth is changed, several parameters are tested, different bath heights, \( H \) and distances from the tip of the lance to the bottom of the vessel, \( h \), are set to achieve different submergence depths. The results are compared between them and with the literature. The influence of the injection system is assessed, several volumes are introduced in the injection system, pressure measurements are done and compared with the flow visualization. To validate the measurements with the 28 l chamber, \( V_c \), in the injection system, visualization is made without the added \( V_c \) to validate the frequency calculated from the images. Comparing the frequency obtained from the images and the one from the pressure signal without \( V_c \) allows to know the uncertainty when using \( V_c \) in the injection system.

It should be underlined that several unexpected situations occur when changing the conditions on the setup and that the presented test matrix reflects only the successful tests done.
4. Results

4.1 Theoretical model

4.1.2 The detachment criterion

The detachment criterion is studied in this section, the experimental results are compared with the theoretical using both criteria. To understand the different behavior for the two lances it is useful to compare the flow in both cases. When comparing the Reynolds number for both, it shows that in both cases the jetting regime is not reached. This allows higher flow rates to be tested and a comparison between different Reynolds numbers keeping a constant flow rate.

![Reynolds number comparison between the 2 lances](image)

Figure 4.1. Reynolds number comparison between the 2 lances

The experimental values for the 27 mm lance, shown in figure 4.2, follow the theoretical model with $s=R(t)$, however with an offset and the accuracy of the model is quite low. An average deviation of 2.69 Hz is calculated, with a maximum of 3.15 Hz. The average error in the prediction of the bubbling frequency is 27 %.

The behavior of the 9 mm lance, figure 4.3, is quite similar and the criterion $s=R(t)$ is the one that gives values closer to the experimental ones. The accuracy of the model is better in this case, the average deviation is 1.62 Hz with a maximum of 2.4 Hz. The average error in this case is 17% The detachment criterion used appears to be dependent of the lance diameter. It is known from the literature that the lance diameter plays a role on the detachment of the bubbles, particularly for low flow rates.
A study of the detachment criterion is made. Taking equations 2.11 and 2.12 and assuming the detachment criteria to be $s = K.R(t)$, solving for $K$:

$$K = \left( \frac{\pi \rho^3}{F^{5+16\lambda^3 Q}} \right) = \frac{50.98}{F^5\lambda^3 Q}$$  \hspace{1cm} (4.1)

Where:
F – bubbling frequency (Hz)

\( g \) - gravitational acceleration (m/s²)

\( \lambda \) – added mass coefficient

\( q \) – volumetric flow rate (m³/s)

The value of the constant \( K \) can now be calculated based on the experimental results. For each flow rate a value for \( K \) is calculated and a curve can be fitted. The curves are expected to show different behavior due to the different conditions on the flow and to the different diameter. Two curves are obtained, one for each lance. These curves, representing the evolution of \( K \), are shown in figures 4.4 and 4.5. Two expressions are taken for each lance diameter, depending on the Reynolds number. The aim of this study is to understand the behavior of the detachment criteria for both lances and allow a better choice for it depending on the lance size. The existing model takes \( K \) as a constant and it is shown that it is not, a new model is presented taking this assumption into account.

For the 9 mm lance:

\[
\begin{align*}
\text{Re} < 500 & \quad \rightarrow \quad K = 2 \times 10^{-6} Re^2 - 8 \times 10^{-4} Re + 0,7701 \\
\text{Re} \geq 500 & \quad \rightarrow \quad K = 6 \times 10^{-12} Re^3 - 5 \times 10^{-8} Re^2 + 7 \times 10^{-5} Re + 0,7433
\end{align*}
\]

For the 27 mm lance:

\[
\begin{align*}
\text{Re} < 300 & \quad \rightarrow \quad K = 1 \times 10^{-5} Re^3 - 1 \times 10^{-5} Re^2 + 2,3 \times 10^{-3} Re + 0,4532 \\
\text{Re} \geq 300 & \quad \rightarrow \quad K = 5 \times 10^{-9} Re^2 + 2 \times 10^{-5} Re + 0,5537
\end{align*}
\]
4.1.3 Proposed model

