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Investigation of Interfacial Gas-Liquid Flows using the Brightness Based Laser Induced Fluorescence Technique

By

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Abstract

In multiphase flows, certain flow regimes are characterized by the presence of waves that propagate along the interface between both phases, and they are hence known as interfacial flows. This thesis reports on the investigation of interfacial structures present in the slug and annular flow regimes in vertical gas-liquid flows. In order to achieve this, results were obtained using the Brightness Based Laser Induced Fluorescence (BBLIF) technique, which is a powerful visual diagnostic tool that allows for highly detailed spatial and temporal measurements of film flows over both the axial and longitudinal coordinates. The BBLIF was therefore employed in two different experimental campaigns.

In the first campaign, the dynamics of the falling film surrounding a Taylor bubble in slug flow conditions was investigated, in order to study its influence on the gas exchange process between the Taylor bubble and the wave region. This was achieved by employing a specially designed apparatus that held a Taylor bubble in a fixed position while simulating a downwards flow of liquid. It was observed that increases in the liquid flowrates lead to increases in the mean film thickness of the falling film, and on the relative amplitude, velocity and frequency of the waves present in it.

It was also shown that the wave behaviour is the driving force behind the entrainment events, as it was observed that the turbulence generated by the incoming waves led to perturbations in the skirt of the Taylor bubble, leading to gas entrainment. Two new mechanisms of entrainment have been identified and characterized for the first time. They consist of (i) *entrainment through crater generation* and (ii) *entrainment through self enhancement of entrainment by action of re-coalescing bubbles*, with both occurring simultaneously in slug flow conditions. It was concluded that the action of re-coalescing bubbles has been overly disregarded in terms of its impact on the entrainment behaviour.

In the second experimental campaign, the effect of flow orientation (in vertical flows) on the dynamics of the annular flow regime was investigated. This was conducted by obtaining

measurements in upwards and downwards flows at two different axial locations. Close to the inlet, the mechanism of disturbance wave formation from the coalescence of small, high frequency wavelets has been observed and seen to be unaffected by the flow orientation at this stage. At 330 – 430 mm, where the flow is almost fully developed, it was observed that, with the exception of the lowest liquid Reynolds number, the frequency of the disturbance waves is higher for the downwards orientation, although they travel at the same velocity in both cases. Despite the higher number of waves present in downwards flow, the wave width is the same for both flow orientations, being equally reduced with increasing gas superficial velocity.

The behaviour of the ripple waves that cover the base film was also analysed. The analysis showed that there is an increase in the ratio between the ripple and disturbance wave velocities with increasing gas flowrate for the upwards case, whereas for the downwards case, the ratio is constant under the same conditions. This difference was linked to the differences in the base film thickness in both flow orientations due to gravitational action, being higher for the upwards case.

Lastly, the prediction of the disturbance wave velocity and frequency, together with the mean film thickness in the annular flow regime in the entrainment region was analysed. It was observed that existing models in the open literature for the prediction of these parameters do not perform well in the estimation of the data from the current experimental work. This was attributed to the fact that all the correlations reviewed were empirically determined from the particular set of results from which they were derived. In this thesis simplified monotonic relationships were established based on universal rules applicable to the annular flow regime. The major contribution of this work to the multiphase flow field is that these universal correlations have been validated for a large number of air-water systems and benchmarked against a multitude of systems that vary in terms of their duct properties (size, circular or rectangular geometry), flow orientation (vertically upwards and downwards, or horizontal), or flow conditions. This set of rules is of significant importance, since it allows for increased predictive accuracies during flow assurance design processes in multiphase flow systems.

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It's what you do in the dark...

...that puts you in the light

List of Publications

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Nomenclature

<u>Symbol</u>	<u>Meaning</u>	<u>unit</u>
a	Absorption coefficient	(-)
a_t	Temporal acceleration	(m/s ²)
a_x	Spatial acceleration	(s ⁻¹)
A	Area	(m ²)
A_N^2	Normalized power spectrum	(-)
Bo	Bond number	(-)
C	Compensation matrix	(-)
C_{DTB}	Taylor bubble distribution parameter	(-)
d	Dark level of camera	(a.u.)
d_{sep}	Distance separation	(m)
D	Pipe diameter	(m)
D_h	Hydraulic diameter	(m)
E	Entrainment rate	(kg/ m ² s)
E_c	Equivalent circumference	(m)
Eo	Eotvos number	(-)
f	Frequency	(Hz)
f_F	Fanning friction factor	(-)
f_i	Interfacial friction factor	(-)
Fr	Froude number	(-)
g	Acceleration due to gravity	(m/s ²)
G	Mass flux	(kg/ m ² s)
h	Film thickness	(m)
Δh_w	Mean wave amplitude	(m)
I, INT	Intermittency	(-)
J	Intensity of light recorded	(a.u)
k	Wave number	(radm ⁻¹)
K	Reflection index	(-)
Ku	Kutataledze number	(-)
L	Length	(m)
L_f	Loading factor	(m ² /s)
$\dot{m}, \dot{M}$	Mass Flow rate	(kg/s)
n	Refractive index	(-)
N	Number of samples	(-)
Oh	Ohnesorge number	(-)
P	Pressure	(Pa)

Per	Perimeter	(m)
$\frac{dp}{dx}$	Pressure gradient across pipe length	(Pa/m)
$\dot{Q}$	Volumetric flow rate	(m ³ /s)
R	Radius	(m)
R^2	Coefficient of determination	(-)
R_{ab}	Cross-correlation function	(m ² s)
R_{aa}	Auto-correlation function	(m ²)
R_n	Radius of curvature	(m)
Re	Reynolds number	(-)
$Re_G^{-0.25} K E_{SG}$	Blasius friction factor	(-)
s_m	Standard mean error	(a.u.)
S	Slip ratio	(-)
St	Strouhal number	(-)
t, T	Time	(s)
t_{sep}	Time separation	(s)
u, U, V, c	Velocity	(m/s)
u^*	Friction velocity	(m/s)
U_{GS}, U_{SG}, V_G	Gas superficial velocity	(m/s)
U_{LS}, U_{SL}	Liquid superficial velocity	(m/s)
U_{TB}	Rise velocity of Taylor bubble in pure slug flow conditions	(m/s)
U_0	Rise velocity of bubble through a stagnant column of liquid	(m/s)
U_m	Mixture velocity	(m/s)
$\langle V \rangle$	Average disturbance wave velocity	(m/s)
x	Axial distance/ x coordinate	(m/a.u.)
x_g	Gas quality	(-)
X_F	Fast Fourier Transformation	(a.u.)
XX_{mod}	Modelled results	(a.u.)
XX_{exp}	Experimental results	(a.u.)
y	y coordinate	(a.u.)
$\bar{y}$	Mean values of y	(a.u.)
$\hat{y}$	Predicted values of y	(a.u.)
W	Width	(m)
We	Weber number	(-)
z	Axial distance	(m)
$\langle \rangle$	Averaging of value	(a.u.)

Greek symbols

$\alpha, \varepsilon, \varepsilon_g$	Void fraction	(-)
α_t	Attenuation factor	(-)
α_L	Liquid holdup	(-)
β	Inclination angle from horizontal	(deg)
Δ	Delta, shift	(a.u.)
δ	Film thickness	(m)
ν	Dynamic viscosity	(kg/ms)
μ	Kinematic viscosity	(m ² /s)
ρ	Density	(kg/m ³)
σ	Surface tension	(N/m)
θ, α	Angles	(rad)
λ	Wavelength	(m)
η_{FC}	Number of combinations tested	(-)
τ	Shear stress	(N/ m ²)
τ_t, τ_0	Time delay	(s)
τ_w	Wall shear stress	(N/ m ²)
ω	Angular frequency	(rad/s)

Subscripts

0	Reference/true
abs	Absolute
b,base	Base
core	Core
dist	Disturbance wave
D	Deposition
ent, E	Entrained
f, film	Film
G	Gas
GS	Gas superficial
i	Interfacial
in	Input
lf	Liquid film
L	Liquid
LS	Liquid superficial/liquid slug
m	Mixture
max	Maximum

mean	Mean
min	Minimum
OH	Owen and Hewitt
rec	Recoalescence
T	Total
TB	Taylor Bubble
w	Wall
w, wave	Wave
width	Width

Superscripts

+	Dimensionless
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Chapter 1. **Introduction**

A major problem to be faced in today's world is the increasing global energy demand which is often coupled with factors such as fierce competition within the industrial sector, regulatory impositions and environmental impacts. These are some of the major challenges faced by the petroleum, power generation, chemical and process industries. As a result, it is important that improvements in areas such as safety, reliability, sustainability, efficiency or significant decreases on maintenance frequencies of industrial processes are achieved. Multiphase Flows are encountered in such industries, which include nuclear plants, heat exchangers, steam generators, boilers, chemical reactors, pipelines and risers. Consequently, research in this field becomes a vital parameter in order for these perspectives to be addressed.

In contrast to single phase flow, multiphase flows are much more complex to understand since they involve the simultaneous flow of at least two fluids in the same geometry, which can produce a large number of spatial configurations of the phases due to the deformable interface between them, better known as flow patterns. Research in two-phase gas-liquid flows has been carried out since the mid twentieth century, with motivation initially based on the needs of the nuclear power and chemical industries. Since the later part of the twentieth century, the emergence and subsequent proliferation of the oil and gas industry into the world's day to day activities, led to enhanced research focus in this area.

1.1 Interfacial gas-liquid flows

As discussed above, in two-phase gas-liquid flows, different flow regimes can be encountered depending on parameters such as the flowrates and the properties of both phases; the dimensions of the structure in which both phases are travelling and on the orientation of the flow. Certain flow regimes are characterized by the presence of waves that propagate along the interface between both the liquid and gaseous phase, and are hence known as interfacial flows. In vertical configurations, two of such interfacial flows are the slug and annular flow regimes.

The slug flow regime is characterized by its intermittent and transient (time dependant, i.e. unsteady) behaviour, where in vertical configurations, it is characterized by the presence of large bullet-shaped bubbles, denominated as Taylor bubbles, which occupy most of the pipe cross-section and move upward with a constant velocity (Hewitt, 1981). The liquid around the elongated bubbles moves downward as a thin falling film until it reaches the skirt of the bubble and mixes with the liquid just underneath it, which is often referred to as liquid slug. In this liquid slug, some entrainment of the gas from the Taylor bubble can be seen in the form of smaller bubbles which are initially concentrated in a very small area of the liquid slug, which is called the wake region. In the annular flow regime, the liquid travels in the form of a thin and wavy film in contact with the walls of the duct, while being sheared by a co-current high-velocity gas stream that occupies the core of the duct. A very important feature of annular flows is the presence of thick, fast-moving interfacial wave structures, best known as ‘disturbance waves’. These are generally characterized as having amplitudes several times higher than the mean thickness of the liquid film, which entrain liquid droplets into the gas core.

Both flow regimes can be encountered in a wide range of industrial applications. These can range from the oil and gas wells, transfer pipelines and risers present in the oil-and-gas industry; condensers and evaporators encountered in nuclear reactors and chemical reactors encountered in chemical processing plants (Chu and Dukler, 1975, Dasgupta et al., 2017). In

both regimes, interfacial structures can be encountered (i.e. waves in the falling film of the Taylor bubble in the slug flow regime, and disturbance waves in the annular flow regime) that are of particular interest of the multiphase flow community, and will be the topic of this work.

1.2 Overview

Despite many efforts that have been employed in the research of multiphase flows over the years, certain phenomenological events associated with each of the flow regimes in question is still not fully understood by the multiphase flow community. For instance, the dynamics of the falling film surrounding the Taylor bubble in the slug flow regime and how it affects the gas exchange between the main bubble and the liquid slug that follows it, is not fully understood. For that reason, one of the experimental campaigns reported in this thesis consists of a specially designed apparatus that generates a stationary Taylor bubble, and was employed to investigate such dynamics in slug flow in a vertical pipe. Additionally, no systematic direct comparison of the properties of disturbance waves in upward and downward annular flows has been previously conducted and reported in the literature. Consequently, a new cycle of experiments is reported in this thesis, where both upward and downward annular flow situations are investigated in the same pipe, at the same distance from the inlet, with the same gas and liquid flowrates. Finally, successful prediction of parameters that govern the annular flow regime, such as the disturbance wave velocity and frequency, or the mean film thickness, to name a few, across different system configurations (including multiple orientations) is still yet to be achieved and was therefore investigated in the present work.

These factors are of particular importance, since it has been shown that they play a predominant role in the heat and mass transfer characteristics of each regime (Hazuku et al., 2008, Zhao et al., 2013), thus ultimately impacting the pressure drop or the heat exchange across various industrial systems. As a result, being able to understand such types of flows and to advise the different industries about parameters such as pumping requirements or flow assurance design processes is crucial. This would result in the minimization of environmental

impacts associated with these industries and in increases in the efficiency of multiphase transportation.

The lack of knowledge associated with the multiphase flow field can be partly linked to the fact that in comparison to the single-phase flow research field, whose studies can date back to the eighteen hundreds, research on multiphase flow systems is relatively more recent. As a result, the understanding of the physical rules that govern these flows is still a work in progress by the research community. This is coupled with the technical barriers (due to the available technology) that the community has had in terms of developing adequate measurement techniques that allow for an accurate study of the flows in question. Researchers have therefore attempted to understand such flows with relatively simple techniques. These techniques either do not allow for simultaneous measurements in many points, or have low spatial resolution that leads to averaging of small-scale structures, or whose temporal resolution is not high enough due to the small timescale of the investigated processes, or both (Alekseenko et al., 2010).

1.3 Aims and objectives

Recently, non-intrusive methods have been developed in order to avoid the disruption of the original measured flow. From these, optical measurements have been in the vanguard of the measurement techniques being developed. An example of such a technique is the Brightness Based Laser Induced Fluorescence (BBLIF) technique, which is a powerful diagnostic tool that is based on the dependence of local intensity of excited fluorescence light on the local thickness of the liquid layer. It therefore allows for high spatial (by up to 40 μm per pixel) and temporal (by up to 10 kHz) resolved field measurements of local film thickness to be acquired in both longitudinal and transverse coordinates. As a result, as opposed to pointwise measurement techniques, the BBLIF allows for the measurements of any film flow in a transparent duct over a certain area. Therefore, BBLIF was the measurement technique employed in this research, thus allowing for the investigation of the following parameters of the slug and annular flow regimes:

- Investigation of the falling film surrounding the Taylor bubbles present in the slug flow regime;
- Observation and characterization of the entrainment process between the Taylor bubbles and the wake region;
- Investigation of the disturbance wave formation mechanism in annular flows;
- Study the effect of flow orientation on the evolution of the annular flow regime further downstream from the inlet, where a full characterization of the disturbance waves in the developed region will be obtained;
- Observation of the liquid entrainment into the gas core and bubble entrainment into the liquid film in the annular flow regime.

This project is part of the research consortium of Multi-scale Examination of Multiphase physics in flows (MEMPHIS). It consists of a collaboration that combines the efforts of leading scientists on the topic of Multiphase Flows from four prestigious universities in the United Kingdom: University of Nottingham, Imperial College of London, University of Birmingham and University College of London. The ultimate goal of the MEMPHIS project is creation of the next generation of computational modelling tools for the prediction of complex multiphase flows. As a result, there are some deliverables from this study that were agreed upon in order to enhance the knowledge of the group as whole. These are as follows:

1. Provide modellers within the MEMPHIS group with highly detailed datasets on the slug and annular flow regimes, which will allow for the validation and calibration of the CFD codes being developed;
2. Perform an extensive analysis of the data acquired with the BBLIF technique, which will allow for a better understanding of the mechanisms behind these two types of flows to be obtained.

Additionally, as part of the Royal Society International Exchange Scheme, a research collaboration between the University of Nottingham and the Kutateladze Institute of Thermophysics in Novosibirsk, Russia, was established. The latter is the major responsible party for the development of the BBLIF technique. As part of this collaboration, an exchange

of high level of information regarding experimental work and techniques was achieved. Ultimately, this allowed for a visit to their institute to perform experimental work from which the upwards annular flow data discussed in this study was extracted. Additionally, the researchers from the Kutateladze Institute of Thermophysics provided the datasets of raw data for the downwards annular flow configuration, which were fully analysed at the University of Nottingham.

It can therefore be concluded that with the application of the BBLIF technique in the study of film flows within the slug and annular gas-liquid flow regimes in vertical pipes, that the experimental work here reported will address all the categories of experimentation: (i) experiments designed to understand flow physics; (ii) experiments designed to develop physical models; (3) experiments designed to calibrate CFD models; (4) experiments designed to validate CFD models.

1.4 Thesis structure

The outline of the thesis structure is given below:

Chapter 1 provides an introduction to the research project. It details some of the challenges faced by the multiphase flow community due to the complexity of such flows. More specifically, some problems associated with the slug and annular flow regimes in vertical flows are addressed. These serve as the backbone of the motivation behind this study, which will be conducted using the Brightness Based Laser Induced Fluorescence (BBLIF) technique, which is a powerful diagnostic tool in the study of gas-liquid flows.

Chapter 2 reviews the relevant literature associated with this field. It starts by discussing the basic terminology and definitions associated with fluid dynamics. The increase in complexity from moving from single into multiphase flows is addressed, and the various methods employed over the years to characterize the different flow patterns encountered in vertical gas-liquid flows are covered. Finally, a summary of the efforts employed in the study of the slug and annular flow regimes is provided.

In **Chapter 3**, the progress in the measurement techniques employed on the study of gas-liquid flows is discussed. This is followed by the more recent advances made in the state of the art measurement techniques, in whose category the BBLIF is included. The principle behind the implementation of this technique is described, together with all the technical details that need to be taken into consideration in order to accurately employ it. Additionally, the experimental facilities where the study of the slug and the annular flow regimes were conducted are discussed in great detail. Finally, the different processing techniques employed to analyse the data obtained through the BBLIF, from which qualitative and quantitative results are extracted, are reviewed.

Chapter 4 presents the investigation of a stationary Taylor bubble, where the dynamics of the falling film that surrounds it in the slug flow regime is simulated. This allows not only for the characterization of the falling film in terms of its film thickness to be conducted, but also for the characterization of the waves present in it in terms of their amplitude, velocity and frequency. The link between the wave behaviour in the falling film and the gas exchange process that takes place between Taylor bubbles and the wake region was established. From this, two new different modes of gas entrainment have been identified and described in great detail.

Chapter 5 discusses the findings obtained from the upwards and downwards annular flow experimental campaign for the same flowrates in an 11.7mm pipe. The objective of this Chapter is to investigate how the flow orientation affects the parameters that characterize the annular flow regime. It starts by considering the flow development right after the inlet section, where the mechanism behind the disturbance wave formation is presented and characterized in terms of wavelet frequency, speed and acceleration. This is complemented by results obtained further downstream, where the flow is considered to be developed. Here, a highly detailed description of a multitude of parameters that describe the disturbance wave behaviour is provided, and a direct comparison between the upwards and downwards flow is established. Finally, the behaviour of the ripple waves present in the base film is discussed, where their behaviour in relation to the disturbance waves is compared for both flow orientations.

Finally, **Chapter 6** discusses the importance of understanding the physical forces that govern many of the phenomenological events that occur in the annular flow regime. A review of the practices typically employed by the multiphase flow research community in the prediction of three key parameters that characterize the annular flow regime is made. More specifically, these comprise the disturbance wave velocity and frequency, together with the mean film thickness parameter. Taking into consideration the basic factors that are believed to govern these parameters, correlations for each of these parameters are then proposed. Unlike previous published correlations, successful universal predictions have been established for a large number of air-water systems, regardless of the duct properties (size, circular pipe or rectangular duct), flow orientation (vertically upwards and downwards, or horizontal) in air-water systems, or flowrate conditions.

Chapter 7 discusses the conclusions drawn from this study, including this study's contribution to the multiphase flow field and provides suggestions of future work.

Chapter 2. Literature Review

As discussed in Chapter 1, multiphase flows can produce a large number of spatial configurations of the phases due to the deformable interface between them. The next Section will summarise the basic definitions and terminologies that engineers have developed to characterize each phase present inside a duct, more specifically, the gas and liquid phases.

2.1 Basic definitions and terminology

First, it is important to consider the two phases flowing in a duct. They travel at a particular mass flowrate referred to as the total mass flowrate, which is the sum of the flowrate of the two phases:

$$\dot{M}_T = \dot{M}_G + \dot{M}_L \quad (\text{Eq. 2.1})$$

where $\dot{M}_T$, $\dot{M}_G$ and $\dot{M}_L$ are the total mass flowrate and mass flowrate of the gas and liquid phases respectively.

The fraction of the flow travelling as gas/vapour is called the quality, and is given as:

$$x_G = \frac{\dot{M}_G}{\dot{M}_G + \dot{M}_L} \quad (\text{Eq. 2.2})$$

The total volumetric flowrate, $\dot{Q}_T$, is the sum of the volumetric flowrate of the liquid phase, $\dot{Q}_L$, and the volumetric flowrate of the gas phase, $\dot{Q}_G$:

$$\dot{Q}_T = \dot{Q}_G + \dot{Q}_L \quad (\text{Eq. 2.3})$$

The volumetric flowrate of the liquid phase, $\dot{Q}_L$, is related to the mass flowrate of the liquid phase, $\dot{M}_L$, as follows:

$$\dot{Q}_L = \frac{\dot{M}_L}{\rho_L} \quad (\text{Eq. 2.4})$$

And the volumetric flowrate of the gas phase, $\dot{Q}_G$, is given as follows:

$$\dot{Q}_G = \frac{\dot{M}_G}{\rho_G} \quad (\text{Eq. 2.5})$$

The total mass flux of the flow, G_T , is defined as the total mass flowrate, $\dot{M}_T$, divided by the pipe cross-sectional area, A_T :

$$G_T = \frac{\dot{M}_T}{A_T} \quad (\text{Eq. 2.6})$$

The volume fluxes of the phases provide the gas and liquid superficial velocities. This represents the velocity at which each phase will travel as if occupying the entire pipe cross section. As a result, the liquid superficial velocity is expressed as follows:

$$U_{SL} = \frac{\dot{Q}_L}{A_T} \quad (\text{Eq. 2.7})$$

Whereas, the gas superficial velocity is expressed as:

$$U_{SG} = \frac{\dot{Q}_G}{A_T} \quad (\text{Eq. 2.8})$$

The mixture velocity of the flow, U_M , is defined as follows:

$$U_M = \frac{\dot{Q}_T}{A_T} = U_{SL} + U_{SG} \quad (\text{Eq. 2.9})$$

The void fraction, α , is defined as the ratio of the cross-sectional area (or volume) occupied by the gas phase, A_G , to the total cross-sectional area of the pipe, A_T (or volume):

$$\alpha = \frac{A_G}{A_T} \quad (\text{Eq. 2.10})$$

Conversely, the ratio of the cross-sectional area occupied by the liquid phase, A_L , to the total cross-sectional area of the pipe, A_T (or volume), or in other words, the liquid hold up, is given as follows:

$$\alpha_L = \frac{A_L}{A_T} = 1 - \alpha \quad (\text{Eq. 2.11})$$

The average velocity of the liquid phase, u_L , is defined as the volumetric flowrate of the liquid phase, $\dot{Q}_L$, divided by the cross-sectional area occupied by the liquid phase, A_L :

$$u_L = \frac{\dot{Q}_L}{A_L} = \frac{\dot{Q}_L}{(1 - \alpha)A_T} = \frac{U_{SL}}{(1 - \alpha)} \quad (\text{Eq. 2.12})$$

Whereas, the average velocity of the gas phase, u_G , is defined as:

$$u_G = \frac{\dot{Q}_G}{A_G} = \frac{\dot{Q}_G}{\alpha A_T} = \frac{U_{SG}}{\alpha} \quad (\text{Eq. 2.13})$$

In order to characterize a two-phase flow, the slip ratio, S , is frequently used instead of the void fraction, α . The slip ratio is defined as the ratio of the average velocity of the gas phase, u_G to the average velocity of the liquid phase, u_L . The void fraction, α can be related to the slip ratio, S as follows:

$$S = \frac{u_G}{u_L} = \frac{\dot{Q}_G/A\alpha}{\dot{Q}_L/A(1 - \alpha)} = \frac{\dot{Q}_G(1 - \alpha)}{\dot{Q}_L\alpha} \quad (\text{Eq. 2.14})$$

$$S = \frac{u_G}{u_L} = \frac{G_T x_G/A\alpha\rho_G}{G_T (1 - x_G)/A(1 - \alpha)\rho_L} = \frac{\rho_L x_G(1 - \alpha)}{\rho_G (1 - x_G)\alpha} \quad (\text{Eq. 2.15})$$

Equations 2.14 and 2.15 can be rewritten as:

$$\alpha = \frac{\dot{Q}_G}{S \dot{Q}_G + \dot{Q}_L} \quad (\text{Eq. 2.16})$$

$$\alpha = \frac{1}{1 + S \left(\frac{1 - x_G}{x_G} \right) \left(\frac{\rho_G}{\rho_L} \right)} \quad (\text{Eq. 2.17})$$

A key aspect of gas-liquid flow in ducts is how to calculate the pressure gradient. However, it is important to first understand the dimensionless groups that are typically employed in the multiphase flow field.

2.2 Dimensionless groups

Dimensionless groups are useful in arriving at key basic relations among system variables that are valid for various fluids under various operating conditions. Dimensionless groups are based on fundamental considerations of the governing forces and their mutual interactions, leading to important insights into the physical phenomena. According to Kleinstreuer (2003), the use of traditional dimensionless numbers in two-phase flows is very limited in correlating data sets. However, it should be noted that they are often used in obtaining correlations for different parameters in two-phase flows. These are generally derived empirically, based in experimental data. The extension to other systems requires rigorous validation, often requiring modifications of constants or exponents. Still, as shall be seen later, these empirical correlations are only applicable for the set of conditions from which they are derived (Taitel et al., 1980). Below are examples of the fundamental dimensionless groups that are traditionally employed in gas-liquid flows and that will be seen throughout this thesis.

Eötvös number or Bond number, Bo

$$Bo = \frac{gD^2(\rho_L - \rho_G)}{\sigma} \quad (\text{Eq. 2.18})$$

The Bond number represents the ratio of gravitational (buoyancy) and capillary force scales. The length scale used in its definition is the pipe the diameter, D . σ is the interfacial tension between the two phases.

Froude number, Fr

$$Fr = \frac{U^2}{gD} \quad (\text{Eq. 2.19})$$

The Froude number is a ratio of inertial and gravitational forces. Modifications to the Froude number are often made in the multiphase world. These will be seen in later sections.

Kutateladze number, Ku

$$Ku = \frac{\rho^{1/2} U}{[g\sigma(\rho_L - \rho_G)]^{1/4}} \quad (\text{Eq. 2.20})$$

The Kutateladze number represents a balance between the dynamic head, surface tension and gravitational force. This is an example of an empirical dimensionless group that has been typically used as the criterion to the prediction of the flooding limit of open two-phase systems (Chung et al., 1980).

Ohnesorge number, Oh

$$Oh = \frac{\mu_L}{\sqrt{\sigma D \rho_L}} \quad (\text{Eq. 2.21})$$

The Ohnesorge number relates the viscous forces to inertial and surface tension forces. The combination of these three forces into one parameter masks the individual effects of each one. This is another example of an empirical dimensionless group.

Reynolds number, Re

$$Re = \frac{\rho D U}{\mu} \quad (\text{Eq. 2.22})$$

The Reynolds is traditionally defined as the ratio of inertial and viscous forces. It is one of the most widely used dimensionless groups used in multiphase flows, indicating whether the flow is laminar or turbulent. Several modifications can be made to the Reynolds number, which will be seen in later sections.

Strouhal number, St

$$St = \frac{f D}{U} \quad (\text{Eq. 2.23})$$

The Strouhal number describes oscillating flow mechanisms, where f is the frequency of the oscillating structure under investigation. An example of its use can be seen in the description of wave characteristics in annular gas-liquid flows.

Weber number, We

$$We = \frac{\rho U^2 D}{\sigma} \quad (\text{Eq. 2.24})$$

The Weber number represents a measure of the ratio of inertial forces to interfacial ones. Together with the Reynolds number, the Weber number can be typically used in flow pattern maps, which will be described later.

2.3 Pressure drop in gas-liquid flows

As discussed in Section 1.2 of Chapter 1, different phenomenological events associated with different flow regimes in gas-liquid two phase flows play a predominant role in the mass and momentum transfer characteristics of those particular regimes. These, thus ultimately impact the pressure drop across various industrial systems, which is the topic of this section. To address this, the multiphase flow field has over the years employed extensive efforts to develop models that characterize each flow regime, as it was acknowledged that different forces play a dominant role in each of these regimes. This is called flow-pattern-dependent modelling.

Before discussing these, a brief summary of the momentum equation that takes into consideration the pressure drop in both single and two-phase flows will be given. This will provide an understanding of how much more complex the modelling of two-phase flows is in relation to single-phase flow, and why this is still a topic of ongoing research.

Finally, the key elements of the flow-pattern-modelling are the choices made for the sub-models and set of closure equations for the different flow patterns. These will also be covered in this section.

2.3.1 Single-phase flow

For steady, isothermal single-phase pipe flow, the momentum equation for a pipe segment provides the following expression for the pressure gradient (Oliemans and Pots, 2006):

$$-\frac{dp}{dx} = \tau_w \frac{P}{A} + \rho g \sin\theta + \frac{G^2 D}{dx} \left(\frac{1}{\rho} \right) \quad (\text{Eq. 2.25})$$

where A is the cross-sectional area of the pipe, P is the pipe perimeter (πD in this case), τ_w is the wall shear stress, g is the acceleration due to gravity, θ is the angle of the pipe to the horizontal axis, and G is the max flux in kg/m^2s .

The first component of the RHS of the equation relates to the shear stress that the moving fluid imparts to its boundaries, in this case, the pipe walls. It is therefore a frictional component. The second terms of the RHS relates to the weight of the fluid moving along the

pipe, whose gravitational action will be dependent on the pipe orientation angle. Finally, the third component of the RHS of the equation is related to the acceleration component that is acting on the fluid, driving the fluid along the pipe. Combined, they equate to the total pressure gradient across a pipe.

The difficulty in single phase flow is the determination of the wall shear stress, τ_w , which is defined as:

$$\tau_w = f_F \frac{\rho U^2}{2} \quad (\text{Eq. 2.26})$$

where f_F is the Fanning friction factor, which is determined via purely empirical correlations based on the knowledge of the Reynolds number and the relative pipe wall roughness k/D .

2.3.2 Two-phase flow

In comparison to single phase flows within a pipe, two phase gas-liquid flows present a much bigger challenge with regard to the prediction of the pressure gradient across it. This is due to the large number of spatial configurations of the phases due to the deformable interface between them, each having different physical mechanisms that can describe them. As a result, the pressure gradient is substantially higher than would be encountered in a single phase flow (Asali et al., 1985, Zabaras et al., 1986).

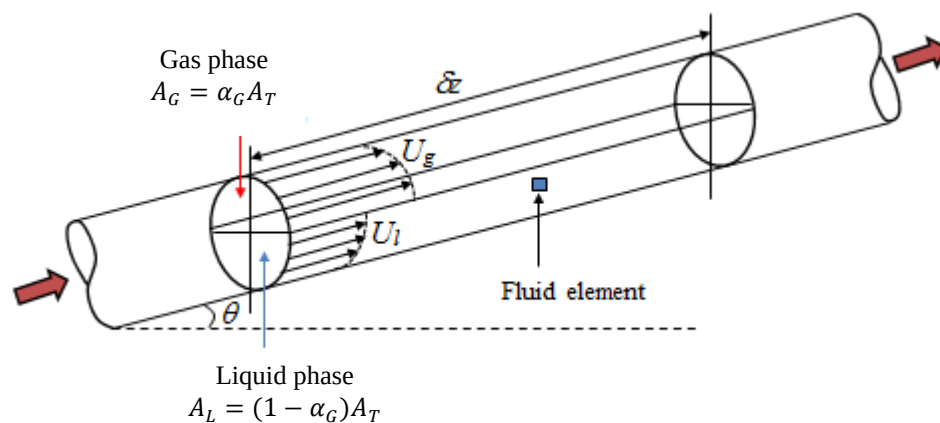


Figure 2.1: Concept of gas-liquid flow in a pipe (Azzopardi, 2006).

In consideration of a finite fluid element within the pipe as shown in Figure 2.1, a force balance can be written:

$$\begin{aligned} \text{The net applied force in the} &= \text{Rate of increase of momentum of the} \\ \text{direction of the flow} &\quad \text{fluid element in the flow direction} \end{aligned} \quad (\text{Eq. 2.27})$$

The net force is a summation of the effects of hydrostatic pressure due to the length of the pipe, the frictional and gravitational forces. In pressure drop terms, this is expressed as follows:

$$-\frac{dp}{dx} = \tau_{WG} \frac{Per_G}{A} + \tau_{WL} \frac{Per_L}{A} + (\alpha_G \rho_G + \alpha_L \rho_L) g \sin \theta + \frac{d}{dx} \left[\rho_G \frac{U_{SG}^2}{\alpha_G} + \rho_L \frac{U_{SL}^2}{\alpha_L} \right] \quad (\text{Eq. 2.28})$$

where Per_G and Per_L are the pipe perimeters occupied by the gas and liquid phases, respectively, along which the corresponding shear stresses, τ_{WG} and τ_{WL} act.

As it can be seen, in comparison to single-phase flow, the level of complexity associated with the momentum equation has increased considerably, as in two-phase flow, solutions for the shear stresses, void fraction, liquid holdup and phase velocities need to be solved. This is typically attempted to be achieved via flow-pattern-dependent modelling.

2.3.2.1 Flow-pattern-dependent modelling

One-dimensional flow pattern and angle-dependent modelling are widely used to calculate two-phase pressure gradients and phase holdups for gas-liquid flow in tubes. In order to apply these models, the set of transport equations for the fluids has to be extended by sub-models or closure relations. The sub-models required depend on the flow pattern. Table 2.1 summarizes, for the one-dimensional two-phase flow models, the different categories of sub-models that are needed to have a closed set of equations for solving gas-liquid tube flow problems. The choice of sub-models for the various flow patterns is crucial for scaling up to practice (pipe size, fluid properties, and pressure-temperature conditions), since these sub-models are empirically based.

Table 2.1: Categories of sub-models for two-phase flow modelling (Oliemans and Pots, 2006).

Flow Pattern	Model and Sub-model
Dispersed Bubble Flow	Drift-Flux Model Distribution Parameter Bubble Rise Velocity
Separated Flow (stratified/annular)	Two-Fluid Model Interfacial Friction Interfacial Velocity Shape of Interference Liquid Entrainment
Intermittent Flow	Drift-Flux + Two-Fluid Model Distribution Parameter Bubble Rise Velocity Holdup in Liquid Cylinder Slug Frequency Slug Cylinder or Film Length Bubble Shape

There is much ongoing two-phase flow research activity aimed at improving the description of physical processes that are assumed to be relevant for the sub-models for various flow patterns. With the aid of the Laser Induced Fluorescence Technique, this study is aimed at being part of the ongoing research. Therefore, it is important to first obtain an overview of the multiple flow regimes that can be present inside a vertical pipe.

2.4 Gas-liquid upwards flow regimes in vertical pipes

When gas-liquid mixtures flow in a vertical pipe, the two phases may be distributed in a variety of patterns. The particular pattern one observes depends on the flow rates, the fluid properties and the tube size (Taitel et al., 1980). Heat and mass transfer rates, momentum loss, rates of back mixing and residence time distributions all vary greatly with flow pattern. It is therefore convenient to define the following five regimes for vertical flow (Hewitt, 1981):

1. Bubble Flow: the liquid phase is continuous, and a uniform dispersion of bubbles flows within the liquid continuum;
2. Slug or plug flow: at higher gas flows, bubble coalescence occurs, and eventually the bubble diameter approaches that of the tube. When this occurs, large, characteristically bullet-shaped bubbles are formed. Typically, the liquid phase flows down the outside of the large bubbles in the form of a falling film, although the net flow of both liquid and gas is in the upwards direction. It is worth noting that this regime is usually not observed in wide-bore tubes (greater than 100mm pipes), although Pioli et al. (2012) showed its presence in very large diameter pipes using very high viscosity liquids (with $\mu=200\text{Pa.s}$). More detail on this regime will be given on the following sections;
3. Churn Flow: with increasing flow velocity, a breakdown of the slug flow bubbles leads to an unstable flow regime in which there is, in wide-bore tubes, an oscillatory motion of the liquid upwards and downwards; thus the name churn flow. It occurs over a range of gas and liquid velocities which increases with increasing pipe diameter (Hanratty, 2013). At low gas flows and small pipe diameters, occasional bridging across the pipe by the liquid phase can be observed (which is not seen in large diameter ones). The oscillation may not occur in very narrow-bore tubes, and a smooth transition between the slug flow and annular flow regimes may be observed;
4. Annular Flow: the liquid flows on the wall of the tube as a film, and the gas phase flows in the centre. The liquid phase travels partly as wavy film, with some of the

liquid phase entrained as small droplets in the gas core. It is also possible for gas bubbles to be entrained in the film. As with the slug flow regime, a more detailed description of this regime will be provided in subsequent sections;

5. Wispy annular film: as the liquid flow rate is increased, the concentration of drops in the gas core increases; ultimately, droplet coalescence in the core leads to large lumps or streaks (wisps) of liquid in the gas core. This regime is characteristic of flows with high mass flux.

A schematic of the different flow patterns present in vertical flow is displayed below:

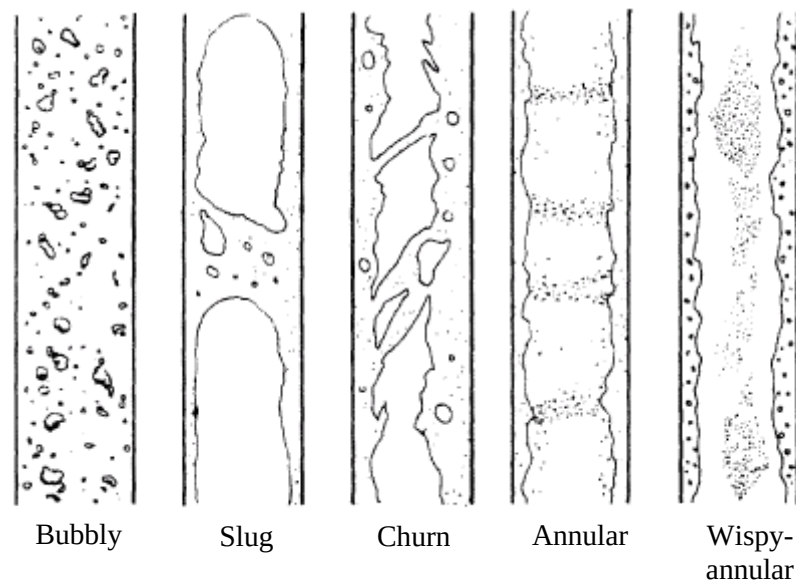


Figure 2.2: The flow regimes in vertical gas-liquid flow (Collier and Thome, 1994).

It is worth referring that due to the gravitational action, the slug and churn flow regimes cannot be encountered in downwards gas-liquid flows in vertical pipes.

2.4.1 Flow pattern maps

A common way to represent the results of observation of the flow patterns described above is to plot them on a two-dimensional graph, with transition lines drawn to represent the extent of the boundaries between the flow regimes (Taitel et al., 1980). However, it is important to acknowledge that transitions between each regime does not occur suddenly, but rather a certain flow pattern progresses to another through an intermediate regime that possesses mixed characteristics (Spedding et al., 1998).

There is a wide variety of flow pattern maps published in literature, which can be divided into two categories: empirically derived and theoretically derived flow pattern maps (Spedding et al., 1998, McQuillan and Whalley, 1985).

2.4.1.1 Empirically derived flow pattern maps

The flow pattern maps arise from experimental work done by researchers for a particular fluid pair and pipe geometry. The selection of the coordinates for the published maps has been of two basic types: using either dimensional or dimensionless coordinates. Examples of the former can be seen for instance in the work of Wallis (1969) which used superficial velocities (U_{SG} and U_{SL}) or of Hewitt and Roberts (1969), who used superficial momentum flux ($\rho_G U_{SG}^2$ and $\rho_L U_{SL}^2$ - see Figure 2.3) as their map coordinates. Given any single pipe size and set of fluid properties, these coordinates will map the transitions, but there is no reason to expect that the location of these transition curves will be unchanged for changes in these variables (Taitel et al., 1980). By using dimensionless coordinates, either using a particular set or a combination of dimensionless parameters (see Section 2.2), researchers hope that the result will apply to pipe sizes and fluid properties other than those of the data used to locate the curves. However, up to this date, there is no pair of dimensionless groups that fully characterize the transition boundaries that exist between flow regimes.

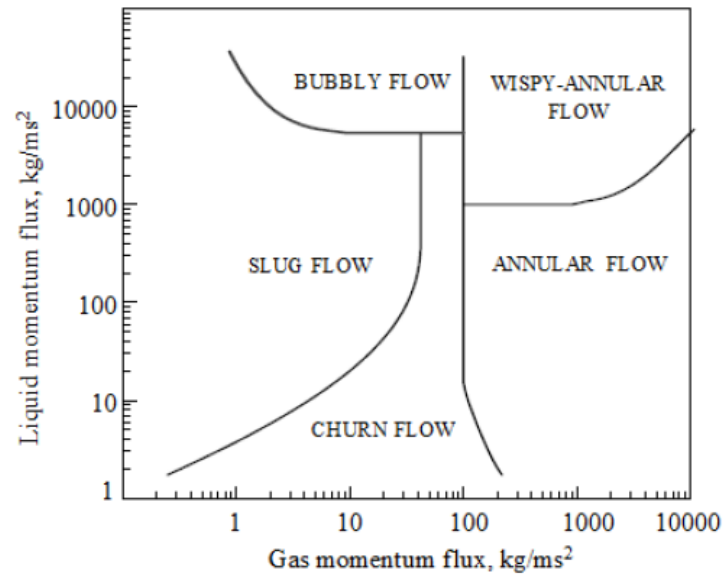


Figure 2.3: Experimental flow pattern map of Hewitt and Roberts (1969) for an air-water system.

2.4.1.2 Theoretically derived flow pattern maps

Due to the fact that the empirically derived flow pattern maps are most applicable for the set of conditions from which they were derived, some of the research focus shifted towards the derivation of theoretical flow pattern maps. Examples of such maps can be found in the work of Taitel et al. (1980) and Mishima and Ishii (1984), who considered the conditions necessary for the existence of each flow pattern. This required for mechanisms which govern the transitions between the various flow patterns to be postulated, from which ultimately a series of equations could be modelled. Therefore, when the phases' physical properties and the pipe diameter are known, this enabled for the flow pattern boundaries to be calculated. Figure 2.4 shows an example of a theoretically derived flow pattern map by Taitel et al. (1980).

However, the success of theoretically derived flow pattern maps goes only as far as the understanding behind the underlying mechanisms that govern each individual flow regime. Up to this date, a full understanding of the behaviour of the different flow regimes is yet an unresolved problem. As a result, no flow regime map has received universal acceptance, as there is no general consensus as to the most appropriate mapping parameters (Spedding et al., 1998, Taitel et al., 1980, Zabaras et al., 1986).

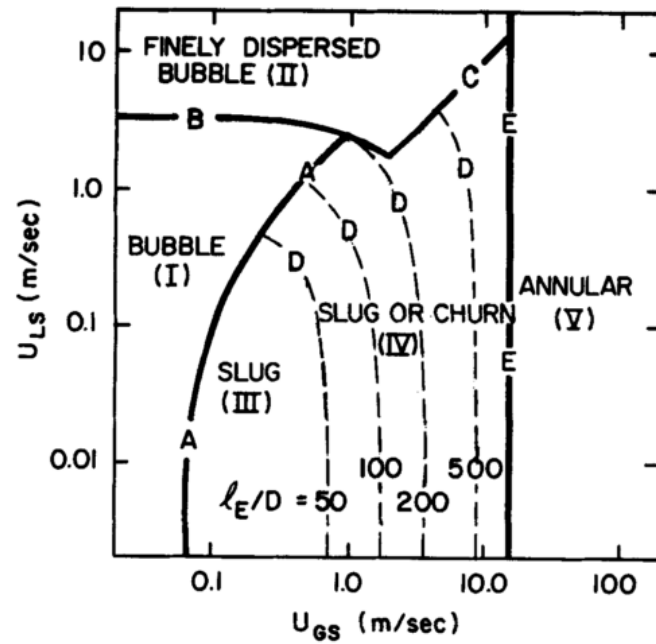


Figure 2.4: Theoretically derived flow pattern map of Taitel et al. (1980) for an air-water system in a 50 mm pipe.

Predicting the flow pattern present given a set of flow conditions is crucial, together with its transition boundaries. However, as discussed above, it is vitally important to model with great detail and accuracy the different flow patterns, as these will dictate the pressure drop and mass and heat transfer rates, which is the overall goal of the multiphase flow research.

The following subsections will summarise the attempts made in better characterizing and understanding the physical mechanisms behind the slug and the annular flow regimes. This information will be the used as the backbone of experimental work and data analysis described in Chapters 4, 5 and 6.

2.5 The slug flow regime

In vertical slug flow, large bullet-shaped bubbles, denominated as Taylor bubbles occupy most of the pipe cross-section and move upwards with a constant velocity (Hewitt, 1981). The liquid around the elongated bubbles moves downward as a thin falling film until it reaches the skirt of the bubble and mixes with the liquid just underneath it, which is often referred to as liquid slug, as shown in Figure 2.5. In this liquid slug, some entrainment of the gas from the Taylor bubble can be seen in the form of smaller bubbles, which are initially concentrated in a very small area of the liquid slug, which is called the wake region. Each slug sheds liquid in its tail to the subsequent film, which accelerates as it moves downward (Talvy et al. (2000)). Due to the complexity and the importance that this regime has on industrial applications, slug flow has been extensively reviewed in literature over the years.

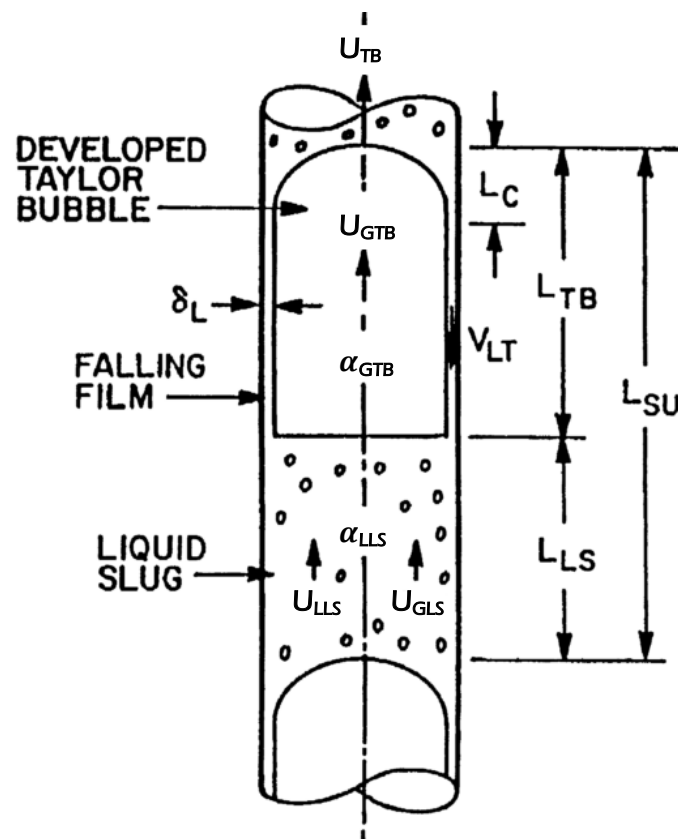


Figure 2.5: Schematic diagram of slug flow (Abdul-Majeed and Al-Mashat, 2000).