From equations 2.11 and 2.12 and assuming \( s = K \cdot R(t) \):

\[
F = 2.28K^{-\frac{3}{5}}\lambda^{-\frac{3}{5}}q^{\frac{1}{5}}
\]

Where:

- \( F \) – bubbling frequency (Hz)
- \( K \) – detachment criterion
- \( \lambda \) – added mass coefficient
- \( q \) – volumetric flow rate (m\(^3\)/s)

The two models are now compared with the experimental results. As shown in figures 4.6 and 4.7 the new model predicts better the bubbling frequency than the old one. In the case of the 9 mm lance, for the old model, the standard deviation is 1.62 Hz and the highest value is 2.39 Hz for the high flow rates region, for the new model, the standard deviation is 0.41 Hz with a maximum of 1.55 Hz, again in the high flow rates region. The average error of the old model is 17 \%n with a maximum of 22\% in the low flow rates region. For the new model a value of 2\% is calculated. For the highest flow rate the average error is 11\%, this is the highest value calculated for the average error, with the new model. The accuracy is greatly increased and the frequency can be better predicted.
Figure 4.6. Comparison between theoretical models and experimental values, d = 9 mm

For the 27 mm lance the new model predicts the frequency with high accuracy and the average error is 1%. This is of course overestimated and so the value for the error taken will be the corresponding to the highest error amongst all the values, the error is then 3%. With the old model an average error of 27% is calculated, with the highest value reaching 35%. The standard deviation for this model is 1.62 Hz with a maximum of 2.39 Hz. For the proposed model a value of 0.13 Hz is calculated for the standard deviation with a maximum of 0.32 Hz. Also for the 27 mm lance the proposed model predicts better the bubbling frequency.

Figure 4.7. Comparison between theoretical models and experimental values, d = 27 mm

The two different expressions found should be seen as references, not as a general model. Having a different diameter for the lance it is possible to assume a value for K based on the
curves shown in figures 4.4 and 4.5, and increase the accuracy when predicting the bubbling frequency. Another assumption for the use of this model is that the vessel diameter is large enough and no effect of the walls on the bubble growth is expected.

4.2 Influence of the lance diameter

The effect of the lance diameter on the bubbling frequency is shown in figures 4.8 and 4.9. For a higher lance diameter, in this case 27 mm, the frequency is higher until \( q \approx 2 \) l/s. This is in agreement with the previous assumption that the bubbling behavior depends on the diameter of the lance and with the results of [Neven, (2005)]. For very low flow rates, below 0.5 l/s, he describes the opposite behavior, however no points were taken in the mentioned range and comparison is then impossible. It is now clear that the detachment criterion should be adjusted, depending on the lance diameter. Another option would be to consider as a characteristic dimension the diameter of the bubbles produced by both lances, however this turns out to be quite difficult. The 27 mm lance is opaque and in the images it appears as black, which doesn’t always allow measuring the bubble diameter. Another problem arises for low flow rates, the bubbles are not spherical and an equivalent diameter should be calculated for each shape of the bubble (for each flow rate). A correlation between the bubble diameter and the lance diameter should be found in order to complete the model. Only then the model can be independent of the lance diameter.

![Figure 4.8. Frequency comparison between lance diameters](image)

Figure 4.8. Frequency comparison between lance diameters
4.3 Effect of submergence depth

Several lance submergence depths are tested, the results are as expected. A lower submergence depth will increase the bubbling frequency. The results are in agreement with the literature. In this case, the difference between each submergence depth, \( l \), is 0.5 m. These variations are higher than the ones expected to occur in the industrial case and so can be seen as extreme cases, however when comparing results between authors one has always to take into account the different parameters that influence the bubbling frequency. This is why it is useful to quantify the expected differences when changing each parameter.

The tests were made with air, due to the high consumption of helium. The comparison between different gasses will be made in the following section. After comparison, a correction can be made and the values for helium calculated based on the nominal conditions (\( l=0.85 \) m).