In the early slug flow studies, the research efforts were mostly focused in generating models that assume a steady slug flow behaviour, with the main goal to predict parameters such as Taylor bubble lengths (with void fraction estimation), Taylor bubble constant rising velocities and Taylor bubble frequencies. More specifically, the undisturbed rise velocity of an individual Taylor bubble, U_{TB} , has been extensively studied (Nicklin and Davidson, 1962, Collins et al., 1978), and it is recognized that it is expressed as the addition of the velocity of a Taylor bubble rising through a stagnant column of liquid (i.e the drift velocity, U_0) and the contribution of the liquid velocity, U_L , as shown by the following relationship:

$$U_{TB} = U_0 + C_{DTB}U_L \quad (\text{Eq. 2.29})$$

where C_{DTB} is the Taylor bubble distribution parameter based on the assumption that the bubble follows the maximum local velocity in front of the nose tip. According to the works of Nicklin and Davidson (1962), Shemer and Barnea (1987), Polonsky et al. (1999), this ranges from 1.2 for fully developed turbulent flow, to 2 for laminar flow. Moreover, in a case of a Taylor bubble rising through a stagnant liquid column, the drift velocity U_0 is established as:

$$U_0 = 0.35 \sqrt{gD} \quad (\text{Eq. 2.30})$$

The relationships above are applicable therefore in situations where a fully developed, steady-state slug flow regime is present, in which the Taylor bubbles and liquid slugs rise steadily and follow each other at constant distance, which is not always the case, especially near the entrance region. Given the intermittency and instability of the flow regime, variations in the bubble and liquid slug length exist inside the pipe that create an effect in the translational velocity of the Taylor bubbles, which cannot be defined as constant. For instance, in the event of a Taylor bubble being located at a small distance from a trailing bubble, its own presence can lead the trailing bubble to travel at a faster speed than the Taylor bubble itself, particularly if this preceding bubble is located behind long slugs. This can lead to the merging of these two consecutive bubbles. This phenomena has therefore a direct impact on the overall pressure drop of the system, whose contributions have been reported by Moissis and Griffith (1962), Pinto et al. (1998), Talvy et al. (2000), van Hout et al. (2001). It was concluded that

differences in bubble size and velocity distributions, and consequently, merging behaviour, will occur until a sufficient liquid slug length is achieved, where the velocities of trailing bubbles are unaffected by leading ones (van Hout et al., 2001). Different models have been generated with a suggested a minimum stable slug length for a steady state slug flow regime to be present, which can range from 16D to 20D according to Taitel et al. (1980), Barnea and Brauner (1985) and Shemer and Barnea (1987) respectively, for vertical flow.

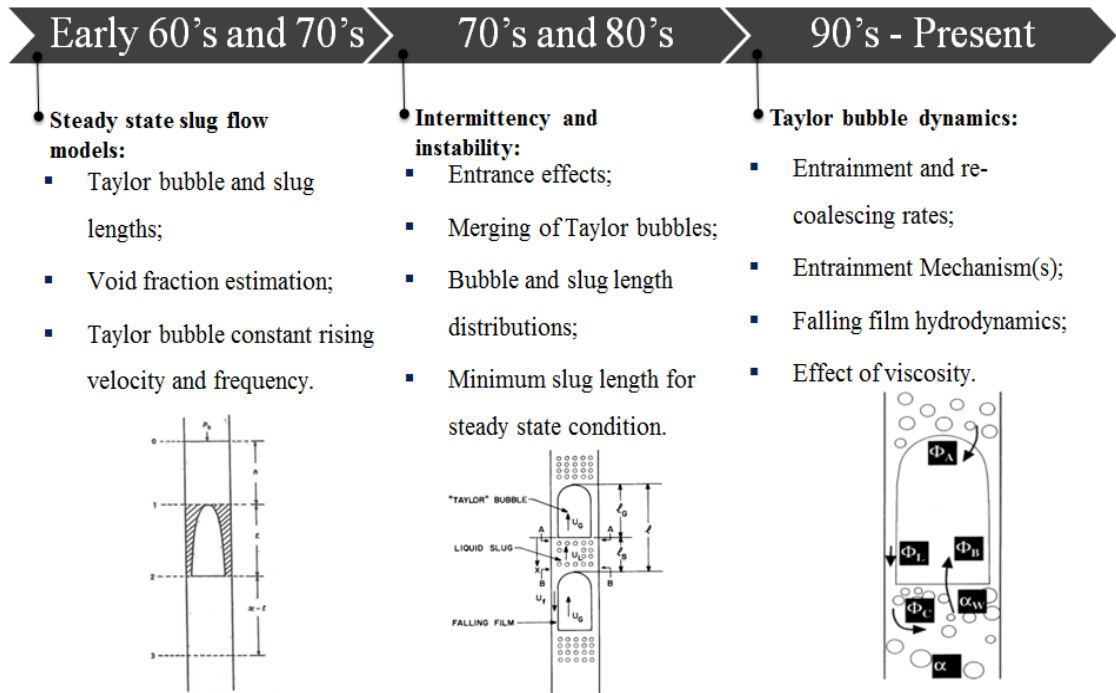


Figure 2.6: Timeline showing the research progress in the study of the slug flow regime.

The summary above and in Figure 2.6 provide a flavour of the typical early studies performed in the characterization of the slug flow regime. However, despite many attempts to predict the main parameters of the Taylor bubble existence in steady state slug flow, while taking into account factors such as merging of bubbles and entrance effects, a fully successful pressure drop prediction is yet to be fully achieved. This is not only due to the high complexity in terms of the inherent intermittency of the regime, but mainly due to the fact that the gas exchange process between a Taylor bubble and its surroundings is still unknown. More specifically, the pressure drop is not only dependent on the amount of air present in the Taylor bubble, but also dependent on the amount of gas absorbed by the Taylor Bubble from the

preceding liquid slug; the entrainment of gas from the Taylor Bubble into the succeeding liquid slug (wake region) and on the partial re-coalescence of this same entrained gas.

In the typical slug models mentioned above, values for the entrainment and coalescence rates (Q_{ent} and Q_{rec} respectively) are given. However, according to Dukler and Fabre (1992), due to lack of understanding of the underlying mechanisms behind the entrainment and re-coalescence rates, these models are not capable of providing sufficient accuracy in the predictions of these parameters since they are largely empirically based and only accurate for the set of parameter from which they were derived. As a result, the focus of slug flow research has shifted towards the dynamics of the Taylor bubble itself. More recent studies have mainly focused on obtaining a better understanding of the interactions that occur between the falling film and the skirt of the Taylor bubble, where entrainment and re-coalescence occurs, since there is evidence that they are intertwined. The fast movement of the Taylor bubbles in the slug flow regime makes measurements of its hydrodynamics difficult. Consequently, the measurement and behavioural understanding of parameters such as entrainment and re-coalescence rates and the falling film profile have not been fully achieved. To overcome such problems, different studies were carried out with various specially designed apparatus to generate a stationary Taylor bubble, which is also the case of the work presented in Chapter 4 of this thesis.

The pioneering stationary Taylor bubble studies of Riiser et al. (1992), Bacon et al. (1995), Su and Metcalfe (1997) employed different geometries in terms of injecting air into the system in order to generate a stagnant bubble, while simultaneously having present a downwards liquid flow around the bubble, representing the falling film present around a Taylor bubble. This falling film ultimately impinges into a liquid column, as summarised by Delfos et al. (2001b). The primary focus of these preliminary studies was the measurement of bubble growth together with gas entrainment measurements, thus attempting to establish a relationship between both parameters. Riiser et al. (1992) provide the first study of these parameters and their data is therefore quite limited, whereas Bacon et al. (1995) provide a

broader data matrix obtained with different geometries. Su and Metcalfe (1997) further investigate the effects that different liquid viscosities and surface tensions have on the entrainment rate by adding different additives, with later on Abdulahi (2013) concluding that the entrainment rate is inversely proportional to the viscosity of the liquid tested for a given set condition.

There are obviously some discrepancies between this artificial type of Taylor bubble and conventional upwards slug flow. For instance, in the latter case, the tube wall is running downwards relative to the Taylor bubble. Therefore, the falling film velocity relative to the Taylor bubble is higher than in the stationary cases. Consequently, the turbulence level in a moving slug flow will be inherently higher. However, in their comparison between the results published by the pioneering stationary cases and the conventional slug flow studies and theoretical models, Brauner and Ullmann (2004) concluded that the established comparison substantiates the artificial system as a quantitative predictive tool. They attest for its validity in helping predicting parameters such as bubble length, physical properties of fluids, tube diameter and inclination on the rate of gas entrainment. However, it is shown that data obtained with a stationary bubble in liquid downflow may display smaller gas entrainment rates than a similar upward rising Taylor bubble and therefore, may underestimate the aeration of the liquid bridge in slug flow. Nonetheless, as Riiser et al. (1992) points out, the advantage of having a standing tail allows for an accurate measurement of the entrained rate together with the drift of small bubbles in the slug and to control the void fraction.

It is however important to replicate as much as possible an actual Taylor bubble configuration. As a result, in more recent studies, in which category this thesis is, special attention has been paid to mimic the shape of the elongated bubble nose and the relative velocities of the liquid and the elongated bubble in slug flow (Brauner and Ullmann, 2004). As a result, air was injected in the testing section through an hemispherical cap, as defined by Dumitrescu (1943), which for the study in their thesis had a radius of curvature (R_n) expressed as $R_n=0.375D$. According to Kockx (1999), the purpose of the cap is to enhance

the stability of the bubble in the centre of the main vertical pipe and to simulate the shape of a real Taylor bubble as accurately as possible.

Furthermore, due to the advancement of measurement techniques, it was possible to have a greater insight of the underlying mechanisms behind both the entrainment and re-coalescence events. Delfos et al. (2001a) measured the re-coalescence rate and the radial distribution of the re-coalescence events by injecting helium into the wake region at different radial locations and detecting the amount of helium present in the air that is re-coalesced back to the artificial bubble. By applying a mass balance relationship for a stationary Taylor bubble, the following is established:

$$Q_{\text{ent}} = Q_{\text{in}} + Q_{\text{rec}} \quad (\text{Eq. 2.31})$$

where Q_{in} is the gas flowrate injected into the artificial bubble. By measuring the re-coalescing rate, Delfos et al. (2001a) could re-arrange Equation 2.31 to derive the entrainment rate for a particular flowrate condition. These results would be used later on by Delfos et al. (2001b) and Kockx et al. (2005) in their investigation of the entrainment mechanism. Their work can be regarded as a continuation of the early work reported by Delfos (1996). In his work, Delfos (1996) reports the first observations on the falling film, and the apparent impact that its behaviour has on the gas entrainment events, which are concluded to be similar to the case of turbulent plunging jets falling into a stationary pool of liquid.

The effect that plunging jets have on gas entrainment is a topic that has been widely covered and established in literature. The studies of Van de Sande and Smith (1973), McKeogh and Ervine (1981), Biń (1988), Sene (1988) report a critical minimum jet velocity above which gas entrainment will occur. Biń (1988) provides a diagram describing how this event occurs, as shown in Figure 2.7a). Derivations of the impact jet diameter, which is correlated to the gas entrainment is made by various authors, with Biń (1993) estimating that this is a function of jet length, gravity, liquid flow rate and relaxation diameter, whereas Van de Sande and Smith (1973) propose a correlation which was based on the Weber number, Reynolds number as well as nozzle design parameters. Finally, McKeogh and Ervine (1981)

measured the jet turbulent intensity, generating a power law relationship which correlated the jet surface roughness, jet radius, jet length, and the jet breakup length.

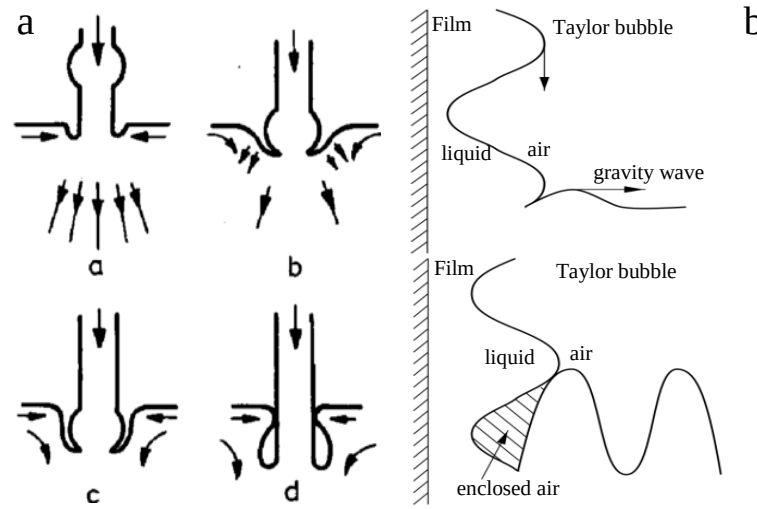


Figure 2.7: a) Air entrainment mechanism for low viscosity jets (Biñ, 1988); b) Entrainment mechanism at the bottom of Taylor bubble due to distortions on the falling liquid film (Kockx et al., 2005)

Delfos (1996) applied these concepts in his stationary Taylor bubble study, since, as with the case of plunging jets, it was observed that it is only after roughness or waves appeared on the falling film surrounding the bubble, that gas entrainment increased perceptibly. This led to the conclusion that entrainment is assumed to be caused by the fact that the free surface of the liquid pool (i.e., the skirt of the Taylor bubble) is not capable of responding to the (transverse) oscillations of the incoming film as schematically shown in Figure 2.7b). The similarities between both cases are evident. When a wave on the film surface approaches the pool, it generates a gravity wave, which propagates on the pool surface as shown in Figure 2.7b). When the slope of the induced gravity wave is large enough and the waves on the film surface travel fast enough, the crest of the gravity wave will contact the next wave on the film surface and air will be enclosed, leading to its entrainment. Additionally, according to Delfos et al. (2001b), the entrainment rate is proportional to both the velocity at which the film flow enters the Taylor Bubble wake and the intensity of the turbulent velocity fluctuations in the film. Hence, they conclude that the entrainment process is governed by the wall shear generated

turbulence, which according to Kashinsky et al. (2008) in their investigations with a stationary bubble, increases with increasing distance from the nose of the bubble. In other words, the rate of gas entrainment is determined based on an energy balance between the rate of turbulent kinetic energy generated and the rate of bubble surface energy production (Brauner and Ullmann, 2004). Through this proposed entrainment mechanism, Delfos (1996) proposed an expression that predicts the entrainment rate given the following parameters, assuming for simplicity that the waves present in the falling film possess a sinusoidal waveform:

$$Q_{\text{ent}} = IU_w \Delta h_w \pi (D - 2h_f) \quad (\text{Eq. 2.32})$$

where I is the intermittency factor, U_w is the wave velocity, Δh_w is the mean wave amplitude and h_f is the mean film thickness. Through the manipulation of the intermittency factor, using a laser induced fluorescence technique, Kockx et al. (2005) shows that Equation 2.32 successfully estimates the entrainment rate when comparing with the results obtained by Delfos et al. (2001b).

However, despite the recent advances in the characterization of the dynamics of the behaviour of a Taylor bubble, the falling film behaviour is yet to be fully understood. This will be of vital importance in terms of allowing for validation of CFD simulations. Furthermore, it is necessary to attest if the entrainment mechanism postulated by Kockx et al. (2005) is the sole driver of entrainment. These points will therefore be covered in Chapter 4.

2.6 The annular flow regime

2.6.1 General description

As discussed in Section 2.4, the annular flow regime is generally observed at high gas flowrates and encountered in a wide range of industrial applications. These can range from the oil wells, transfer pipelines and risers present in the oil-and-gas industry; condensers and evaporators encountered in nuclear reactors to chemical reactors encountered in chemical processing plants (Chu and Dukler, 1975, Dasgupta et al., 2017). In this regime, the liquid travels in the form of a thin and wavy film in contact with the walls of the duct, while being sheared by a co-current high-velocity gas stream that occupies the core of the duct. Additionally, gas bubbles can be entrained into the liquid film, while liquid droplets can be found in the gas core due to entrainment of the liquid film (see Figure 2.8a).

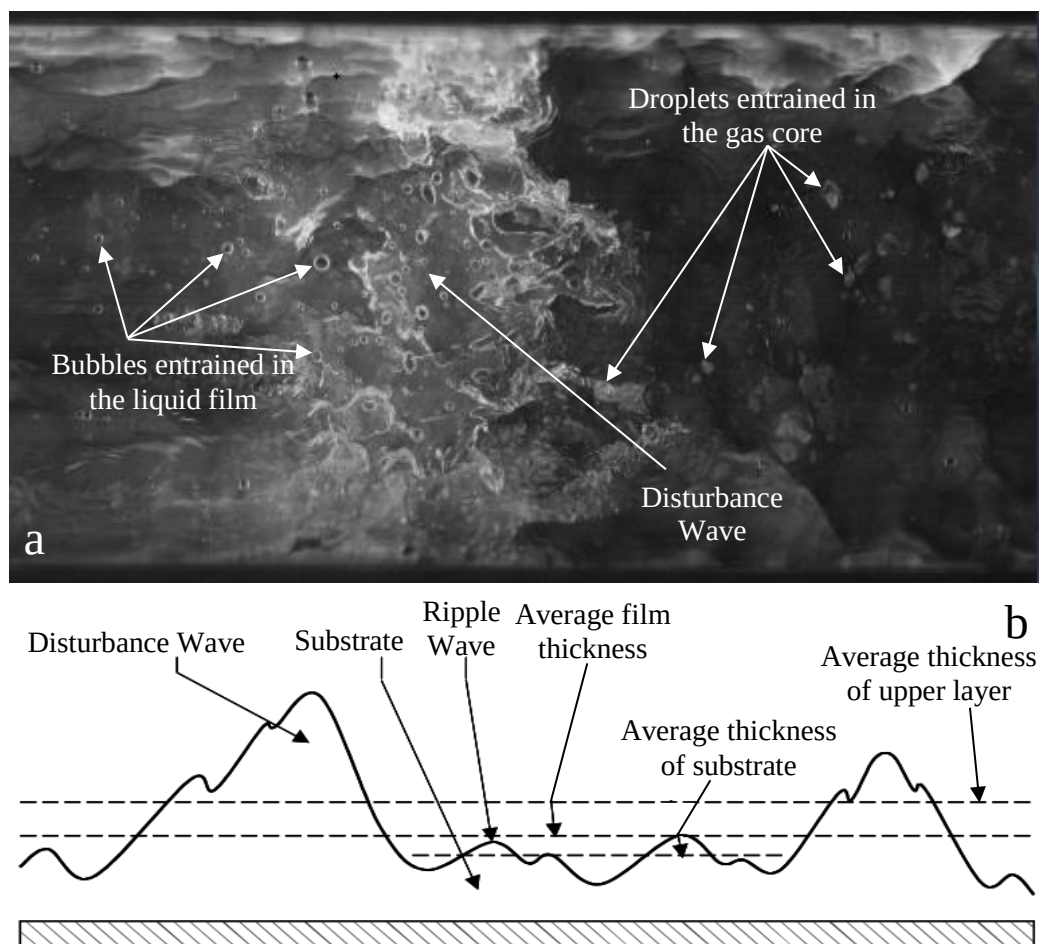


Figure 2.8: a) Snapshot taken with the BLLIF technique during an annular flow experiment; b) Classification of interfacial waves in the liquid film (Hazuku et al., 2008).

A very important feature of annular flows is the presence of thick, intermittent, fast-moving interfacial wave structures, best known as ‘disturbance waves’ (also referred to as ‘roll’ waves in the literature – See Figure 2.8b). These are generally characterized as having an amplitude several times higher than the mean thickness of the liquid film (there is not an actual agreement on the exact threshold value above which a wave is classed as a disturbance wave), by being entirely coherent across the circumference of the pipe (in small diameter cases), by moving with an approximately constant velocity and by carrying mass along the tube (Azzopardi, 1986, Hanratty and Hershman, 1961). These set of conditions presume that the flow has achieved a developed state, which takes considerable distances from the inlet for stabilization to occur, although there is still conflicting evidence on the exact length required for this to occur (Wolf et al., 2001).

In addition to the presence of disturbance waves in the liquid film, the base film is covered with a large number of non-coherent structures which are much smaller in amplitude, wavelength and velocity, commonly known as ‘ripple’ waves (Hall Taylor and Nedderman, 1968). These are usually overtaken by a disturbance wave, with new ripples forming in its wake, therefore not having a continuous life (Hall Taylor et al., 1963). However, when on top of the disturbance waves, these ripples can travel faster than the disturbance waves and eventually be torn off in the form of droplets due to the shearing action of the gas phase at the disturbance waves’ crests (Alekseenko et al., 2014), through the mechanism of ligament break-up. Together with the bag break-up mechanism (more likely to occur close to the churn flow transition), this is the primary mode of entrainment. The overall behaviour of a ripple wave can be defined by the point of its inception (Alekseenko et al., 2015), which can be largely affected by the existence of an eddy motion under the humps of disturbance waves (Alekseenko et al., 2009, Zadrazil and Markides, 2014).

At very low liquid flowrates, ripple waves dominate the two-phase interface. Above a critical liquid flowrate, disturbance waves appear in the flow (Andreussi et al., 1985, Schadel, 1988). Additionally, when above the critical liquid flowrate, several transitions can take place depending on the gas velocity (Hewitt and Hall-Taylor, 1970, Wallis, 1969). When the gas

velocity is very small, the interface presents a relative stability. However, with the increase in gas velocity, it can be said that the interface becomes wavy due to the Kelvin-Helmholtz instability, where the gas phase has a shearing action on the liquid phase (Lamb, 1975, Levich, 1962). When this occurs, the entrainment rate is seen to also increase perceptibly. Therefore, it can be said that the annular flow regime is a sheared dominated regime, where the gas phase is mostly responsible for the motion of both the liquid film and the liquid droplets in the gas core. Moreover, Nicklin and Koch (1969) state that the film thickness in annular flow assumes the value necessary to satisfy the momentum balance between the wall shear and gravity. As the film thickness changes due to random variation, the interfacial shear adjusts to maintain the value needed to support the film.

2.6.2 Interfacial shear stress

The prediction of the behaviour of disturbance waves is of significant importance for researchers due to their dominant role in the heat and mass transfer characteristics of the annular flow regime (Zhao et al., 2013, Hazuku et al., 2008). It has been found that heat transfer rates are enhanced in the areas where disturbance waves are present, whereas the laminar regions in between consecutive disturbance waves display much lower heat transfer values (Hewitt and Hall-Taylor, 1970). Additionally, the presence of disturbance waves influences the shear stress at the gas-liquid interface, together with the wall shear stress underneath them. Furthermore, as discussed above, it has been established that liquid entrainment into the gas core is linked to the presence of the disturbance waves, which itself has an effect on the balance of the forces acting in such conditions. For instance, when a droplet is created from the gas-liquid interface, its initial velocity is much smaller than the gas velocity (van 't Westende et al., 2007). Due to the drag force exerted on the droplet, it will accelerate, increasing its kinetic energy. When the droplet impinges onto the gas-liquid interface, its kinetic energy is converted partly to kinetic energy of the liquid film (pushing the liquid upward), but mostly to heat (via friction with the wall, according to Lopes and

Dukler (1985) and Fore and Dukler (1995a)). These factors ultimately have an impact on the overall pressure drop across the system.

Since pressure drop is one of the most important parameters used to characterize a flow system, several methods have been proposed to model or correlate the interfacial friction factor, f_i , in annular flows (Fore et al., 2000), in an attempt to solve the two-phase pressure drop equation (Equation 2.28). The interfacial friction factor in annular flow is therefore related to the interfacial shear stress, τ_i , as defined by the following equation (Fore et al., 2000, Schubring and Shedd, 2011):

$$f_i = \frac{2\tau_i}{\rho_G U_G^2} \quad (\text{Eq. 2.33})$$

where U_G is the mean gas velocity in the gas-droplet core, defined as:

$$U_G = \left(\frac{D}{D - 2\delta} \right)^2 \cdot U_{SG} \quad (\text{Eq. 2.34})$$

and δ is the mean film thickness.

The annular flow regime is often understood through the triangular relationship postulated by Hewitt and Hall-Taylor (1970). This asserts a close relationship between the liquid film flowrate, the liquid film thickness and the gas-liquid interfacial shear. The liquid film flowrate is computed by integrating the liquid film velocity profile, which depends on the shear across the liquid film thickness, which is a function of both the gas and liquid velocities in the system. Typically, the film thickness is conceptualized as a fully roughened sand surface to the gas core that enhances interfacial shear and pressure losses (Schubring et al., 2010a, Asali et al., 1985). Single-zone roughness models dominate the literature, where the average film thickness and the effective roughness are assumed to be linearly correlated, and the friction factor is defined by the relation (Asali et al., 1985):

$$f_i \sim \frac{\delta}{D} \quad (\text{Eq. 2.35})$$

Examples of a single-zone film roughness model can be found in the more simplistic model of Wallis (1969) and a more complex model of Owen and Hewitt (1986).

2.6.2.1 The Wallis model

In the single-zone film roughness model of Wallis (1969), a simple explicit expression for the gas shear at the gas-liquid interface, τ_i , as a function of the average film thickness is proposed:

$$\tau_i = 0.079 Re_G^{-0.25} K E_{SG} \left(1 + 300 \frac{\delta}{D}\right) \quad (\text{Eq. 2.36})$$

In the original Wallis correlation, in place the factor $0.079 Re_G^{-0.25} K E_{SG}$ (the Blasius friction factor), a constant of 0.005 was used instead.

The proposed correlation is then compared with the experimental interfacial shear, τ_i , which is typically obtained using the following expression from the work of Fore et al. (2000):

$$\tau_i = -\frac{D - 2\delta}{4} \left(1 - \frac{\rho_{core} U_G^2}{P_{abs}}\right) \frac{dP}{dx} - \rho_{core} g \frac{D - 2\delta}{4} - R_D (U_D - U_E) \quad (\text{Eq. 2.37})$$

where R_D is the rate of droplet deposition (assumed to be equal to the rate of droplet entrainment, E), with U_D and U_E being the velocities of depositing and entraining droplets. It is generally assumed that since droplets are entrained from waves, their initial entrained velocities are equal to the disturbance wave velocity. ρ_{core} is the core density, with P_{abs} is the absolute test section pressure.

The Universal Velocity Profile (UVP) is assumed within the film. It provides a description of the mean velocity within a wall-bounded, turbulent boundary layer:

$$u^+ = \begin{cases} y^+ & \text{if } y^+ < 5 \\ -3 + 5\ln(y^+) & \text{if } 5 < y^+ < 30 \\ 5.5 + 2.5\ln(y^+) & \text{if } 30 < y^+ \end{cases} \quad (\text{Eq. 2.38})$$

The UVP is non-dimensionalised in wall coordinates (u^+ and y^+), which are defined by the following equations:

$$u^+(y) = \frac{u(y)}{u_L^*} \quad (\text{Eq. 2.39})$$

$$y^+ = \frac{y u_L^*}{\nu_L} \quad (\text{Eq. 2.40})$$

$$u_L^* = \sqrt{\frac{\tau_I}{\rho_L}} \quad (\text{Eq. 2.41})$$

$$\delta^+ = \frac{\delta u_L^*}{\nu_L} \quad (\text{Eq. 2.42})$$

In these equations, ν_L is the kinematic viscosity of the liquid. A dimensionless flowrate,

$\dot{m}_{L,\text{film},OH}^+$, is defined as follows, with μ_L , as the dynamic viscosity of the water:

$$\dot{m}_{L,\text{film},OH}^+ = \frac{\dot{m}_{L,\text{film}}}{\pi D \mu_L} \quad (\text{Eq. 2.43})$$

By integrating the UVP, the dimensionless flowrate can be related to the film height:

$$\dot{m}_{L,\text{film},OH}^+ = \begin{cases} 0.5(\delta^+)^2 & \text{if } \delta^+ < 5 \\ -64 + 3\delta^+ + 2.5\delta^+ \ln(\delta^+) & \text{if } 5 < \delta^+ < 30 \\ 12.05 - 8.05\delta^+ + 5\delta^+ \ln(\delta^+) & \text{if } 30 < \delta^+ \end{cases} \quad (\text{Eq. 2.44})$$

The entrained fraction, E is then estimated based on the mass balance:

$$E = \frac{\dot{m}_{L,\text{Ent}}}{\dot{m}_L} = \frac{1 - \dot{m}_{L,\text{film}}}{\dot{m}_L} \quad (\text{Eq. 2.45})$$

The work of Schubring et al. (2010a) discusses in greater detail the application of the model of Wallis (1969) to their experimental data, where the average film thickness, δ , is required as an input. In their work, they found that there is a mean absolute error (MAE) of 22.7% for the model of Wallis (1969) when comparing it with the experimental interfacial shear stress obtained using Equation 2.37. For the highest liquid flow series, the Wallis correlation predicts a weak and non-monotonic trend with gas flow, which contrasts sharply with the increase seen in experimental data. This indicates that the behaviour of annular flow with high liquid flowrate is not predicted accurately by the Wallis correlation.

2.6.2.2 The Owen and Hewitt model

This model computes film height and pressure loss given values for the entrained fraction, as opposed to the film thickness (as in the Wallis model). The model is composed of liquid film and gas core submodels, which are outlined below.

The liquid film sub-model requires interfacial shear, $\tau_{i,OH}$, and the film flowrate, $\dot{m}_{L,film,OH}$ and estimates the interfacial velocity and the film thickness. The characteristic shear, τ_{OH} , in the film is defined by averaging $\tau(y)$, obtained by a force balance in the film:

$$\tau_{OH} = \tau_{i,OH} \frac{D - 2\delta}{D} - \left(\frac{dP}{dx} + \rho_L g \right) \left[\frac{\delta D}{2} - \frac{\delta^2}{3} \right] \quad (\text{Eq. 2.46})$$

In the Owen and Hewitt model, the characteristic shear, τ_{OH} , is used instead of the interfacial shear, τ_i .

The gas core sub-model requires the entrained droplet mass flowrate, $\dot{m}_{L,Ent,OH}$, along with the core diameter, D_{core} , area, A_{core} , density, ρ_{core} and velocity, $U_{core,h,OH}$ to be derived. These are found using a homogeneous model of the gas and liquid droplets in the core. By assuming the gas to follow the ideal gas law, incompressible behaviour in the liquid droplets, and no axial variation in the entrained fraction or film thickness, Owen and Hewitt's equation for interfacial shear can be simplified to P_{abs} as the absolute pressure in the test section:

$$\tau_{i,OH} = -\frac{D_{core}}{4} \left(1 - \frac{\rho_{core} U_{core,h,OH}^2}{P_{abs}} \right) \frac{dP}{dx} - \frac{D_{core}}{4} \rho_{core} g \quad (\text{Eq. 2.47})$$

Once more, Schubring et al. (2010a) used their film thickness experimental data to predict both the pressure loss and entrained fraction using the Owen and Hewitt model. They concluded that the mean absolute error for the modelled pressure loss was 17% for their data. Likewise to the Wallis model, the model diverges strongly at higher flowrates. The overall performance of this model is no better than that of single-zone correlations that do not require film thickness information, such as those of Chisholm (1973) (15% MAE) and Müller-Steinhagen and Heck (1986) (13% MAE).

2.6.2.3 Multi-zone model

Visualizations of the film topology in the annular flow regime show however that roughness is not homogeneous. Instead, a major source of roughness comes from the presence of the intermittent disturbance waves. More recently, it has been suggested in literature that wave characteristics such as disturbance wave velocity and frequency must be explicitly considered in order to correlate interfacial friction factors, which is one of the motivations of the present work.

There are several motivations for a multi-zone film modelling approach in annular flow: physically, there is a sharp distinction between base film and disturbance wave zones in terms of their roughness. As a result, models are required to account for this factor, where the output is not only average shear (as in the case of the Wallis model), but shear in both zones. As a result, base film average shear (to which most of the tube is exposed) and wave zone shear (to which waves are exposed and from which droplets can be entrained) can be quantified separately, as seen in Figure 2.9.

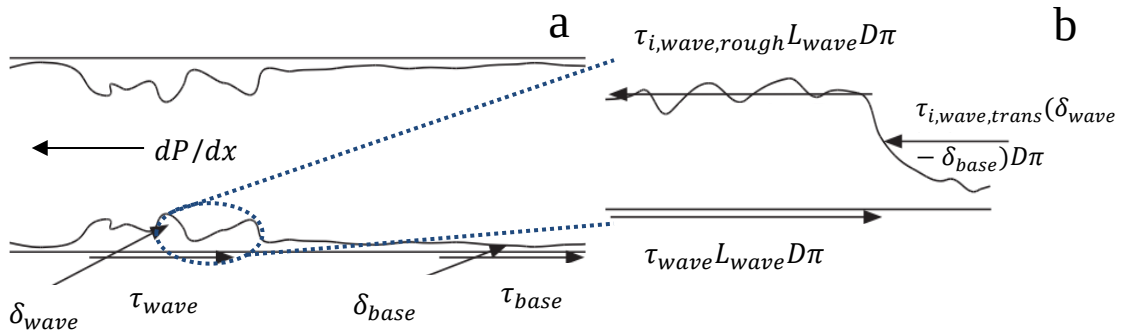


Figure 2.9: Schematic of annular flow and modelled force. a) Short section of the flow; b) Detail near a wave (Schubring and Shedd, 2011).

An example of a pioneering work implementing this concept is the model of Hurlburt et al. (2006), which uses a roughness-modified log law to model interfacial data. In particular, the following velocity profile is recommended, where U_G , u^* , y_G^+ , and ν_G are the physical velocity, friction velocity, axial distance from the interface and kinematic viscosity, respectively, all within the gas core:

$$\frac{U_G(y_G^+)}{u^*} = 2.44 \ln(y_G^+) + 5 - \Delta B \quad (\text{Eq. 2.48})$$

$$\Delta B = 2.44 \ln \left(1 + c_B \frac{\epsilon u^*}{v_G} \right) \quad (\text{Eq. 2.49})$$

The fraction of measurements assigned to the wave zone is termed the wave intermittency, INT_w , which is used to separate the measurements between the base film and the wave region. Experimentally, different authors employ different methods of measuring the wave intermittency, which is defined as the total time that waves are present in the film over a particular time series. This will be covered in Chapter 5. Nonetheless, the average film thickness and corresponding roughnesses are correlated as follows:

$$\delta = \delta_{wave} INT_w + \delta_{base} (1 - INT_w) \quad (\text{Eq. 2.50})$$

For the base film, the mean liquid velocity, $U_{L,base}$, interfacial shear, $\tau_{i,base}$, are estimated as follows:

$$U_{L,base} = u_{base}^* \left[\left(1.5 (\delta_{base}^+)^{\frac{2}{3}} \right)^{-2} + (9.5 (\delta_{base}^+)^{0.1})^{-2} \right]^{-0.5} \quad (\text{Eq. 2.51})$$

$$\tau_{i,base} = 0.5 C_{f,i,base} \rho_G (U_{G,base} - U_{L,base})^2 \quad (\text{Eq. 2.52})$$

Equation 2.51 combines the laminar film model of Asali et al. (1985) (first term within square bracket) and the turbulent film model of Henstock and Hanratty (1976) (second term) to estimate the interfacial velocity. The calculation in the wave zone is similar, where the Henstock and Hanratty (1976) relation is used exclusively:

$$U_{L,wave} = u_{wave}^* (9.5 (\delta_{wave}^+)^{0.1}) \quad (\text{Eq. 2.53})$$

$$\tau_{i,wave} = 0.5 C_{f,i,wave} \rho_G (U_{G,wave} - U_{L,wave})^2 \quad (\text{Eq. 2.54})$$

The correlated average interfacial shear is then found by:

$$\tau_{i,HEA} = (1 - INT_w) \tau_{i,base} + INT_w \tau_{i,wave} \quad (\text{Eq. 2.55})$$

For the implementation of the model, Schubring et al. (2010) found that the mean absolute error is 33%, thus showing inferior prediction capability compared to previous single-zone models. The effect of the liquid flow on τ_i (particularly at low gas flow) is underestimated, while the effect of gas flow is overestimated.

It can be seen that from previous models, a measurement of the liquid film thickness is a basic requirement, with a possible substantial increase in the level of complexity if this need complementing with the knowledge of other parameters such as entrainment fraction. This traditional modelling paradigm is problematic, as it frequently replaces a simple measurement with a more complex one (Schubring and Shedd, 2011). A model that requires only flowrates and thermodynamic state is preferable, as device performance could be optimized without expensive prototyping. Schubring and Shedd (2011) claim to have developed such a model. The model predicts film thickness, pressure gradient, disturbance wave velocity and entrained fraction for air-water annular flow data. The required inputs are flowrates, fluid properties and geometry. However, information of base film thickness is required, which resembles the traditional modelling discussed above.

As a result, a better understanding in terms of how the film thickness distribution, in which the dynamic characteristics of the disturbance waves (velocity, frequency, etc) are included, and how these vary according to changes in gas and liquid flowrates is required. Finally, a model that can correlate these parameters will be of vital importance to the successful implementation of multi-zone models to predict the interfacial shear stress, and ultimately the pressure drop.

2.6.3 Disturbance wave characteristics

The study of annular flows in a variety of configurations has been conducted over the years in an attempt to improve the understanding of such types of flows and to advise the different industries on parameters such as pumping requirements, the fraction of liquid that is entrained, or the onset of flooding conditions.

A complete description of the disturbance wave characteristics involves measuring and understanding parameters such as: wave velocity, wave frequency, distance separation (wavelength), time separation, amplitude, wave width and finally, wave intermittency.

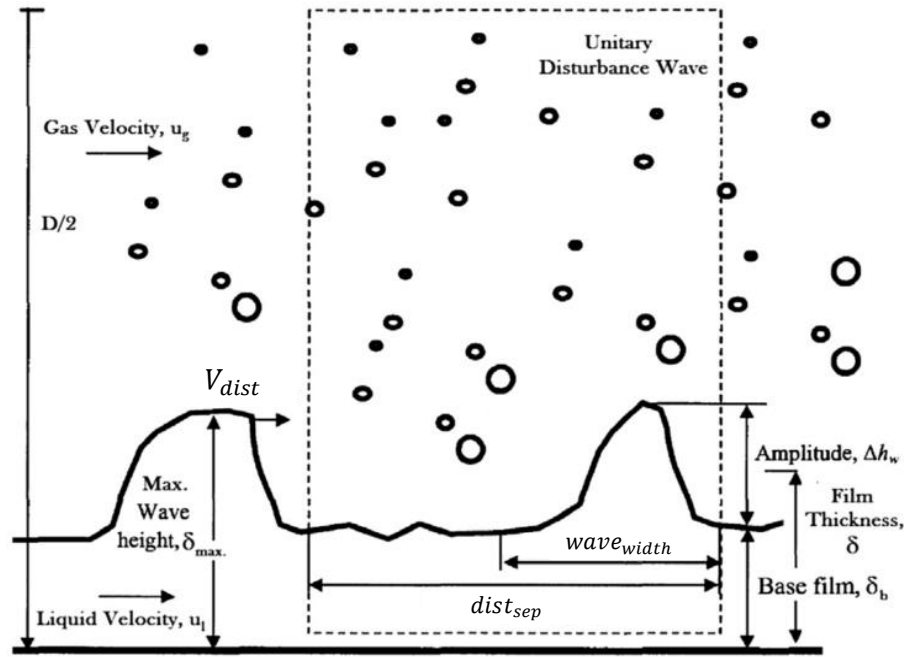


Figure 2.10: Schematic view of an unitary disturbance wave (Berna et al., 2014).

Referring to Figure 2.10, the following terms are of significance in the characterization of the disturbance wave shape. The wave velocity, V_{dist} , is simply the average disturbance wave displacement velocity. The distance separation, $dist_{sep}$, is equal to the average wave velocity, divided by the number of peaks that appear in the time series (or wave frequency) (Azzopardi, 1986). The time separation, t_{sep} , is equal to the total measured length of the film thickness time series, divided by the wave frequency. The wave amplitude, Δh_w , is obtained as the average of points above the average film thickness in the film thickness time series. The wave width, $width_{wave}$, is the distance between the starting and ending point of a single wave. Finally, as discussed above, the wave intermittency, INT_w , which is correlated to the wave width, is defined as the total time that the disturbance waves are present in the film thickness time series, over the total time of the series.

Azzopardi (1986), (1997) provide a summary of how phase flowrates, pipe properties and axial location affect the basic parameters characterizing the disturbance wave behaviour, namely, their velocity and frequency.

In terms of the frequency, the results can be summarized as follows:

- Wave frequency increases with both gas and liquid flowrates (Nedderman and Shearer, 1963, Hall Taylor et al., 1963);
- For vertical downflow, the frequency is independent of the gas flowrate for low gas rates, but shows an (approximately) linear dependence at higher gas flowrates (Thwaites et al., 1976);
- Frequency decreases with downstream distance (Hall Taylor and Nedderman, 1968, Gill et al., 1969, Alekseenko et al., 2015). This decrease is due to coalescence of disturbance waves, two joining to form one, and can be accounted for by a simple theory based on the probability distribution of the disturbance wave velocity (Hall Taylor and Nedderman, 1968, Wilkes et al., 1983);
- Wave frequency decreases with tube diameter (Martin, 1983). Also waves in larger diameter tubes are not continuous around the tube periphery (Azzopardi et al., 1983);

In terms of the velocity, the results can be summarized as follows:

- Disturbance wave velocities increase with both gas and liquid flow rates (Hall Taylor et al., 1963, Nedderman and Shearer, 1963). However, the effect of gas is greater than that of the liquid;
- There is a small increase in wave velocity along the tube when the liquid is introduced as a film but a steady state is soon achieved (Gill et al., 1969, Brown, 1978);
- Individual velocities are normally distributed about a mean (Hall Taylor et al., 1963), and the absolute standard deviation tends to be constant (Hall Taylor and Nedderman, 1968);
- Wave velocities depend linearly on wave height. Pashniak (1969) has shown this to be approximately correct for individual waves.

Not only it is important to obtain a description of the disturbance wave characteristics when the flow is considered to be in a developed condition, but it also important to understand the mechanisms behind their formation and evolution of their behaviour with axial location. This is largely covered in the work of Wolf et al. (2001) and Alekseenko et al. (2015) and will be discussed and complemented with this work in later sections.

In relation to the film thickness topology in general, descriptions of the important parameters are given below. The wave peak height (or maximum wave height), δ_{max} , is computed as the addition of the wave amplitude with the average film thickness. The base film thickness, δ_{base} , is defined as the average of the points below the average film thickness time series.

Lastly, it is important to note that there is a lack of characterization of the ripple waves that cover the base film in between successive disturbance waves.

Bearing all these aspects in mind, Berna et al. (2014) summarizes extensively the different (mostly empirical) correlations published in the literature to predict basic parameters such as: average film thickness, base film thickness, wave amplitude, wave velocity and wave frequency. These will be discussed in more detail throughout Chapters 5 and 6, where they will be tested against the experimental data acquired with the BBLIF technique.

However, despite the large amount of studies in literature that attempt to characterize the disturbance wave behaviour under various conditions, there has not been a clear focus on how the flow orientation (in vertical flow) for a constant set of pipe diameters and phase flowrates and properties affects their behaviour. That is one of the main motivations for the experimental campaign in an 11.7mm pipe, whose results are presented in Chapter 5.

Furthermore, there is not a universal consensus on which forces play a dominant role in the prediction of the different parameters characterizing the annular flow regime, especially if one considers the effect that both different duct dimensions and flow orientations (both vertical and horizontal) have on the flow. This will be covered in more detail in Chapter 6.

Chapter 3. Methodology

3.1 Measurement techniques and parametric requirements

3.1.1 Intrusive and non-intrusive methods

In the multiphase flow field world, more specifically, in two-phase gas-liquid flows, the measurement methods that allow for the study of the events occurring inside a particular duct can be divided into two groups: non-intrusive and intrusive methods (Biddinika et al., 2009), as shown in Figure 3.1.

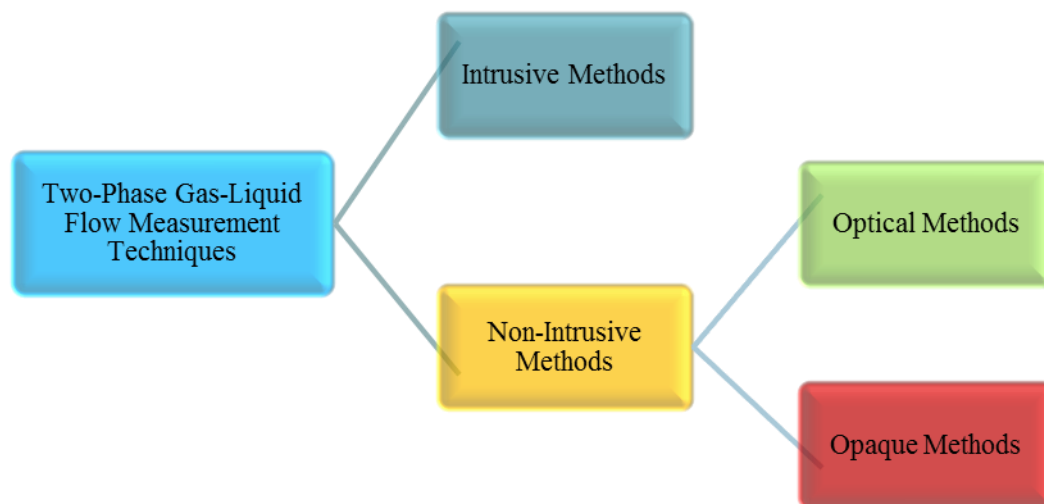


Figure 3.1: Diagram showing the main classes of flow measurement methods available for studying gas-liquid flows

Intrusive methods, such as electrical resistivity method or hot-film anemometry, have been applied to measure the flow in the early application of two-phase flow measurements, while progressively, optical probes or four point optical probes and wire-mesh tomography have been used in certain conditions. Due to their intrusiveness, they can have an effect on the flow being measured, which is not desirable.

Therefore, recently, non-intrusive methods have been developed in order to avoid the disruption of the original measured flow. These can be subdivided into two other categories:

optical methods and opaque methods (Hassan, 2002), as shown in Figure 3.2. Optical methods, such as Laser Induced Fluorescence (LIF), Particle Imaging Velocimetry (PIV), Laser Doppler Velocimetry (LDV) and Pulsed Laser Velocimetry (PLV) can be applied to two-phase flows.

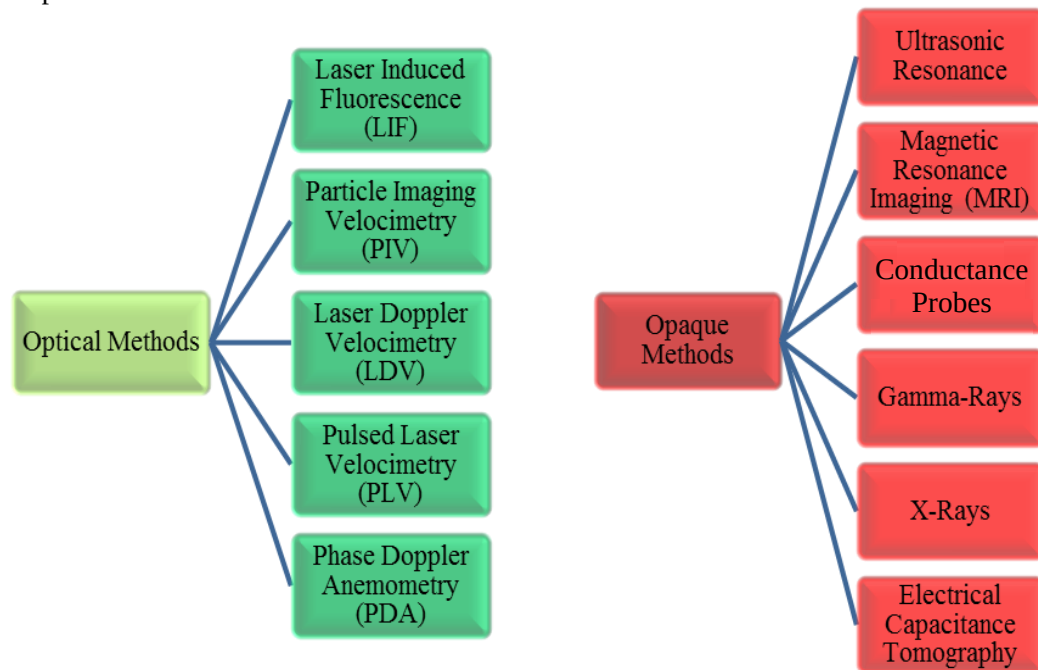


Figure 3.2: Diagram showing the two sub-classes of non-intrusive methods available for the study of gas-liquid flows: optical and opaque methods

Examples of non-intrusive methods that are applicable for opaque materials are: ultrasonic resonance, magnetic resonance imaging (MRI), conductance probes, gamma-ray, X-ray methods, and electrical capacitance tomography (Hassan, 2002). Most of these methods are based on principles that rely on obtaining measurements of the gas-liquid phase distributions across the cross-section of a duct, but only in a single plane. This is achieved based on the comparison of their conductive (Sekoguchi and Mori, 1997), capacitive (dos Reis and Goldstein Jr, 2005), magnetic (Daidzic et al., 2005) or atomic properties (Hoffmann and Johnson, 2011). Ultrasonic resonance and conductance probes differ from the rest of the techniques in the opaque category, in the sense that they are used to obtain measurements of ‘only’ the film thickness of the liquid layer (Zhong et al., 2014).