The average increase in frequency when passing from \( l=1.35 \) m to \( l=0.85 \) m is 0.424 Hz and when passing from \( l=0.85 \) m to \( l=0.35 \) m 0.418 Hz. A mean value of 0.42 Hz is the increase in frequency when the submergence depth decreases 0.5 m. Which means that, the frequency will have a maximum when the lance is nearly at the free surface of the bath. When the lance is submerged in 0.5m of water, the frequency is expected to decrease 0.42 Hz.
The tests were made with the 27 mm lance. The same behavior is expected from the 9 mm lance, however due to time constrains tests with the smaller diameter lance were not made. The impact of different submergence depths on the 9 mm lance should be the same as the curves maintain their shape, shifting only downwards or upwards depending on the submergence depth.

### 4.4 Air vs Helium

A comparison between two gases is made. Air is a heavier gas and so the impact of gas momentum on the bubbling frequency can also be studied. The Reynolds numbers for each lance are shown in figure 4.11.

It is clear that in the case of the larger lance the gas momentum doesn’t play an important role on the bubbling frequency. Helium gives higher frequencies when the Reynolds number is
higher for air. The fact that helium is a lighter gas explains this phenomenon. The buoyancy force is higher and promotes an easier detachment of the bubble leading to higher bubbling frequencies. This can been in figure 4.12.

![Comparison between air and helium, d=27 mm](image1)

Figure 4.12. Comparison between air and helium, d=27 mm

For the 9 mm lance the same behavior for both gases occurs, until Reynolds increases to 3500. After this the frequency for helium starts decreasing while for air continues rising. It appears that at this point momentum starts playing a more important role on the bubbling frequency. This can be seen on figure 4.13.

![Comparison between air and helium, d=9 mm](image2)

Figure 4.13. Comparison between air and helium, d=9 mm

An important aspect that comes out, Helium is practically independent of momentum while air is not. This leads to the following plots were the adimensional frequency (Strouhal number) is plotted versus the Weber number. This seems more meaningful when one seeks to understand
the interaction between the gas and the liquid, the Weber number compares the inertia forces of the gas with the surface tension of the liquid. It is shown in figure 4.14 that for air the Weber number will reach higher values, meaning that the surface tension will stop playing an important role for air, for a much lower frequency than for helium. An interesting result is that both curves follow a power a law, if the results are the same for both lances a method capable of accurately predicting the bubbling frequency has been found.

![Figure 4.14. Comparison between air and helium, d=9 mm](image)

The 27 mm lance behaves in quite a similar way, the results are shown in figure 4.15. For the 27 mm lance it is seen that both, air and helium, have a more similar behavior than for the 9 mm lance, however the difference in Weber number is still one order of magnitude lower for helium.

![Figure 4.15. Comparison between air and helium, d=9 mm](image)
The Weber number used is based on the lance characteristic dimension. An interesting analysis would be to compare the Strouhal number with the ratio between Weber and Eotvos number, this way a characteristic length of the bubble and a characteristic length from the geometry are used. As the bubble diameters were not object of study this is not done.

4.5 Sonic hole

A sonic hole is used to confirm the flow rates calculated for the rotameters, this way, independent measurements are made and can now be compared. It should be underlined that the system was not prepared to introduce the sonic hole. Although in theory the sonic hole can be inserted in any system, in the case of the P3 facility the task was not so easy, because of practical problems. The lance support is more than 2 meters high and the sonic hole has to be attached before it. A way is found to attach it, however for each range of flow rates (for each sonic hole), the nozzle containing the hole as to be taken out of the system in order to replace the sonic hole with another. This revealed to be very time consuming and should be avoided. Another aspect that limited the use of the nozzle was the difficulty of controlling the flow rate, this is done by controlling the pressure, however, the valves don’t have the necessary precision to allow an easy control of the pressure and consequently of the flow rate. This leads to much lost time adjusting the flow rate. For these reasons only one sonic hole is taken and compared with the rotameters.