With regard to the optical methods available, phase Doppler anemometry (PDA) and laser Doppler velocimetry (LDV) are commonly used to measure the size, velocity and

concentration of spherical particles, droplets or bubbles suspended in gaseous or liquid flows (Liu et al., 2010). Pulsed laser velocimetry (PLV) and particle image velocimetry (PIV) are used to record the position of seeding particles at two or more instances and provide information concerning the instantaneous structure of the flow field in a single plane for either gaseous or liquid phase (Coupland, 2000, Zadrazil and Markides, 2014). Laser induced fluorescence techniques rely on the use of fluorescent dyes dissolved in the working liquid to obtain film thickness information, and will be discussed in more detail in the next section.

3.1.2 Parametric requirements and CFD considerations

In terms of choosing an appropriate measurement technique to study the events occurring inside a particular duct in two-phase gas-liquid flows, there exists no ‘gold standard’ approach for the evaluation of each of the measurement techniques (Banowski et al., 2017). Each has a bespoke configuration to measure a particular parameter (i.e. film thickness, or droplet velocity, etc) and therefore cannot be universally applied to measure various parameters. Consequently, the parameters to be investigated need to be taken into consideration in order to evaluate the measurement techniques available, and hence lead to the optimum selection of a technique that fulfils the main requirements of the investigation in question.

As discussed in Section 1.3, it is in the scope of this project to study the interfacial wave structures such as waves in the falling film of a Taylor bubble in slug flow or disturbance waves in annular flow. This is to be achieved by obtaining highly detailed film thickness information in these regimes. Additionally, observations of non-periodical structures such as liquid entrainment, droplet deposition and bubble entrainment inside a pipe are to be obtained. This will allow researchers to qualitatively obtain a better understanding of the phenomenological events occurring inside the pipe, with the possibility to quantify and characterize some of these parameters. Moreover, it is important to stress that it is intended for the modellers within the MEMPHIS consortium to ultimately model the flows herein investigated. It is then required for highly detailed surface field comparisons to be achieved between experimental and computational data, which will allow for the validation of the

codes developed. This can be achieved first in a qualitative manner, which provides a first indication of the effectiveness of the code, and later on quantitatively, where the values of the different parameters that characterize the different flows will be compared. Additionally, the use of the appropriate technique can be useful throughout the calibration of the CFD models, where detailed experimental information can be used for instance in the selection of grid-density or to measure the code's ability to predict specific parameters that are of importance to the design objectives, without necessarily verifying that all the features of the flow are correctly modelled (Marvin, 1988).

3.1.3 Screening process and measurement technique selection

As can be expected, the investigation of such interactions requires a measurement technique that would allow for the tracking of both the spatial and temporal evolution of each parameter mentioned. This also includes the instantaneous measurements of local film thickness at many points along the channel with high spatial resolution (field measurements). The latter implies a small interrogation area, where there is a small distance between neighbouring points of measurement. The temporal resolution should also be high enough due to the small time of the investigated processes (Aleksenko et al., 2010). Researchers have attempted to understand the flow without such a system, and some interesting results have been deduced with relatively simple techniques, such as conductivity or high-speed video observations, which allow for measurement of velocity, frequency, spacing and lifetime of waves. However, in order to measure all the parameters discussed above and in Section 1.3, most modern experimental techniques do not fit to these requirements. For instance, most optical techniques discussed (PIV, LDV, PLV and PDA) are used in the measurement of parameters that are outside the scope of this thesis, and therefore were not taken into consideration.

Other techniques do not allow for simultaneous measurements at many points; or have low resolution (either spatial or temporal) that leads to either averaging of small-scale structures or to not capturing events whose temporal length is smaller than the technique's acquisition

frequency (Alekseenko et al., 2010). In some cases, the techniques are constrained by both factors. With regard to pointwise measurement techniques, these include ultrasound resonance and conductance probes. Although some opaque methods such as MRI, gamma-rays, X-rays and electrical capacitance tomography (ECT) provide information of the gas-liquid phases distribution across the entire cross-section of a duct (as opposed to a single point), this is achieved only over a single axial location. Therefore they also do not fulfil the requirements within the scope of this study. In terms of low spatial resolution, most opaque methods (with exception of ultrasonic resonance) have been typically used in the study of void fractions in the bubbly and slug flow regimes, where the compromise of low and/or temporal resolution associated with these methods can be accepted. Only very recently (2017), X-ray tomography has achieved a spatial resolution of 1-2 mm (Banowski et al., 2017, Bieberle et al., 2017), which is still insufficient for the scope of this study, given that for instance, the longitudinal size of ripple waves in the annular flow regime can be in the order of 2 – 3 mm. Therefore, a large amount of averaging of the signal is present in the results obtained with X-ray tomography. This applies as well to the case of conductance probes, which is the technique that has been mostly employed in the study of the film thickness in the annular flow regime, with reported spatial resolutions of 3, 5 and 6 mm for the studies of Damsohn and Prasser (2009), Sekoguchi and Mori (1997) and Belt et al. (2010) respectively.

However, due to technological advancements in high speed cameras and laser equipment, the application of laser induced fluorescence (LIF) techniques in the study of film flows has taken a more prominent role in the literature due to the higher spatial resolutions that can be achieved. For instance, Alekseenko et al. (2007) compared the results obtained through the application of the Brightness Based Laser Induced Fluorescence (BBLIF) technique (one derivative of LIF), with a spatial resolution of 0.1mm/pixel, against results obtained using conductance probes with a resolution of 3mm. It was observed that the average amplitude obtained with conductance probes for all the waves present in regimes without entrainment to be several times lower than that measured with BBLIF, due to the averaging of the signal of the lower resolution technique. The fact that LIF techniques also allow for film thickness

measurements over an area of the duct under investigation (as opposed to a single point), makes them desirable for the study of film thickness in two-phase, gas-liquid flows, and were therefore chosen for the work reported in this thesis. The principles behind the implementation of these techniques are detailed in the next section.

3.2 Brightness Based Laser Induced Fluorescence (BBLIF) and Planar Laser Induced Fluorescence (PLIF) techniques

For the reasons outlined above, a version of the laser induced fluorescence (LIF) was used in order to obtain measurements of the parameters that are in the scope of this study.

The Brightness Based Laser Induced Fluorescence (BBLIF) technique is a powerful diagnostic tool that is based on the dependence of local intensity of excited fluorescence light on the local thickness of the liquid layer. Fluorescent dye, dissolved in the liquid, is excited by an external light source (typically a laser was used by Alekseenko et al. (2012b)). Upon excitation from the laser source, the fluorescent dye present in the liquid phase absorbs the light energy and re-emits it at a different wavelength that can be recorded by a high speed camera. As a result, the amount of light re-emitted to the camera is proportional to the amount of dye present at a particular point in the pipe, which is itself proportional to the amount of liquid (i.e. film thickness) present at that same point.

The BBLIF differs from the Planar Laser Induced Fluorescence (PLIF) technique in that PLIF obtains film thickness information from a single plane based on the intensity thresholding that can be applied at gas-liquid interface upon exciting (with a laser sheet) the fluorescent dye that is dissolved in the working liquid at a right angle (or slightly smaller) from the camera. This thus represents that PLIF needs optical access from two sides, as shown in Figure 3.3.

It can be seen in Figure 3.4, the BBLIF technique only requires access from one side. PLIF uses the fluorescent dye to “tag” one of the film thickness layers, while in BBLIF, the film

thickness information is obtained based on the intensity of the light re-emitted by the fluorescent dye.

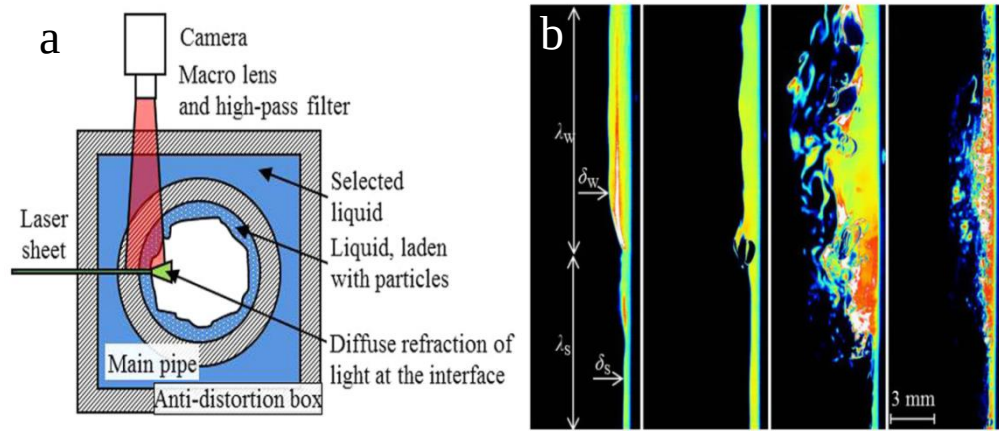


Figure 3.3: a) Schematic illustration of a typical PLIF technique setup; b) Sample of instantaneous images obtained using the PLIF technique showing how the gas-liquid interface (i.e. film thickness) can be acquired (Zadrazil et al., 2014).

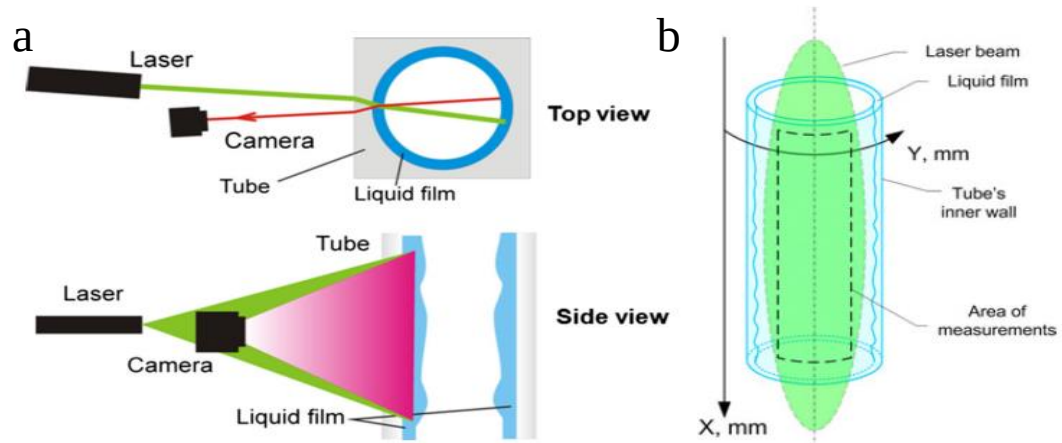


Figure 3.4: a) Schematic illustration of a typical BBLIF technique setup; b) Area of measurements and coordinate system for the three-dimensional approach (Alekseenko et al., 2012a)

These configurations mean that BBLIF allows for film thickness information to be obtained over a considerable range of both axial and longitudinal locations (volumetric configuration), which is a significant advance on PLIF. Nevertheless, both LIF techniques, as presently constructed, have some limitations. These can be in the form of limitations on the reconstruction of the gas-liquid interface in flows with high gas entrainment or an overestimation of the film thickness due to total reflection from the gas-liquid interface

(Häber et al., 2015). The former is more prone to occur when implementing PLIF, whereas the latter is associated with the BBLIF technique. This is discussed in the work of Zadrazil et al. (2016). They showed that there are potential errors in the PLIF measurement related to the presence of entrained gas bubbles within the liquid film, where in some cases, non-existing bubbles appear due to a mirror effect. Additionally, bubbles located out of the plane of the laser sheet can be visible in PLIF measurements. Both affect the overall film thickness measurement obtained.

On the other hand, there are also limitations with the application of the BBLIF technique, mainly during the investigation of annular flows, due to optical distortions that appear under the fronts of fast ripples present at the crests of disturbance waves. For points within the disturbance waves, these distortions can yield non-physical film thickness values that are in the order of several millimetres higher than the true value, as shown in Figure 3.5b. It can be seen that in some instances, values of film thickness of up to 5mm are reported in an 11.7mm pipe, meaning that a disturbance wave would be covering almost half of the pipe diameter, which is simply not the case. This is due to the total internal reflection of the exciting light under a high-slope of gas-liquid interface. This is the most significant shortcoming of the BBLIF technique, and a consequence is that characterization of the fast ripples can only be rendered as velocity and frequency parameters. In terms of its effect in the calculations of mean film thickness, or wave amplitude, this issue can be overcome by setting a threshold value above which the film thickness is considered to be non-physical, and cutting-off the film thickness values above that level. A bespoke threshold value was set for all datasets of the annular flow experimental campaign. This is discussed in more detail in Chapter 5. It is worth mentioning that in the base film and at the rear slope of the disturbance waves, Alekseenko et al. (2014) estimated that the overall error of the film thickness measurements is 5 – 6%. This is composed of a 2 – 3% error due to camera noise, in addition to another 2 – 3% error caused by non-uniformity of individual pixels after the compensation matrix, $C(x,y)$, procedure, which will be detailed later.

Therefore, given that the biggest source of uncertainty associated with the employment of BBLIF can be minimized (through means of thresholding) and the fact that it allows for the acquisition of much more detailed information on the main events and interactions occurring between both phases inside the pipe than PLIF, BBLIF was selected for the film thickness measurements reported in this thesis.

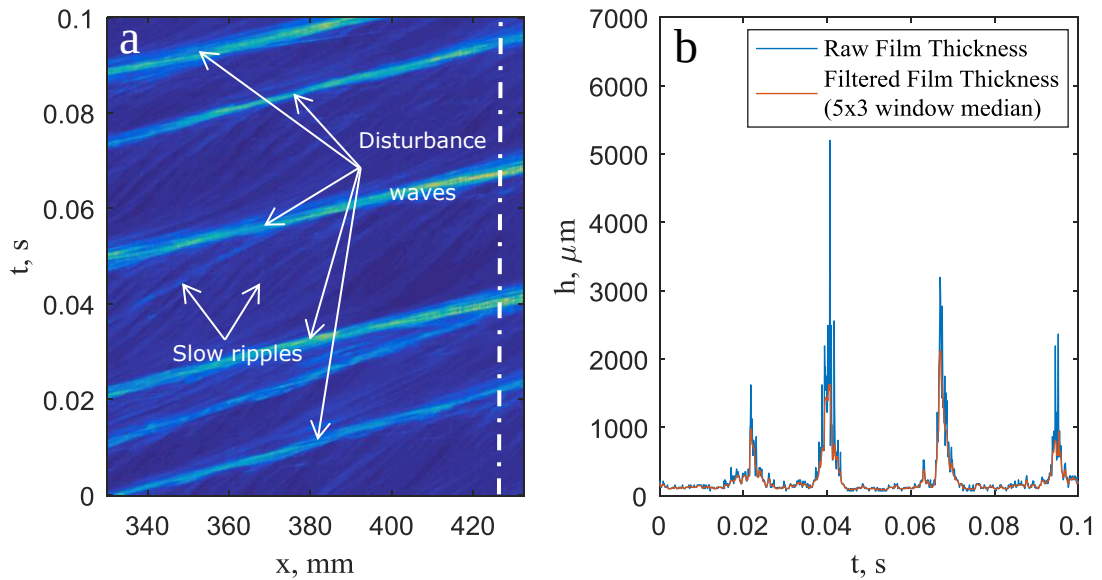


Figure 3.5: a) Example of a spatiotemporal record obtained for upwards annular flow in an 11.7mm pipe; b) Film thickness time series obtained from the dashed line in a). The overshoots in film thickness due to optical distortions that appear under the front of fast ripples are clearly seen. The blue and orange lines correspond to the instantaneous raw and filtered signal, respectively.

The basic requirements for the implementation of the BBLIF technique were: a clear pipe section (typically Perspex or glass) so that the laser light can reach the fluorescent dye in the liquid phase and consequently be re-emitted; the fluorescent dye used needs to fully dissolve in the working liquid and the working wavelength of the laser source should match the maximum wavelength in the absorption spectrum of the dissolved dye. This ensures that the maximum amount re-emitted fluorescence is obtained. Additionally, it is desirable that the clear pipe section is made with a square outside or a flat surface in order to decrease optical distortions.

The following sections will detail how the BBLIF technique was employed in the experimental campaigns reported in this thesis.

3.2.1 Details of the BBLIF technique

The local intensity of the fluorescent light recorded by the high speed camera when BBLIF is employed as in Figure 3.4b, $J(x,y)$, is exponentially related to the local film thickness, $h(x,y)$. This level of proportionality is given as follows (Alekseenko et al., 2012b):

$$J(x,y) = C(x,y) \cdot [1 - \exp(-ah(x,y))] \cdot [1 + K \cdot \exp(-ah(x,y))] + d(x,y) \quad (\text{Eq. 3.1})$$

where a is the absorption coefficient of fluorescent light; K is the reflection index at the liquid-gas interface; $C(x,y)$ is the compensation matrix, used to compensate for spatial non-uniformity of excitation light; $d(x,y)$ is the dark level of the camera. All these quantities are defined either in auxiliary experiments or during the calibration procedure for each individual experimental setup.

3.2.2.1 Calculation of the absorption coefficient, a

The absorption coefficient, a , is a function of the dye and working liquid used, and of the concentration of the dye present in the working liquid (typically around 10-15mg/l). In all the experiments conducted in this thesis, the fluorescent dye and working liquid selected were rhodamine 6G dye and water, respectively. The reason for this selection is that rhodamine 6G is soluble in water (non-reversible) and its maximum absorption wavelength is close to the range of the wavelength of the lasers employed in the experiments (527-532nm), as shall be

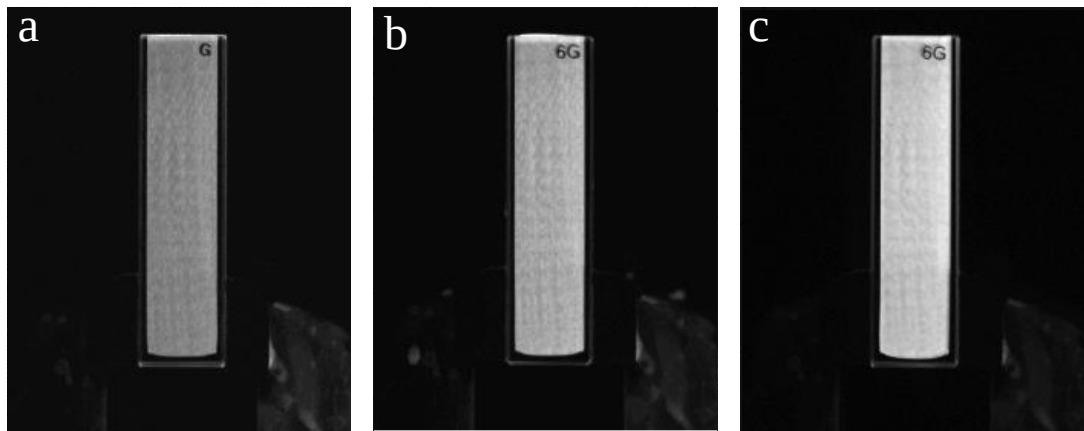


Figure 3.6: Sample images of the method employed to determine of the absorption coefficient, a , using cuvettes with different thicknesses: a) 1mm; b) 2mm; c) 5mm. As expected, higher brightness is observed as the thickness of the samples increases.

described in more detail in the subsequent sections. Additionally, although all the experimental campaigns in this thesis were performed in isothermal conditions, rhodamine 6G is thermally stable and any effect that factors such as salinity of the water have on its fluorescence are constant throughout the campaigns and taken into consideration during the determination of the absorption coefficient, a . To achieve it, cuvettes of different thicknesses are filled with a sample of the final rhodamine 6G-water solution that is to be used in the experiments. The laser light (in a volumetric configuration) is then aimed at the cuvette and a set of images are recorded using a high speed camera. This is repeated for the other two cuvettes (Figure 3.6), while ensuring that they are placed at the exactly same place as the previous one and ensuring that no property of the laser and camera system has been changed, so that direct comparison is established. The images acquired are then analysed in MATLAB, and only the section of the image in which the mixture is present inside the cuvette is taken into consideration, where a mean of the intensity recorded is taken from all the images, for all the different cuvettes. A ratio of the mean intensity values measured is then made, with the 1mm cuvette as the denominator and a plot of the intensity ratio against cuvette thickness is made. The data is then compared with a best fit relationship using a re-arranged Equation 3.1 (see Appendix A), from which the absorption coefficient, a , is determined, as shown in Figure 3.7.

This procedure should be repeated twice a day, as the absorption coefficient can change slightly over time, due to factors such as evaporation or leakages.

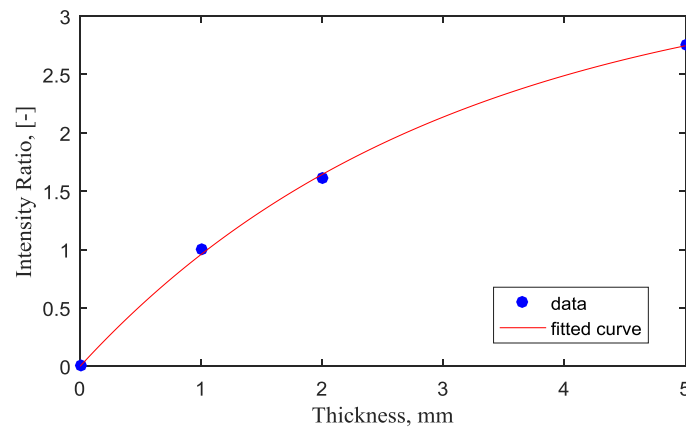


Figure 3.7: Determination of the absorption coefficient, a , based on the results obtained in cuvette experiment illustrated in Figure 3.6.

3.2.2.2 Determination of the reflection index, K

The reflection index at the gas-liquid interface was determined using the Fresnel equations, which describe the behaviour of light when moving between media of different refractive indices. For all the experimental campaigns, water ($n_1 = 1.33$) and air ($n_2 = 1$) flows were investigated, where there was a normal angle of incidence between the laser light and the reflected light emitted by the fluorescent dye dissolved in the liquid phase upon excitation. For such case, the reflection index is given by the following Fresnel equation:

$$K = \left| \frac{n_1 - n_2}{n_1 + n_2} \right|^2 \quad (\text{Eq. 3.2})$$

This resulted in a K of 2% for all the experimental campaigns in this thesis.

3.2.2.3 Determination of the compensation matrix, $C(x, y)$

The compensation matrix, $C(x, y)$, is required to be measured in order to compensate for spatial non-uniformity of excitation light, since the laser beam intensity is higher in the centre than at its edges. The method involves obtaining time-averaged brightness of fluorescence, $\langle J(x, y) \rangle$, emitted by a reference flow whose time-averaged film thickness, $\langle h_0 \rangle$, is known in the area of the pipe where film thickness measurements are to be obtained. Equation 3.1 is then re-arranged (see Appendix A) in order to obtain the only unknown, $C(x, y)$. Each individual experiment in this thesis required a bespoke solution for the reference flow in question. Therefore, more details on how the compensation matrix has been measured will be provided during the explanation of each individual experimental arrangement.

3.2.2.4 Determination of the dark level, $d(x, y)$

The dark level, $d(x, y)$, is defined as the level of brightness at the darkest (black) part of a visual image or the level of brightness at which no light is emitted from a screen, resulting in a pure black screen. If the black level is not correctly adjusted, visual information in the recorded signal could be displayed as black, or black information could be displayed as above black information (gray). In order to take it into consideration, a long record is obtained when

the aperture of the camera is at its minimum and then the average intensity matrix of this record is subtracted from every single image recorded during normal experiments.

3.2.2.5 Optical distortions and limitations of BBLIF

Figure 3.8a shows the top view of the working section and the notation of the angles characterizing the passage of the optical beam from the inner surface of the tube to the camera. Here, α denotes the circumferential coordinate of the point investigated, θ denotes the entering angle of the optical beam into the camera, L is the distance from the camera lens to the outer surface of the tube, S is the shortest distance between the inner and outer surfaces of the tube, and R is the tube radius. The small angles approximation for θ as a function of α is as follows:

$$\theta = \frac{R \sin \alpha}{L + \frac{n_1}{n_2} (S + R(1 - \cos \alpha))} \quad (\text{Eq. 3.3})$$

Here, n_1 and n_2 are the refraction indexes of air ($n_1 = 1$) and Plexiglas ($n_2 = 1.47$) respectively. The number of camera pixels which registered the image of the regarded points depends linearly on θ .

Figure 3.8b shows the dependence of θ on α . One can see that this dependence is very close to linear over the range of $-45^\circ < \alpha < 45^\circ$. This range limits the circumferential size

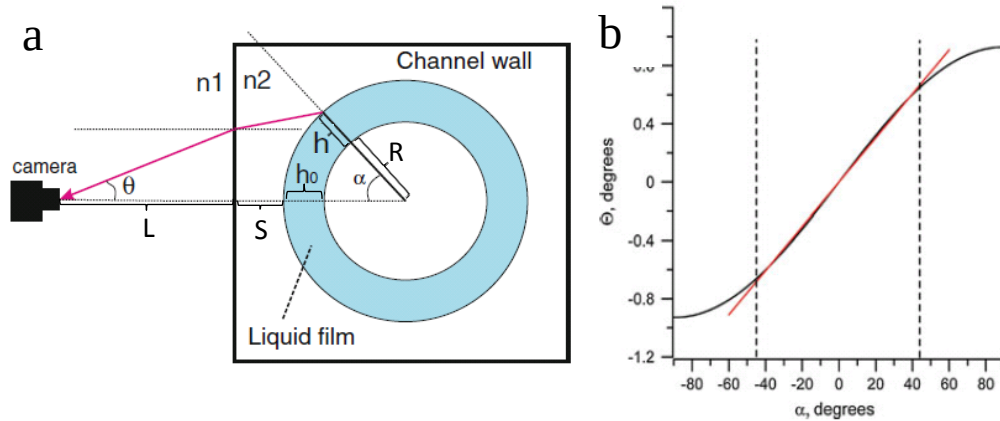


Figure 3.8: a) Passage of the optical beam from the inner surface of the tube to the camera. b) Calculation of the circumferential optical distortion (Alekseenko et al., 2012a).

of area of measurements in the experiments. Thus, the circumferential size of the area of measurements is equal to one-fourth of the tube perimeter.

When the optical beam passes angularly through the liquid film, the measured film thickness is overestimated by the BBLIF technique (Figure 3.9). This overestimation can also be calculated. The ratio of the film thickness measured by the camera (h) to the real film thickness (h_0) depends on θ and α as follows:

$$\frac{h}{h_0} = \frac{1}{\cos(\arcsin(\frac{n_2}{n_3} \sin(\alpha + \frac{n_1}{n_2} \theta)))} \quad (\text{Eq. 3.4})$$

Here, n_3 is the refractive index of the working liquid. Figure 3.9 shows this dependence. It can be seen that, in the working area, the ratio h/h_0 is not greater than 1.6. At the same time, since the calibration procedure of the compensation matrix is made in situ, this overestimation is expected to be partially compensated because the reference signal is expected to be distorted in some way.

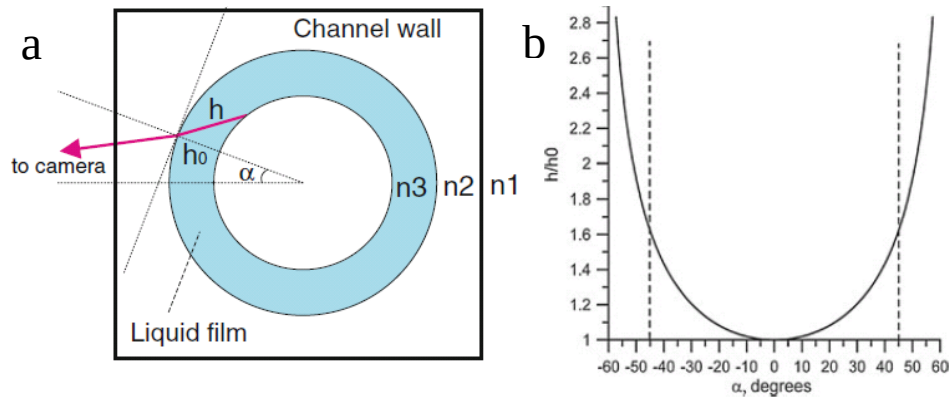


Figure 3.9: Angular passage of the optical beam through the liquid film. b) Calculation of the overestimation of the film thickness (Aleksenko et al., 2012a)

3.2.2.6 Analysis of BBLIF results

The application and analysis of the results obtained through the BBLIF technique can be done in two different ways: through 3D and 2D-approaches. In all the different experimental arrangements employed in this thesis (further described in Section 3.3), results were obtained while employing a 3D-approach. In this approach, the laser beam is scattered over a wide area of the tube's inner surface (volumetric), with results recorded by a high speed camera over the limited $-45^\circ < \alpha < 45^\circ$ range mentioned above. This provides the possibility to observe with a high level of both temporal and spatial detail phenomenological events and the structures associated with a given flow regime. For instance, Figure 3.10 shows the

application of the 3D-approach in a rectangular duct. All the main properties of the fast ripples for instance (length, width, velocity, curvature), can be subsequently measured from a sequence of these images. Figures 3.11-3.13 show some of droplet entrainment mechanisms that can be now observed with great detail using the 3D-approach of the BBLIF technique.

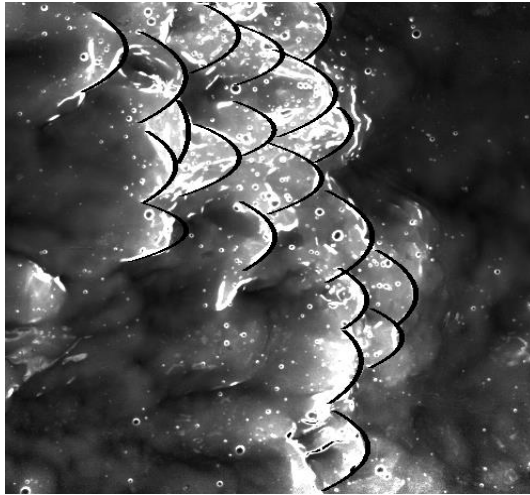


Figure 3.10: Application of the 3D-approach in a gas sheared liquid film in a rectangular duct (Cherdantsev et al. 2014).

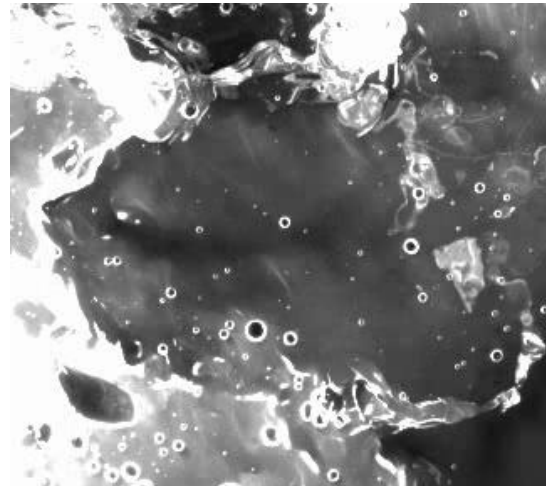


Figure 3.11: Bag break-up (Cherdantsev et al. 2014).

Figure 3.11 shows an example of bag break-up of a ripple wave occurring at a crest of a disturbance wave. Bag break-up occurs due to stretching the whole front of a fast ripple into a liquid bag, consisting of a thin liquid sheet surrounded by thick rim. Both sheet and rim are torn into droplets.

Figure 3.12 shows an example of a ligament break-up, which occurs at the junctions between the two fast ripples located near the crest of a disturbance wave. A liquid ligament can reach up to 10 mm length and 1 mm width. The probability of ligament break-up is expected to increase with gas velocity because of the increasing number of junctions.

A feature that had not been widely reported before the implementation of the BBLIF technique in the study of gas-liquid interfacial flows is the phenomenon of secondary entrainment as shown in Figure 3.13. It occurs due to impacts of entrained droplets back onto the film. A cavern with a highly asymmetric rim is created by the impact, and the rim can be torn into droplets.

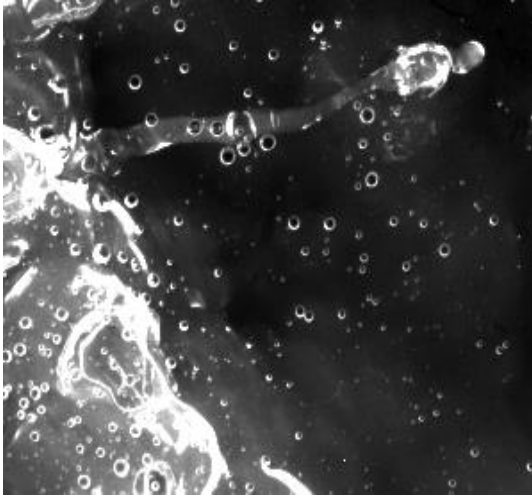


Figure 3.12: Ligament break-up (Cherdantsev et al. 2014).

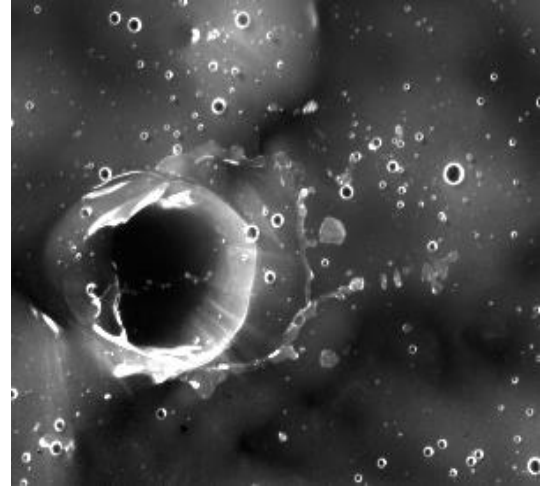


Figure 3.13: Secondary break-up (Cherdantsev et al. 2014).

The examples above provide a flavour of the high level of detail that a visual technique such as BBLIF can provide in terms of qualitative information about what is occurring inside a duct, which is not achievable with the other measuring methods described above. This will prove of significant importance in Chapter 4, where though the observation of the videos recorded during the Stationary Taylor Bubble experiment, different entrainment mechanisms from the Taylor Bubble into the wake region will be identified. Furthermore, although laborious, BBLIF allows to some extent for the extraction of quantitative information out of these qualitative observations, as shown for example in Figure 3.10, where the curvature of the ripples present in the film can be measured.

The main feature of BBLIF is however the reliability of the film thickness measurements, which is the main focus of this thesis, since it focuses on studying and characterizing the structures inherent to different interfacial flow regimes. In order to do so, the film thickness results obtained with the BBLIF will be analysed in a 2D-approach. This is achieved through the construction of spatiotemporal records of the film thickness, $h(x,t)$. A spatiotemporal record is obtained by taking the central portion of each re-constructed image and stacking them together, thus showing the temporal evolution of the film thickness along the axial coordinate, as shown in Figure 3.14.

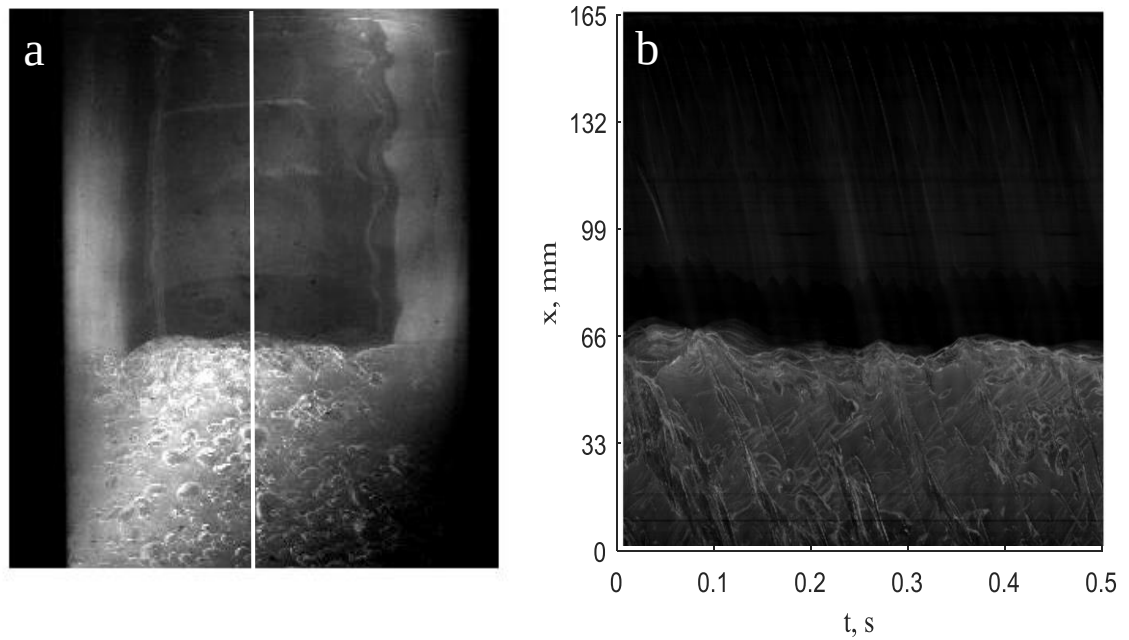


Figure 3.14: Example of the implementation of the 2D-approach to the analysis of results: a) Single film thickness re-constructed image; b) Spatiotemporal plot obtained from central portion of all images as denoted by the white line in a).

The fact that it is the central portion that is taken thus overcomes the extra problem of having to take into consideration the overestimation of the film thickness that is inherent to the BBLIF technique if the spatiotemporal plots are constructed from another longitudinal position within the $-45^\circ < \alpha < 45^\circ$ range. As discussed previously, the brightness of each pixel is directly proportional to the local film thickness. The spatiotemporal plots are therefore a visual display of film thickness temporal records at a wide range of axial locations, which again, is one of the main advantages of the BBLIF technique over pointwise measurement techniques. An important feature of such plots is that it allows not only for qualitative observations, but also for quantitative analysis to be made, such as cross-correlation and Fast Fourier analysis to be performed. These will be described in more detail in Section 3.4.

In summary, the advantages of employing this technique are:

- Non-intrusive technique, therefore, it does not affect the flow behaviour;
- Field measurements of local film thickness can be resolved in both longitudinal and transverse coordinates and in time;
- High spatial resolution: up to $40\ \mu\text{m}$ per pixel and better;
- High sampling frequency: up to 10 kHz and higher;

- Ability to study liquid droplets entrained into the gas core;
- Ability to study gas bubbles entrapped by liquid film;
- It is possible to study droplets and bubbles simultaneously with waves of various types;
- Applicable to any film flow in transparent ducts.

The following subsections will describe in detail the different experimental setups in which the BBLIF technique was employed, together with the different data processing procedures that were applied in the analysis of the data acquired. For all the experiments, the images were recorded in 8-bit format, thus meaning that there are 256 levels of intensity that can be recorded per pixel. The average amplitude of the waves (and therefore, the maximum brightness of the emitted fluorescent light) depends on the flow parameters tested. In order to achieve an optimum correspondence between the brightness of the fluorescent light and the dynamic range of the camera, the exposure time was varied between 5 – 10 μs depending on the flow parameters for all the subsequent experiments.

3.3 Experimental arrangements

This section reports on the experimental arrangements employed in the study of the slug (stationary Taylor bubble experiment) and annular (upwards and downwards annular flow experiment) flow regimes. This will include details on the experimental apparatus employed for each campaign, in addition to descriptions of how the BBLIF technique was set up to obtain film thickness measurements. The choice of flow conditions for the stationary Taylor bubble experiment was such that both conventional and unconventional slug flow conditions were replicated. The reason for the latter is that it allowed for entrainment events to be more easily identified, as shall be seen in Chapter 4. With regards to the upwards and downwards annular flow experiment, the flow conditions chosen were such that direct comparison could be made with the work of Sekoguchi et al. (1985), as will be detailed in the following subsections.

3.3.1 Stationary Taylor bubble experiment

As discussed in Chapter 1, a study of the waves present in the falling film surrounding a Taylor bubble was to be made. It was intended to observe how the dynamics of these waves affected the entrainment events between the Taylor bubble into the wake region. In order to achieve that, a specially designed apparatus to generate a stationary Taylor bubble was used. The following sections show how this study was achieved.

3.3.1.1 Flow loop

To generate a stationary Taylor bubble, a closed liquid circuit and an open gas circuit, as shown schematically in Figure 3.15 were employed. This rig, the so-called ‘Held down Taylor bubble facility’, had been previously been used by Abdulahi (2013). The experimental system allowed investigations of liquid flow rates ranging from 0.537-1.013 litres/second and for gas flow rates from 0-10 litres/minute. Water was used as the liquid and was maintained at $22\pm0.5^\circ\text{C}$, while the gas used was air taken from the laboratory compressed air supply.

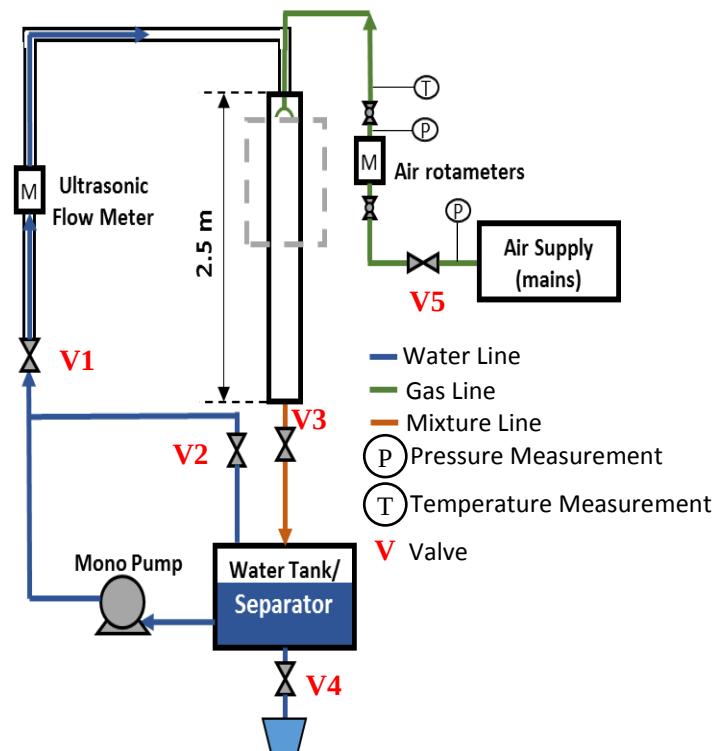


Figure 3.15: Schematic of the Held Down Taylor Bubble facility.

The liquid flow is driven by an adjustable progressive cavity pump whose rotation speed can be controlled manually to achieve a desired flow rate. To select the liquid flow rate, a series of valves are used in conjunction with the pump controls with a bypass circuit incorporated into the system to provide finer control on the flowrate adjustment. The liquid flow measurement was achieved via a turbine flowmeter, whereas the gas flow measurement was achieved via a variable area flowmeter. Details on the accuracy of the metering equipment can be found in Appendix C.

The testing section is made of perspex pipe, primarily to allow visibility of fluid flow, with an internal diameter of 67mm, a wall thickness of 5mm and a length of 2.5m. The diameter of this rig was selected so that there is a possibility of comparing the results obtained from this rig with ones obtained in conventional slug flow experimental campaigns conducted in other rigs within the Multiphase Flow Group at the University of Nottingham, which have the same pipe diameter. However, this is not the objective of this study. At the bottom of the testing section there is a valve to provide a facility to prime the equipment to a fully flooded condition. After passing through the test section, the two-phase mixture was fed to a large separator vessel. The separation of gas from the liquid was enhanced through the presence of baffles, as well as fine and coarse meshes in the tank. The latter also helped in sieving from the liquid any impurity that may be present in the flow loop.

The gas system is an open system with the injection into the testing section shown in more detail in Figure 3.16. Upstream of the injection point, there are pressure regulation points and a rotameter to measure the gas flow rate. The gas injection was delivered by a narrow tube of inner diameter 7mm and outer diameter of 10mm, which includes a collar around the injection pipe to provide flow straightening of the liquid flow upstream of the gas entry point.

3.3.1.2 The injection method

Special attention has been paid to mimic the shape of the elongated bubble nose and the relative velocities of the liquid and the elongated bubble in slug flow (Brauner and Ullmann, 2004). As a result, air was injected in the testing section through a hemispherical cap, which is shown in Figure 3.16. The spherical cap was machined from Perspex material with a base diameter of 50.25mm and a wall thickness of 5mm, as shown in Figure 3.16b). This was shaped in order to simulate the nose of a theoretical Taylor bubble, as defined by Dumitrescu (1943).

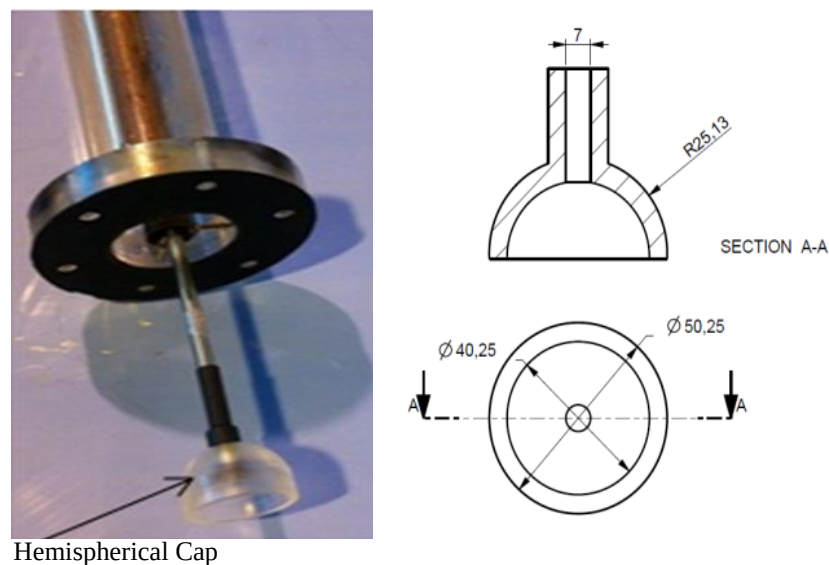


Figure 3.16: Display of hemispherical cap employed.
a) Hemispherical cap; b) Diagram of hemispherical cap.