![Graph showing comparison between rotameters and Sonic hole, Helium](image)

Figure 4.17. Comparison between rotameters and Sonic hole, Helium

The values for both, rotameters and sonic hole, are in agreement, an average deviation of 0.73 Hz is calculated for the sonic hole. When analyzing the results, the uncertainties of both devices should be taken into account. For both it is under 10%, it is however large enough to explain the small difference in the results.
Some problems occurred with the rotameters and a new set had to be introduced on the injection system. Leaks and infrastructural problems can be quite hard to detect, especially with helium. If planned properly, the facility should be prepared to adapt the sonic hole in a more practical way. If this is done the sonic hole should be used to control the flow rate instead of the rotameters.

![Figure 4.18.q=2 l/s, He, Rotameters](image1)
![Figure 4.19.q=2 l/s, He, Sonic hole](image2)

The flow behaves the same way in both cases. A bubble detaches and is followed by another one, coalescence occurs and small bubbles are formed. This is in agreement with the previous results and shows that both, the rotameters and the sonic hole, are reliable choices to control the flow rate.

### 4.6 Volume of the injection system

The volume of the injection system is changed. A volume of 28 liters is introduced and tests are made with different volumes. When the chamber is introduced the constant pressure regime should be achieved. The measurement of the pressure fluctuations on the lance is no longer useful to calculate the bubbling frequency as no peak can be obtained when doing the Fast Fourier Transform (FFT) analysis.
Figure 4.19 shows only one clear peak, looking closer, a smaller peak near 4Hz can be distinguished. The difference in intensity between both is obvious and so it is clear that the pressure fluctuations on the lance will be impossible to use in order to calculate the bubbling frequency. For that flow visualization is made and the bubbling frequency assessed by counting the number of bubbles per second, for each flow rate. This shows to be a very time consuming task, however no other choice exists due to the complexity of the flow, no software can accurately analyze the images and calculate the bubbling frequency. At the same time the pressure is measured on the lance (upwards the chamber) and on the rotameters (downwards the chamber). This is done only to study the behavior of the pressure when the volume of the injection system is increased. The pressure measurements for all the volumes introduced are the same and so it can be concluded that whatever the impact of the chamber on the bubbling frequency is, it doesn’t change with the different volumes tested. 75% of the chamber (21 l) and 50% (14 l) are introduced and the results compared.
The last point seen on figure 4.20 is already on the jetting regime, Reynolds is already higher than 20000. It is noticeable the greater increase in pressure when passing from the bubbling regime to jetting. The results shown are for air. For helium the same tendency is seen, however the increase in pressure with the chamber for helium is very small and for the highest flow rate and increase of 2 kPa is seen, when the chamber is introduced.

The frequency is lower when the volume is introduced in the injection system, this can happen for several reasons. The chamber is connected to the lance through a tube, the diameter of the tube is a few millimeters lower on the chamber. This means there is a slight increase in diameter...
which can affect the flow. The gas is expelled from the tip of the lance, a bubble is formed, the liquid enters the space left by ascending bubble, the gas on the lance goes back until the chamber. The pressure rises again and the hydrostatic pressure is beaten, the bubble formation process starts again, however the gas recovers its position on the lance slower, due to this increase in diameter. The fact that the difference in frequency is higher for low flow rates is in agreement with what was said before. It shows that in order to study the effect of the chamber, it should be closer to the top of the lance and the connections should have the same diameter. It was not possible to connect another valve since the sealing of the chamber contains already a fixed size hole. [Gosset et al., 2007] report no difference when introducing the same chamber, however their tests were made with the 9 mm lance while these were done with the 27 mm.
4.7 Flow visualization

4.7.1 Correlation between pressure signal and image visualization

The correlation between the pressure fluctuations on the lance and the bubbling frequency has been studied in detail by [Neven, 2005] and [Gosset et al., 2007] and therefore no detailed analysis is made. An attempt to correlate the peaks on the pressure signal with what happens in the flow is taken. It is shown that the peaks correspond indeed to the formation of a bubble.

Figure 4.22. Correlation between pressure signal and flow visualization
The images and signal were taken with the sonic hole for the 9 mm lance with \( q = 2 \) l/s. It is important to notice that bubbling is a very complicated regime and different phenomenon can occur. The bubble detaches and is followed by another one formed on the opposite side of the lance. Both detach and follow different paths until the surface. For a better description on bubbling regimes the reading of [Neven, 2005] is recommended. An interesting phenomenon is coalescence which will be explained in the following section.