3.3.1.3 Experimental procedure

After switching on the pump, the bypass valve is shut so that liquid filled up the riser. The pump was then adjusted until the desired liquid flowrate was achieved on the liquid flowmeter. The liquid was allowed to rise within the test section up to a level near the position where the nose of the bubble was formed. This was made possible through a valve located at about 2.9m below the down comer which helped to cause a restriction to flow. With this restriction, liquid built up to a level near the cap or the injection points, which formed a liquid column. Air was then introduced at this point, resulting in the growth of the artificial bubble. Unlike former stationary bubble studies, where the bubble was allowed to grow in proportion to the amount of air being injected into the system, in this study, the size of the bubble was

controlled so that its size was nearly the same for all flow conditions, in order to allow for direct comparison. This was achieved by constantly adjusting the valve V3 until the bubble became stabilised, which took several minutes. By doing so, back pressure was induced into the system, which was taken into account by allowing for some of the liquid to go through a relief channel located at the top of the testing section. The liquid flowrate going through the relief channel was measured so that the absolute downward liquid velocity going into the testing section was obtained. Through this configuration, it is possible to vary the liquid flowrates to be tested. However, it is important to consider which flow conditions truly represent a typical slug flow condition and how these translate into our artificial case. This is mainly dictated by the minimum velocity at which a Taylor bubble is physically encountered inside a pipe, i.e., the velocity of a bubble moving through a stagnant liquid column as described by Equation 2.30. For a 67 mm pipe, this corresponds to a $U_{TB} = U_0$ of 0.284 m/s. To relate the artificial bubble condition with a true slug flow condition, Delfos et al. (2001b) uses a Taylor bubble Froude number that relates the liquid superficial velocity used in the artificial experiment, U_{SL} , and the minimum Taylor bubble velocity, and this will be used in this study:

$$Fr_{TB} = U_{SL}/U_0 \quad (\text{Eq. 3.5})$$

$Fr_{TB} = 1$ represents the situation where a Taylor bubble moving through a stagnant column is being simulated, whereas $Fr_{TB} > 1$ represents co-flowing slug flow conditions. It can be seen from Table 3.1 that in this study, unlike in previous literature, slug flow conditions that would not be physically encountered in conventional slug flow (i.e. $Fr_{TB} < 1$) were tested. The reason for this is that it was observed that at the highest liquid flowrate tested in this study ($Fr_{TB} = 1$), the level of entrainment was very high, and the entrainment events being quite chaotic. By simulating slower (despite them being unphysical) Taylor bubbles, it allowed for the observation of the gradual evolution of the different mechanisms that are at play during the entrainment events, which will be reported later. As a result, the case where co-flowing slug flow exists was not simulated in this study, as it was in previous literature. Furthermore,

for each individual liquid flowrate seen in Table 3.1, measurements with the BBLIF technique were carried out while varying the gas flowrate injected into the system from 0-10 l/m in 2 l/m increments.

Table 3.1: Liquid flow experimental conditions tested in this study and in previous relevant literature.

This study		(Delfos et al., 2001b)		(Riiser et al., 1992)		(Bacon et al., 1995)	
$U_{SL}(\text{m/s})$	Fr_{TB}	$U_{SL}(\text{m/s})$	Fr_{TB}	$U_{SL}(\text{m/s})$	Fr_{TB}	$U_{SL}(\text{m/s})$	Fr_{TB}
0.152	0.536	0.342	1.000	0.200	0.820	0.520	2.000
0.186	0.654	0.409	1.200	0.430	1.770	0.720	2.800
0.219	0.772	0.478	1.400	0.500	2.050	0.830	3.200
0.253	0.890					0.930	3.600
0.287	1.012						

3.3.1.4 Brightness Based Laser Induced Fluorescence technique setup

In this experiment, rhodamine-6G (orange dye) was used as the fluorescent dye with a concentration of 10 mg of dye per litre of water in the system. With this concentration, the physical properties of the solution are identical to the properties of water (Alekseenko et al., 2008). A viewing box with a square outside was used to decrease optical distortions. The box was filled with a glycerol-water solution to match the refractive index of Perspex.

A laser system, model LYD 302-PIV from Litron Lasers, which consists of a pair of Nd:YLF pulsed green lasers with a wavelength of 527 nm and maximum energy of 150mJ was used as the light source for this study. Since the entire Taylor Bubble was under the scope of this study, the laser beam was converted into a divergent beam with elliptic cross-section and aimed at the region of interest through the use of lenses (3D-approach).

The fluorescent light was recorded by a Dantec Dynamics Phantom camera with a reduced region of interest of 600x1280 pixels to match the shape of the pipe. The camera was aimed at the region of measurements with the focus on the nearest inner wall of the channel. The distance from the camera lens to the channel wall was 400 mm. The camera was equipped with a high-pass orange filter (cut-off wavelength of 550 nm), since rhodamine-6G emits fluorescent light with a maximum in the yellow-orange spectral domain (550-560 nm) and this light needs to be distinguished from the laser beam light. The high-pass filter was attached to the camera lens, a Nikon Makro-Planar 2/50 ZF model. The axes of the camera

and the laser head were placed on the same alignment, but at an angle to each other on the vertical plane, with the laser head positioned underneath the camera, as seen in Figure 3.17. Through the procedure described in Section 3.2.2.1, the absorption coefficient, a , was measured, and varied between 0.48 and 0.5 throughout the experimental campaign. The BBLIF results were acquired with a temporal resolution of 2 kHz during 2 seconds for each dataset.

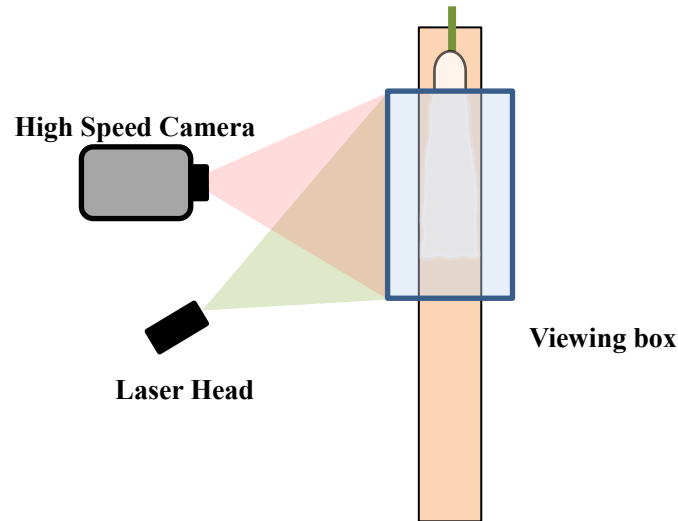


Figure 3.17: Laser and camera setup for the stationary Taylor bubble experimental

3.3.1.5 Calibration for the BBLIF technique

To create the compensation matrix, $C(x,y)$, Alekseenko et al. (2012a) used a thin gravity-driven film as a reference signal, where the average thickness is well described by the Nusselt solution (Nusselt, 1916) of the Navier-Stokes equations for flows with a laminar waveless liquid film. This procedure is inapplicable to the present case for two reasons. First, the liquid Reynolds numbers tested in this study are in the turbulent region, where waves are present in the film and therefore the Nusselt solution does not work properly. Secondly, given the fact that the falling film profile in this type of artificial simulation of slug flow changes significantly with downstream distance, it is therefore not comparable to the case of a thin gravity-driven film. Thus, a different approach was used. For each set of flow parameters tested, additional experiments were performed with recordings of the area of interrogation under white backlit illumination acquired with a sampling frequency of 200 Hz during 5 seconds. As shown in Figure 3.18a), the film thickness profile can be observed in such

images. To find the position of the interface, the *Canny* method of edge detection was applied in MATLAB to the images. This method marks the points of maximum gradient of brightness of the image, as shown in Figure 3.18b).

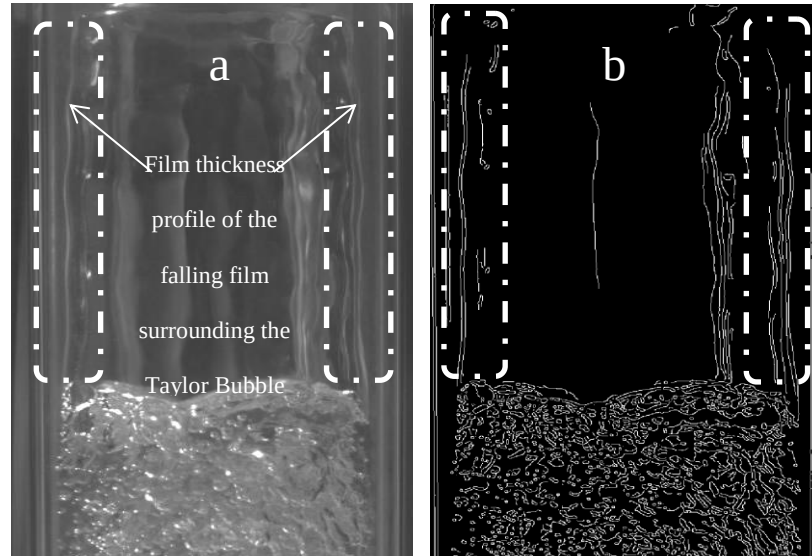


Figure 3.18: a) Sample image of the recordings made for the construction of the $C(x,y)$ matrix at $U_{SL}=0.287$ m/s ($Fr_{TB}=1$) and gas volumetric flow rate of 10 l/m; b) Application of the Canny filter to a).

Inside the areas marked by the dashed rectangles, the lines, corresponding to the inner wall of the pipe and the interface were found using the function *bwlabel* in MATLAB (Figure 3.19a). The interface was identified as the line closest to the wall. The reference film thickness, h_0 , was estimated by time-averaging the distance between the two lines (Figure 3.19b). Similar methods of film thickness identification were applied by Hewitt et al. (1990) and Pan et al. (2015). The implementation of this methodology can be seen in Appendix A.

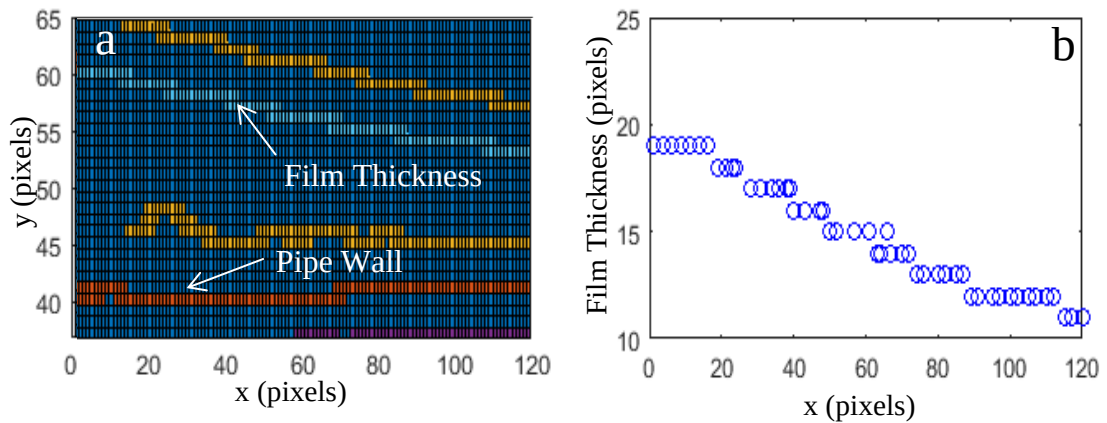


Figure 3.19: Line Detection Stages. a) Labelling of the lines from one of the white sections of Figure 3.18b); b) True film thickness line detected by the code from a).

The spatial resolution of the data recorded for both the experimental results and calibration images varied between 0.15 to 0.165 mm/pixel.

Finally, the non-uniformity of the laser light is removed by constructing $C(x, y)$ during the experiments with the laser beam as:

$$C(x, y) = \frac{\langle J(x, y) \rangle - d(x, y)}{(1 - e^{\alpha \langle h_0 \rangle})(1 + Ke^{\alpha \langle h_0 \rangle})} \quad (\text{Eq. 3.6})$$

The time-averaged brightness, $\langle J(x, y) \rangle$, of the reference signal was recorded with the laser as a light source for the same conditions tested under white backlit illumination in the same area of interrogation. Equation 3.6 was substituted into Equation 3.1, which was ultimately solved to express $h(x, y)$.

The results and the discussion of the results obtained is given in Chapter 4.

3.3.2 Upwards and downwards annular flow experiment

In order to study the effect that the flow orientation has on the behaviour of disturbance waves in vertical gas-liquid annular flows, both upwards and downwards adiabatic air-water annular flows were studied in an 11.7 mm internal diameter acrylic resin pipe, which allows for comparison of the results obtained from the work of Sekoguchi et al. (1985), which covered the same pipe diameter and flowrates tested in upwards annular flow. This experiment was conducted at the Kutateladze Institute of Thermophysics in Novosibirsk, Russia, as part of a collaboration between both universities, which was supported by grant awarded from the Royal Society.

3.3.2.1 Experimental apparatus and procedure

For direct comparison of the effects of flow orientation, the same flow parameters were tested for both experiments, with the Reynolds number, Re_L for the liquid varying from 140 – 400. Here, Re_L is defined based on the liquid flowrate, Q_L , divided by the kinematic viscosity, ν , multiplied by the perimeter, πD , thus being four times smaller than the liquid Reynolds number constructed using the liquid superficial velocity:

$$Re_L = \frac{Q_L}{\pi D v} \quad (\text{Eq. 3.7})$$

The reason for the use of the liquid Reynolds number as described in Equation 3.7, is that it is more representative of the amount of liquid travelling along the walls of the pipe. The range of gas superficial gas velocities tested, V_G , was 22 – 57 m/s and calculated as follows:

$$V_G = \frac{4Q_G}{\pi D^2} \quad (\text{Eq. 3.8})$$

The impact that the flow orientation has on the behaviour of disturbance waves, once these are close to a fully developed condition, was not the sole interest of this study. Additionally, it was also in the scope of the study to see how the flow evolves with axial location, from the point where both phases merge in the pipe, up to a more developed stage. As a result, due to the versatility of the BBLIF technique, film thickness measurements were carried out at different axial locations covering a measurement area with very high spatial and temporal resolution. These comprise of measurements performed close to the inlet section (between 0 - 121 mm or 0 - 10D), and also between 330 – 430 mm (between 28 to 37D), where the flow is considered to be close to fully developed, as shall be demonstrated in Chapter 5.

In order to perform the annular flow experiments in a 11.7mm pipe, the setup shown in Figure 3.20 was employed:

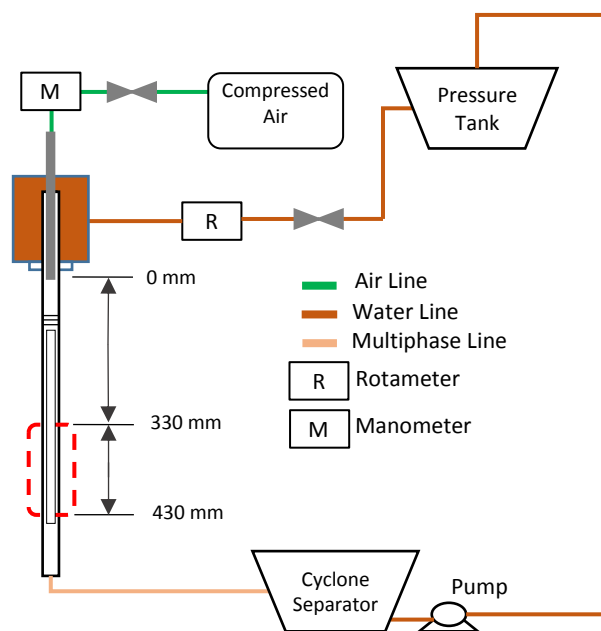


Figure 3.20: Diagram of experimental setup in upwards configuration.

Gas from the mains is first introduced into the test section through a concentric metal tube with an internal diameter of 10.1 mm and wall thickness of 0.3mm. A manometer was used in order to select the desired flowrate, which could be adjusted using a valve, V1. The liquid was driven from the water tank into the mixing section under gravity, and entered the test section through the 0.5mm ring slot between both the test section and the concentric metal pipes. The liquid flowrate was measured with a rotameter and adjusted again using a valve, V2. Details on the accuracy of the metering equipment is given in Appendix C. Through this configuration, it was ensured that an annular flow was more easily generated. The multiphase mixture was then outputted into the slump/separator tank. Before starting the experimental campaign, it was ensured that the water was then pumped into the water tank placed 2.5m above the ground level so that a more uniform flow was achieved. In order to test annular flow conditions in an upwards configuration, both the testing and mixing section were rotated 180° and the same procedure described above was repeated.

3.3.2.2 *Brightness Based Laser Induced Fluorescence technique setup*

In order to implement the BBLIF technique, rhodamine 6G was added to the liquid phase at a concentration of 15 mg/l. A continuous 3W laser with a wavelength of 532 nm was used in volumetric mode (3D approach). The dye concentration used was slightly higher than in the Stationary Taylor bubble Experiment to take into account the lower power of the laser used in this experimental campaign. This ensured that an appropriate amount of fluorescence for BBLIF measurements was achieved. A high-speed Photron FASTCAM camera equipped with a 550 nm cut-off wavelength orange filter was used to record the fluorescent light reemitted by the dye upon being excited by the laser light, as shown in Figure 3.21.

The outer surface of the test section was polished to make it flat in order to reduce optical distortions. The temporal resolution for both experiments was 10 kHz, with 1 and 2 second records for each dataset obtained for upwards and downwards flow respectively. For both experiments, this study will report on the results obtained by analysing the local film

thickness in a 2D approach, with spatial resolutions ranging from 0.1 to 0.45 mm/pixel for upwards and downward flow experiments respectively (both with a 110x1024 pixels matrix).

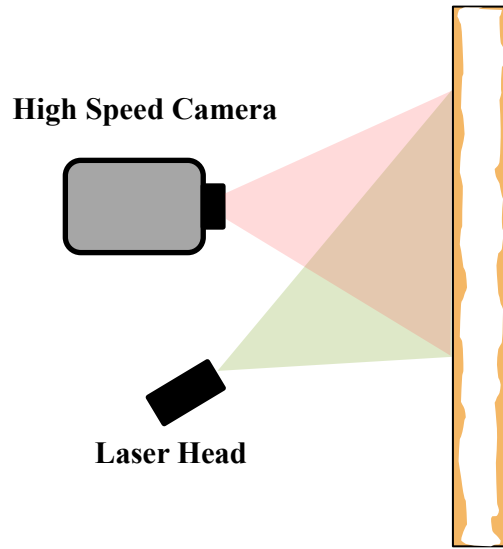


Figure 3.21: Implementation of the BBLIF technique in this study's annular flow configuration, where the outer wall of the test section was polished to reduce optical distortions.

3.3.2.3 Calibration for the BBLIF technique

As discussed in Section 3.3.1.5, the compensation matrix, $C(x,y)$, has been typically constructed by inducing a thin-gravity driven film flow configuration into the test section as a reference signal, in which the average thickness is well described by the Nusselt solution. The same approach was taken for downwards flow, where a thin liquid film with $Re_L=40$ flowing under gravitational action in the absence of gas flow (so-called 'falling film flow') was present. This corresponded to an average film thickness, $\langle h_0 \rangle$, of $98 \mu m$. For the upwards flow, it is impossible to organise such a configuration. Still, the reference matrix is necessary, since it cannot be guaranteed that the local illumination remains the same after turning the working section upside down and re-adjusting the optical system. To create a reference signal in such a case, it was assumed that the flow of a very thin liquid film under very strong gas shearing action is insensitive to the flow orientation. This assumption is supported by observations of Alekseenko et al. (2013), who studied the spectral structure of thin gas-sheared liquid films in downwards annular flows without entrainment. They have noticed that for high enough V_G , the power spectra of film thickness records showed strong similarity at

very different gas velocities. The deviations from the observed universal shape were detected at low gas velocities and were attributed to the influence of gravity. The region of self-similarity for water starts at $V_G > 27$ m/s. Thus, the flow of a thin liquid film with $Re_L=40$ and $V_G=36$ m/s was used as a reference signal for the upwards flow. The value of average film thickness, $\langle h_0 \rangle$, was taken from the BBLIF measurements conducted in downwards flow for the same Re_L and V_G . Images were recorded with the laser light at these flow configurations in order to obtain $\langle J(x,y) \rangle$. Like in the Taylor bubble experiment, $\langle J(x,y) \rangle$ and $\langle h_0 \rangle$ were inserted into Equation 3.6 to estimate the compensation matrix, $C(x,y)$, which was then substituted into Equation 3.1, to ultimately be solved to express $h(x,y)$. Again, as described in Section 3.2.2.1, the absorption coefficient, a , was measured, and varied between 0.55 and 0.63 throughout the experimental campaign. The results and the discussion of the results obtained from this experimental campaign will be provided in Chapter 5.

3.4 Data analysis and treatment

As already discussed in Section 3.2, the analysis of the film thickness data was done using a 2D-approach, through the creation of the spatiotemporal plots for each data set, which was demonstrated in Figure 3.14. All the data acquired was analysed using MATLAB. Before using the spatiotemporal plots to obtain parameters such as mean film thickness, wave velocity and wave frequency, all the plots were smoothed using a median with a 5 by 3 window. This limited the shot noise from the camera, without averaging any structure displayed in the spatiotemporal plots, as seen in Figure 3.5b.

The next subsections will describe the different tools and procedures used in order to obtain the parameters described above, with the MATLAB codes written for their implementation available in Appendix B. Additionally, the uncertainties associated with the different tools and procedures reported in the next subsections are detailed in Appendix C.

3.4.1 Application of the cross-correlation to the film thickness time series

This section will describe how the speed of the structures present in the film were obtained, these being the speed of gravity waves present on the falling film surrounding a Taylor bubble, or the speeds of the disturbance waves present in the annular flow regime. For this to be achieved, time series records ($a = x$ and $b = x + dx$) for each position in the x coordinate of the spatiotemporal plots were cross correlated, which is characterised by the following equation:

$$R_{ab}(\tau) = \alpha R_{aa}(\tau_t - \tau_0) \quad (\text{Eq. 3.9})$$

Where $R_{ab}(\tau)$ is the autocorrelation function, $R_{aa}(\tau)$, displaced by the time delay, τ_0 , and multiplied by the attenuation factor, α_t . The peak value of $R_{ab}(\tau)$ occurs at $\tau_t = \tau_0$. The output of this analysis is the average streamwise wave velocity at the location between the two selected time series. An example of this in action is shown by Figure 3.22a:

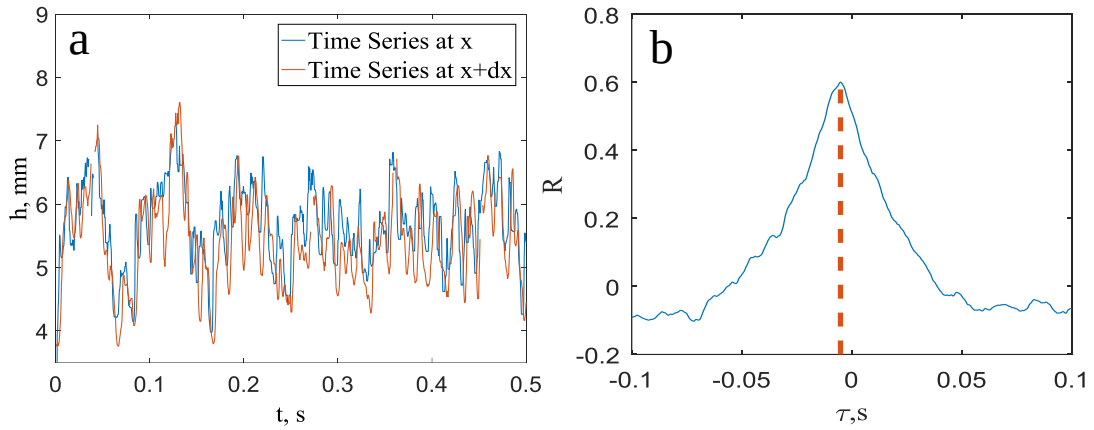


Figure 3.22: Example showing time series separated by a known distance that are to be cross-correlated; b) Example of the time delay obtained from the cross-correlation function, where the peak is clearly recognizable.

As can be seen from Figure 3.22a, there is some delay between both upstream and downstream time series, and the computation of the cross-correlation function is based on this time delay. It is assumed the signals are stationary and ergodic, or in other words, that the collected ensemble (time series) is representative of all the random data generated from the system, and that it is not going to change later in time. This is achieved using the function *xcorr* in MATLAB. Since the distance between both time series is known, the average structural speed at that particular point in the x coordinate is obtained by dividing that distance by the maximum lag time obtained from the cross-correlation function (see Figure 3.22b). More specifically, for all the points in the x coordinate, time series that were 25 pixels apart from this point were selected, whose correspondent time series were divided into four parts. The cross correlation was done between each corresponding record segment. Finally, this step was repeated for 11 pixels (± 5 pixels from the initial point). This was done since such pixel distance is very small (it varies slightly depending on the spatial resolution of a given experimental campaign) in reality from the initial point (Figure 3.23). In the end, 44 values of average structure velocity for essentially one particular position were obtained, from which the median value was taken. This was employed in order to increase the reliability of the measurement and reduce any noise present in the calculation. Furthermore, this was performed for all the data sets of all the experimental campaigns described in the previous sections.