4.7.2 Coalescence phenomena

When a bubble starts growing at the lance tip, the hydrostatic pressure must be surpassed. The pressure rises and the liquid is pushed by the gas until the bubble detaches, when this happens the liquid takes again the space left by the gas. Another bubble starts forming and the process repeats itself. However, this is not always true. The bubble grows (downwards) and when it reaches a certain diameter, starts rising in the liquid. During the rising of the bubble a thin film of gas stays connected to the lance, continuously injecting gas into it. The film breaks and another bubble starts growing, catching the wake of the previous one and so the two bubbles join and burst into smaller bubbles. This phenomenon is called coalescence and can be seen in the pictures below. The instant in time at which these pictures were taken was also correlated with the pressure signal on figure 4.20.
4.8 Geometrical adimensional parameters

So far, it has been seen the influence of several parameters on the bubbling frequency, however no adimensional geometrical parameters exist that can be easily correlated with the evolution of the frequency. Many experiments have been done however, it is not always easy to compare results between them as no details are given, like the submergence depth. Comparing the results of [Neven, 2005] and [Gosset et al, 2007] with the ones of the P3 facility, this goal is reached. See figure 3.2 for a sketch of the facility.

The most important geometrical parameters influencing bubbling are the lance diameter and the submergence depth and so, at first sight $l/d$ could be a good adimensional parameter to characterize the flow based on geometrical dimensions only. Another effect is not mentioned but should be taken into account when doing this analysis, the wall effect. If the diameter of the vessel is not large enough the bubble growth will be influenced by it. [Neven, 2005] studied this parameter and it can be concluded that all the experiments compared, suffer no effect from the wall, when the ratio $D/d$ is large enough.

A comparison is made by [Gosset, 2007], between her values and the ones from [Neven, 2005], (see figure 2.7) however the parameter used is the ratio between diameters $D/d$, where $D$ is the vessel diameter and $d$ the lance diameter. The results in frequency terms are different, this is due to the fact that although they had the same ratio between diameters the dimensions were different. Therefore only the ratio $D/d$ is not a good choice for adimensional parameter by itself.

A study on the $l/d$ parameter reveals that it is not possible to characterize the flow with only one geometrical parameter. The effect of each of the mentioned parameters is different, the frequency will increase with increasing $D/d$ and decrease with increasing $l/d$. Tests are made in order to quantify the influence of both parameters on the bubbling frequency. Tables 3 and 4 give the information about the geometrical parameter for each point and the correspondent author.
The values are compared for the same flow rate, this is done to verify if indeed the geometrical 
influences are independent of the flow rate. The shape of the curves is expected to be the same 
for both flow rates. It appears to be the case, however more points are needed to extract the 
curves. The same behavior can be seen in both figures 4.30 and 4.31, and the chosen 
geometrical parameters appear to describe well the evolution of the frequency depending on the 
scale of the model.
Figure 4.31. Evolution of the frequency with $l/d$, for constant $D/d$, $q=2$ l/s

The parameter $D/d$ gives the information about a possible constrain in bubble growth and $l/d$ relates the submergence depth with the lance diameter. As discussed before, the lower the submergence depth the higher the frequency and so a low $l/d$ will give a higher frequency than a higher one. When the ratio between diameters is increased the bubbling frequency increases. In general the frequency is expected to increase when the scale of the model increases and when the submergence depth is lowered. [Neven,2005] These results have been shown in section 2, when [Gosset et al, 2007] compared her results to [Neven,2005] in figure 2.6. The two described parameters are found to be the geometrical adimensional parameters describing the frequency evolution.

Although not enough points are available to draw the curve, the equation on figure 4.31 gives a general idea on the shape of the curve and on the best type of function to model it. The exponential is the logical choice, as the frequency will increase until $l/d=0$ and after that no bubbling occurs, when $l/d$ increases the frequency will slowly tend to zero. It is very interesting to see that the curve found with the geometrical parameters follows also a power law, as the theoretical model. Further study is needed in order to understand and relate the behavior of both.
5. Conclusions

Several parameters influencing the bubbling frequency are studied. The experimental results are compared to the theoretical ones. The detachment criterion is studied and a new theoretical model is proposed. A new detachment criterion is proposed, based on the experimental values, the new criterion takes a function $K$ instead of a constant value of 1 or 2, as on the previous model. This seems to describe better what happens physically and the results, when comparing both theoretical models, leave no doubt about the better accuracy of the proposed model. This model shouldn’t be seen as a general model, the bubble shape for each diameter, keeping the flow rate constant, will change and so the model depends on the lance diameter. The curves calculated based on the experimental results should be seen as references, for diameter in between the ones used a value of $K$ should be limited by the two curves found. Extrapolation for larger diameters can also be done. The accuracy will of course decrease, when compared to the one calculated in this case, however a better prediction than with the previous model is expected. A general model should not include the lance diameter, however all the adimensional parameters require a characteristic dimension, if not the lance diameter, than the bubble diameter should be used. This poses a problem, because the bubble diameter is calculated based on the model, which depends on the lance diameter. A relation between Eotvos (Bond), Morton and Reynolds numbers and the lance diameter, in order to make the model independent of geometrical parameters, could be a good way to start.

The experimental campaign reveals important results and confirms behaviors found previously in the literature. The lance diameter has some influence on the bubbling frequency, for very low flow rates, below 0.5 l/s, the 9 mm lance gives a higher frequency, from 0.05 l/s until 2 l/s the 27 mm lance reaches higher frequencies and from 2 l/s on the 9 mm lance is the one where higher frequencies are calculated. Comparing in Reynolds number terms it’s interesting to see that from the beginning of transition, for Re = 2000, the 9 mm lance gives higher frequencies than the 27 mm lance. This shows the dependence of the bubbling frequency on the Reynolds number.

Different submergence depths, $l$, are taken. The results are in good agreement with the literature. When comparing the different submergence depths it is seen that the bubbling frequency increases with decreasing submergence depth. What happens is that the detaching bubbles have a lower hydrostatic pressure to beat and a smaller distance until the surface, and so the gas overcomes more easily the pressure of the liquid than for a higher submergence depth. Another phenomena occurs that must be discussed, when the submergence depth decreases the distance between the lance tip and the free surface is lower, as the flow rate increases the bubble grow more and more and the frequency increases, if the submergence depth is low enough a “tunnel” of gas is formed inside the liquid connecting the lance tip to the surface. The wake provoked by each bubble is large enough to promote coalescence and so the detached bubble can suffer this effect, as soon as it detaches another one forms and joins the previous one. [Neven, 2005] in his thesis refers this behavior for very low submergence depths of 0.1 m.
Air and helium are compared for several reasons, the first is to be able to use air instead of helium in the tests, whenever possible, due to financial reasons. Helium is more expensive. Another reason is also to study the behavior of a heavier gas in the same conditions, this is not very relevant for the industrial case, as the density ration between gas and liquid for the industrial case is almost the same as for water and helium. The use of different gases also allows for a comparison of the behavior for different Reynolds numbers, keeping a constant flow rate. For the 27 mm lance helium is found to reach a higher frequency than air for all the flow rates tested. Momentum seems not to play a major role in this case, however this changes when the 9 mm lance is used, both gases show the same behavior until Reynolds is slightly higher than 3000. Then the frequency continues increasing for air while for helium starts decreasing following the behavior of the 27 mm lance. It can be concluded that for smaller diameter lances the momentum of the gas can be an important parameter, depending always, on the gas density. Heavier gases are more likely to feel this effect even if the lance diameter is higher than 9 mm. Seems that for each gas a different diameter will make the transition between buoyancy playing a major role and momentum playing that role.

The sonic hole is used in order to verify the precision of the rotameters. The results are in good agreement with the ones obtained with the rotameters. Only a few points are taken due to time constrains. The sonic hole is a better way of controlling the flow rate and also of keeping it constant. It has, however, the disadvantage of being very hard to maintain the desired pressure, which is reflected on the flow rate. In order to test different flow rates different hole diameter should be used and a calibration for each done.

The injection system volume is increased by introducing a chamber with 28 liters. The pressure fluctuations in the lance are not suitable for the calculation of the bubbling frequency and flow visualization is made in order to obtain bubbling frequency. The bubbles are counted for different time periods and an average frequency is reached. The frequencies found with the chamber are lower than the ones without the chamber, this is especially seen for low flow rates. An explanation about the gas dynamics in the system can give a reason for this. The chamber is connected to the lance through a tube, the diameter of the valve attached to the chamber is a few millimeters lower than the diameter of the lance. This means there is a slight increase in diameter which can affect the flow. The gas is expelled from the tip of the lance, a bubble is formed, the liquid enters the space left by ascending bubble, the gas on the lance goes back until the chamber. The pressure rises again and the hydrostatic pressure is beaten, the bubble formation process starts again, however the gas recovers its position on the lance slower, due to this increase in diameter. The fact that the difference in frequency is higher for low flow rates is in agreement with what was said before. It shows that in order to study the effect of the chamber, it should be closer to the top of the lance and the connections should have the same diameter. It was not possible to connect another valve since the sealing of the chamber contains already a fixed size hole. [Gosset et al., 2007] report no difference when introducing the same chamber, however their tests were made with the 9 mm lance while these were done with the 27 mm. Changing the volume of the chamber seems to have no impact on the pressure in the lance and consequently on the bubbling frequency. The visualization is validated by taking images when the chamber is not introduced and compare the frequency reached with the images with
the one from the pressure signal. These are in good agreement and so the technique can be used with the chamber.

As previously mentioned, flow visualization is made in order to assess the bubbling frequency. In order to see the good correlation between the pressure fluctuations on the lance and the bubble formation, a correspondence is made between the pressure signal and the images and it is concluded that measuring the pressure fluctuations on the lance is a good way to calculate the bubbling frequency. The visualization of the flow also allows a better understanding of the bubbling phenomena. Coalescence is seen and explained with images, which is the best way to do it.

Two geometrical parameters are found that can model the bubbling frequency. The ratio between vessel diameter and lance diameter, $D/d$, and the ratio between lance submergence depth and lance diameter, $l/d$. A comparison of these parameters for the P3 facility and the ones used by [Neven, 2005] and [Gosset et al., 2007] is made. The frequency increases when $D/d$ increases and decreases when $l/d$ increases. Curves are plotted showing the changes in frequency when these parameters change. The best combination is a low $l/d$ and a high $D/d$. It should be kept in mind that $D/d$ must be high enough to assume an infinite medium and negligible wall effects.

A comprehensive study of the top submerged lance injection is made. Several parameters and their influence have been studied. The behavior of the bubbling frequency is correlated with two adimensional geometrical parameters.
6. Recommendations for future work

Further investigation is needed on this type of injection in order to obtain a more accurate (and geometry independent) correlation to predict the bubbling frequency. A new study should focus on the modeling of the added mass coefficient and on the detachment criterion. These parameters should be independent of the reactor geometry and related with the gas and, probably, the bubble characteristic length, the diameter. A first approach is done here, using the Strouhal and Weber numbers, a relation between Weber and Bond can also be used, and with more interesting results probably

Several considerations should be done when preparing the setup, the system should be able to sustain the pressure for all the test. The pressure when using the sonic hole can reach 4 bar, while for the rotameters around 1 bar is sufficient. The rotameters should be used as a first choice, however the results should be validated by means of other technique and for this, the sonic hole is a good comparison. Both techniques are apparently easy to implement, however depending on the size of the model you may have to deal with unpredicted constrains, for example, where to place the sonic hole.

Several ratios \( \frac{D}{d} \) and \( \frac{l}{d} \) should be taken in order to have a complete reference on the frequency behavior when these geometric parameters are changed. This can give an important result, as it is possible just by knowing the geometry of the model to compare different setup’s and to predict if the frequency is going to increase or decrease when you change to another model.
7. List of references