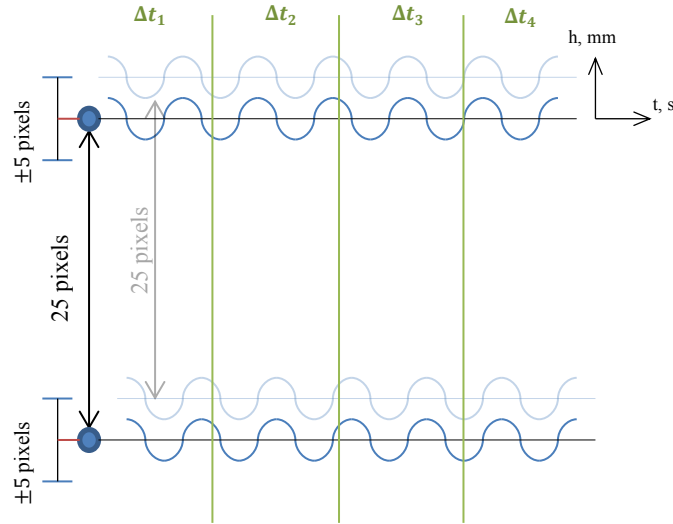


Figure: 3.23: Diagram illustrating the methodology behind the application of the cross-correlation function to two consecutive film thickness time series for higher reliability of wave velocity measurements.

3.4.2 Frequency and power spectral density

An important parameter that can be measured from the spatiotemporal plots is the power spectral density (PSD) of the data, from which the frequency with maximum power can be obtained. In all experimental campaigns, the latter typically corresponds to the frequency of the waves present in the film. This is achieved using a Fast Fourier Transformation (FFT), which when applied to a time series at a particular axial location, $X_F(t)$, with a finite interval, T , is given by the following complex relationship:

$$X_F(f, T) = \int_0^T x(t) e^{-j2\pi ft} \cdot dt \quad (\text{Eq. 3.10})$$

The power spectral of a time series describes how the variance of the data is distributed over the frequency of components into which that particular time series can be decomposed. In other words, the power spectral density analysis helps in the decomposition of the content of a signal into the different frequencies present in the signal, thus helping in the identification of periodicities, more specifically, as discussed above, the identification of waves present in the film.

In this study, the FFT was applied for every coordinate in the x axis of the spatiotemporal plots, by analysing the temporal records that are spaced up to 10 pixels (from $x - 10$ up to

$x + 10$), and the effect of the average film thickness was removed from the analysis using the function *detrend* in MATLAB. Each temporal record was then divided into 5 equal parts, producing several segments to which the FFT is applied using the function *pwelch* on MATLAB with no overlap. All the segments are then squared to obtain the power spectral density (PSD) and averaged into a single value. A running average filter with a window size of 7 was used to smooth the spectrum, without averaging any important features. Finally, the power spectrum was normalized by its total energy. Again, likewise to the application of the cross correlation function, the application of the FFT is only valid under the assumption that the data is stationary.

This approach was applied to the spatiotemporal plots obtained from the Stationary Taylor Bubble experiment to measure the frequency of waves in the falling film, and only to the spatiotemporal plots obtained close to the inlet section (0 – 100 mm) in both Annular Flow Experiments. In the latter, the frequency of the periodic wavelets that lead to the formation of disturbance waves further downstream was estimated.

As reported by Huang et al. (1998), for a successful application of this method (FFT), the system must be linear and the data must be strictly periodic or stationary, otherwise the resultant spectrum can make little physical sense. Due to the non-periodicity associated with the disturbance wave behaviour, in the measurement of their frequency (330 – 430 mm), a much more simplistic method that is widely used in the analysis of multiphase flow data was employed. It consists in counting the number of waves present in the spatiotemporal plots whose thickness is above a pre-selected threshold value. The determination and identification of the disturbance waves present on the film in the annular flows experimental campaigns was done through a tracking algorithm that is described in the following section.

3.4.3 Modified tracking algorithm for disturbance wave identification

One of the aims from the annular flow experimental campaign, which will be covered in Chapter 5 is to provide an extensive characterization of the disturbance wave behaviour under different flow orientations. In order to do so, a tracking algorithm based on the principles developed by Alekseenko et al. (2014) was constructed and applied to the spatiotemporal plots recorded. In order to implement it, several steps had to be taken. First, the film thickness of the first pixel in the x coordinate for a given spatiotemporal plot was taken. Using MATLAB, it is possible to compute the peaks present in the data, as shown in Figure 3.24a.

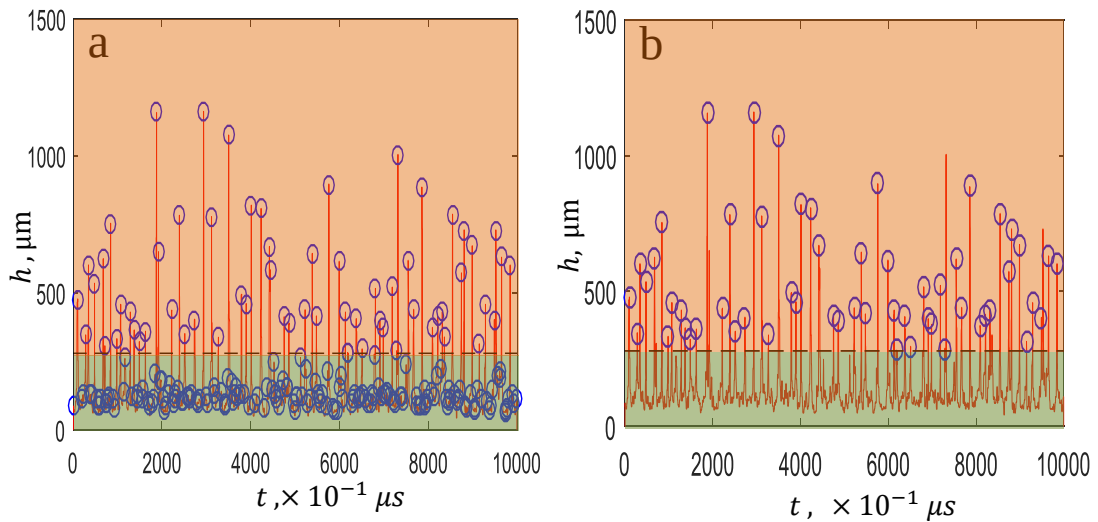


Figure 3.24: Initial stage in the implementation of the tracking algorithm, where the initial position of the disturbance waves is located by differentiating them from other waves by the mean of a threshold (dotted line). The orange and green regions refer to the regions where disturbance and ripples waves can be observed, respectively.

It can be seen from Figure 3.24a that not only the peaks corresponding to the disturbance waves were detected, but also the peaks relative to the ripple waves present in the base film. In order to differentiate between these, a thresholding to the film thickness was applied, which was chosen to be 2.5 times higher than the median film thickness, which is slightly higher than classically semi-empirical criterion employed in previous studies differentiate between both types of waves (Chu and Dukler, 1974, Zhao et al., 2013). Furthermore, detected peaks that were located within 50-100 points (depending on the flow regime) were taken as a single wave. It is worth noticing that the overshoot in film thickness due to the fast ripples present in the crest of the disturbance waves (as discussed earlier) enhance the contrast between the disturbance waves and the base

film. This makes their identification easier, as seen in Figure 3.24b, where only the peaks above the threshold value were considered. Now that the initial position of each disturbance wave in the spatiotemporal plot is known, it is required for its full trajectory to be found. This is done based on the knowledge of the average wave velocity, V_{dist} , which can be measured using the cross correlation procedure described earlier in Section 3.4.1. By knowing the initial position of the wave and its velocity, it is possible then to predict its location after for instance, 50 pixels in the axial location. This assumes however, that all the disturbance waves are travelling at a speed equal to the average speed measured using the cross correlation, which is not true as their individual velocities vary around this mean value. In order to take this into consideration, computation of the location of each individual wave after 50 pixels is done with their individual velocity ranging between $0.6 * V_{dist} < V_{dist} < 1.4 * V_{dist}$. From all the trajectories measured for each individual wave, the point with the highest value of film thickness was chosen, as it is the one corresponding to the true disturbance wave trajectory. This was done for each individual wave, for every 50 pixels until the end of a given spatiotemporal plot. An example of the result of the application of such procedure is seen in Figure 3.25.

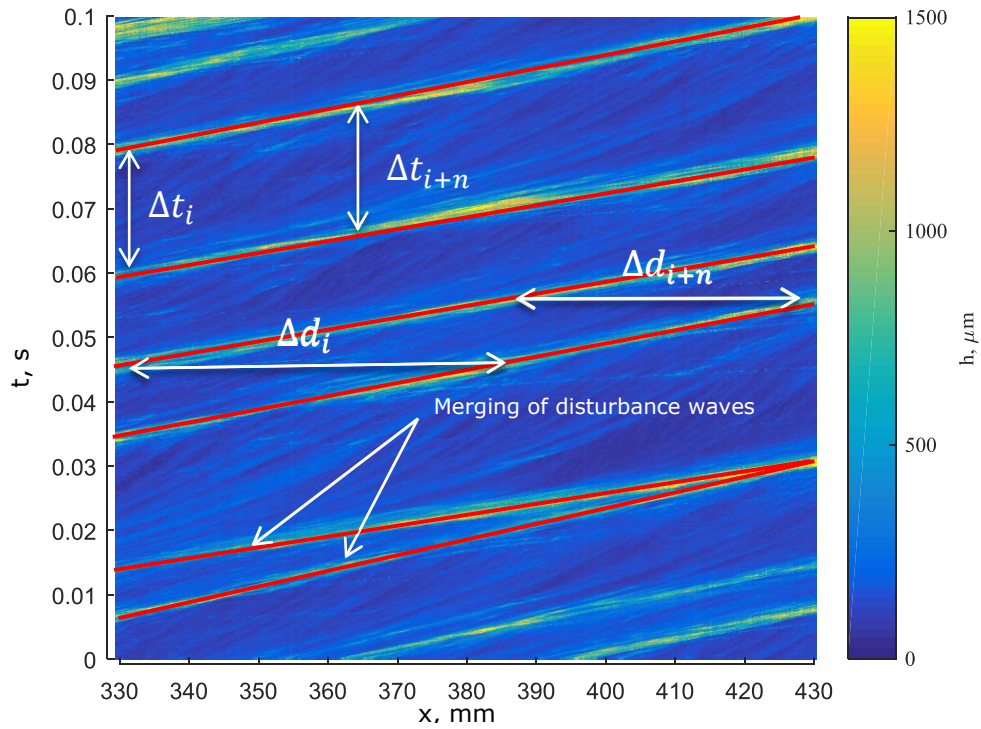


Figure 3.25: Example of a spatiotemporal plot with the trajectory of the disturbance waves clearly identified (red lines).

This tool will allow for the disturbance waves to be characterized not only by averaged values of parameters such as frequency, velocity, time and distance separations, but also by their distribution, given that the spatiotemporal location of each individual wave has now been obtained.

To measure the average time separation between disturbance waves, the time difference between consecutive waves was measured for every 50 pixels in the longitudinal axis, as shown diagrammatically in Figure 3.25, and then a mean of these values was calculated. This provides an overall mean of the time separation between each consecutive pair of waves. This is necessary because each individual wave has its own individual velocity around the mean value. For the spacing between disturbance waves, the following approach was taken. Consider a consecutive pair of disturbance waves that is characterised by the time, t_1 and t_2 , at which they reach a particular downstream position, x , and by their velocities at this point, V_1 and V_2 , for each wave respectively. The wave spacing can be defined as the difference between their x -coordinate at the time moment $t = (t_1 + t_2)/2$. To obtain the average wave spacing, d_{sep} , this distance was measured using the following formula for each wave pair, from which the average was taken:

$$d_{sep} = \frac{(V_1 - V_2)(t_2 - t_1)}{2} \quad (\text{Eq. 3.11})$$

3.4.4 Intermittency of disturbance waves

Another important parameter that helps in the characterization of the disturbance wave behaviour for a particular set of conditions is its intermittency, or in other words, the total time that the disturbance waves are present in the signal over the total length of the time series record. In order to measure the intermittency of the disturbance waves, it is required for the position of a disturbance wave to be known in a given film thickness time series, which is possible through the same method used in the tracking algorithm, which was described in Section 3.4.3. By knowing the highest location of each disturbance wave, it was possible to find out the points where the disturbance wave starts and finishes. This was achieved by computing the first point where the film thickness crosses the median film thickness level immediately before and after this peak point (as shown diagrammatically in Figure 3.26), and then summing the time spent by each individual disturbance wave in the time series and dividing by the total time of the time series. This was performed for the film thickness time series from all the spatiotemporal plots. As a result, the total intermittency is a computation of the mean from the implementation of this technique for all film thickness time series.

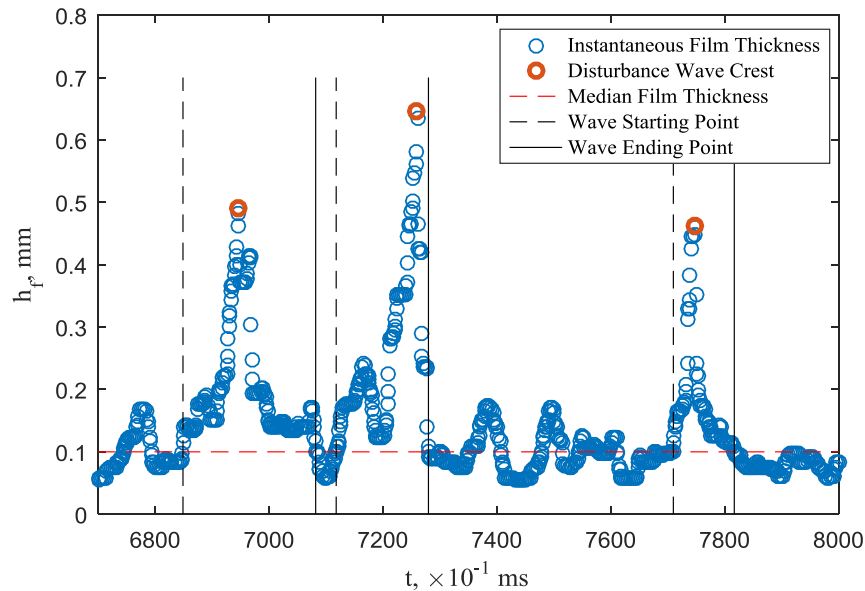


Figure 3.26: Schematic of the implementation of the method to measure the intermittency of disturbance waves for a single film thickness time series.

3.4.5 Omega-K analysis to obtain ripple wave velocity

An important parameter that is in the scope of this thesis is the velocity of the ripple waves present in the base film in annular flows, and how their velocity is related to the disturbance wave velocity under the different flow scenarios being reported here. In order to obtain it, two different approaches were taken. The first one, which is more automated, is the application of an Omega-K analysis to all the spatiotemporal plots. It consists of the application of the Fast Fourier transform not only to the temporal domain of the spatiotemporal plots, but also to the spatial one (2D FFT). The result is shown in the form of plots of angular frequency, ω , against the wave number, k , which is a function of the wavelength, λ , as shown in the example in Figure 3.27a:

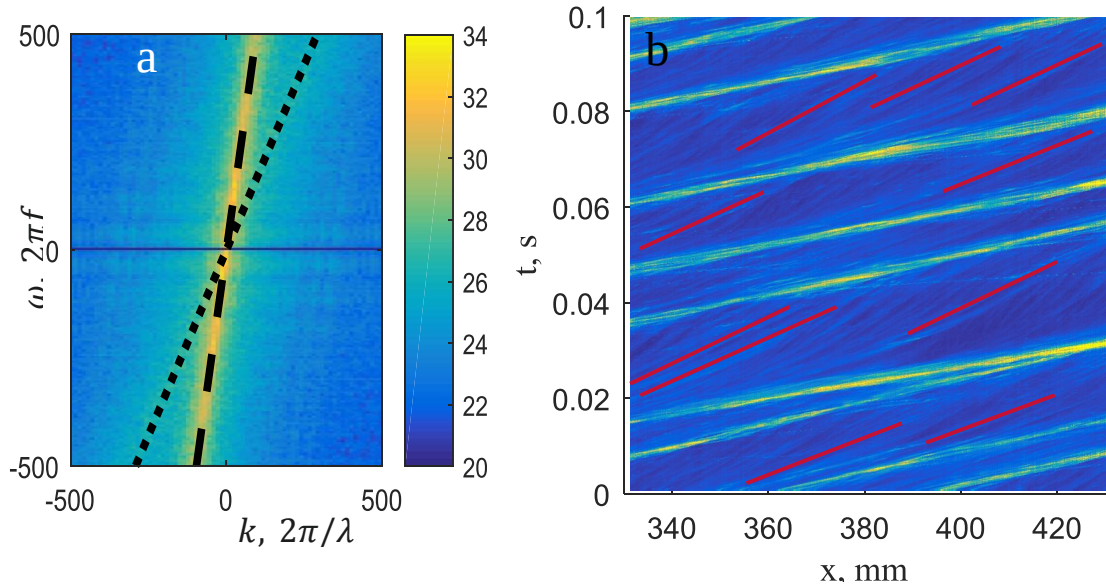


Figure 3.27: a) Example of the application of the Omega-K analysis to a spatiotemporal plot. The dashed and dotted lines correspond to the disturbance and ripple waves respectively; b) Example of the procedure taken to measure the gradient of 10 randomly selected ripples (denoted by the red lines).

Figure 3.27a shows that two bright lines were obtained from the analysis, which were marked with two best fit lines, which correspond to both the disturbance (brighter area) and the ripple waves (dimmer area), since they are the two predominant structures in the base film. The gradient of these lines corresponds to their average velocity, given by the following relationship:

$$c = \omega / k = f \lambda \quad (\text{Eq. 3.12})$$

The velocities obtained from the Omega-K analysis for the disturbance waves are in agreement with the velocities obtained from the application of the cross-correlation method described in Section 3.4.1. However it is important to note that in some cases, no significant feature relative to the ripple waves could be detected from the Omega-K plots. In those cases, since the disturbance wave velocity was already known, the average ripple velocity was measured by manually calculating the gradient of 10 randomly selected ripple waves present across each spatiotemporal plot (as shown for example in Figure 3.27b), and computing the mean from all the gradients.

3.5 Summary and conclusions

This chapter enumerated and described the BBLIF measurement technique, the experimental arrangements and the data processing tools employed in the study of interfacial waves in gas-liquid flows. The following chapters report on the findings and discuss the implications of the results obtained from the study of such flows after analysing them with the processing techniques described in the latter stages of this chapter.

Chapter 4. Gas Entrainment in a Stationary Taylor Bubble

In Chapter 2, a detailed summary of the traditional studies employed in the characterization of the slug flow regime was provided, together with more recent studies that attempt to replicate the nose of the Taylor bubble as closely as possible, by means of a specially designed apparatus to generate a stationary Taylor bubble. The latter is also the configuration studied as reported in this thesis, with the description of the experimental setup employed described in Chapter 3.3.1. However, previous studies in general provide information regarding only mean values of a given set of measured parameters.

The knowledge of the mean values is, however, insufficient for meaningful modelling, and therefore data is also required on the range of variation of the instantaneous slug flow parameters and their statistical moments (Shemer, 2003). This type of data is scarce in literature, and thus being able to provide it will enable advances in the current state-of-the-art predictive frameworks that CFD models currently offer. Furthermore, it is important to obtain visual observations of the mechanisms behind entrainment and re-coalescence rates in order to attest and confirm that the mechanisms reviewed in Chapter 2 are the sole driver of these events. Having these factors in mind, this study was performed with the aim of providing a more complete description of Taylor bubble hydrodynamics, including measurement/observation of the following flow parameters:

- Observation of the entrainment process;
- Film thickness of the falling film surrounding the Taylor Bubble;
- Velocity, amplitude and frequency of waves present in the falling film.

As can be expected, the investigation of such interactions requires a measurement technique that would allow for the tracking of both spatial and temporal evolution of waves and entrained bubbles. This was conducted using the BBLIF technique, whose setup for this experimental campaign was provided in Section 3.3.2.2 of Chapter 3. The following sections

will describe the results of the parameters discussed above obtained from the BBLIF, together with discussion and the conclusions drawn from these results.

4.1 Film thickness time series, instantaneous film thickness profile and spatiotemporal plots

Figure 4.1a) shows a sample of the images recorded at $Fr_{TB}=1$ ($U_{SL}=0.287$ m/s, $Re_L=19200$). If the central portion of the image (white solid line in Figure 4.1a) is analysed in terms of its local film thickness, the instantaneous raw film thickness profile that is extracted through the application of the BBLIF equation can be obtained. This is represented by the blue line in Figure 4.1b), which will be used subsequently in the analysis of the different parameters set for this study. As mentioned in Chapter 3, it can be seen that whenever brighter spots are present in the image recorded (i.e. thicker film section), this is represented by the presence of peaks in the instantaneous film thickness profile as illustrated in Figure 4.1b), thus validating the application of the BBLIF technique.

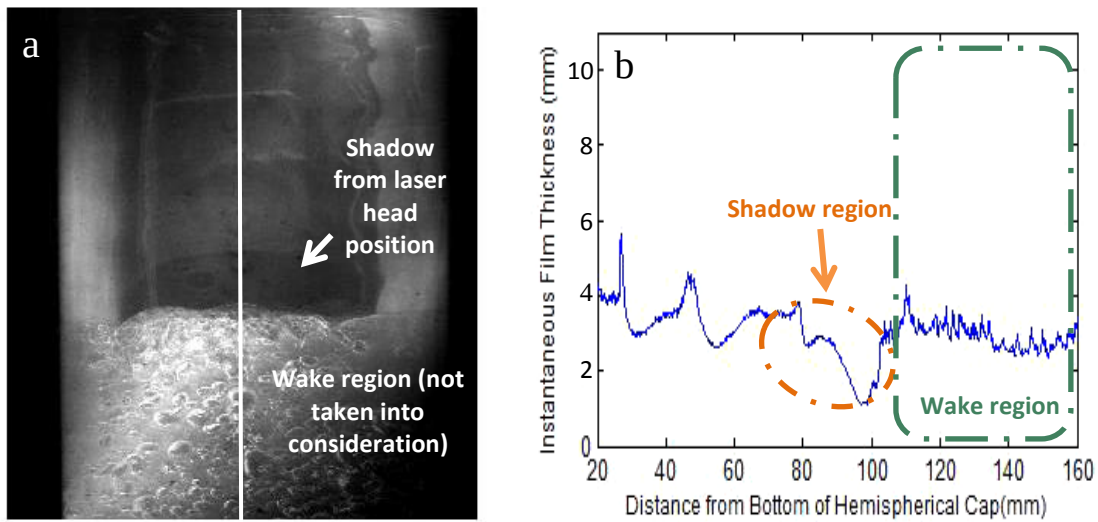


Figure 4.1: The application of the BBLIF technique at $Fr_{TB}=1$ ($U_{SL}=0.287$ m/s): a) Image recorded; b) Processed film thickness profile obtained for the central region of a) (denoted by the white line).

A feature that is going to be encountered in every image recorded when using the laser is a shadow region just above the skirt of the artificial bubble, as is indicated in Figure 4.1. This is an unfortunate event that has arisen due to set-up that was employed for the camera and the laser head (shown in Figure 3.17 in Chapter 3). It can be seen that the laser head is placed underneath the high speed camera at an angle that is not perpendicular to the testing section. As a result, the laser beam comes from a position a short distance below the skirt and the wake region of the artificial bubble, thus producing a shadow in the falling film area with a profile similar to the profile of the skirt of the bubble. This unfortunately means that the true film thickness information in that particular section of the image is lost, since the intensity values recorded are not representative of the true film thickness of the liquid layer. However, extrapolation of the results measured in the rest of falling film can be done in order to know what the values of the different parameters that are to be measured near the skirt of the artificial bubble are. This is of high importance in order to relate the falling film behaviour with the entrainment mechanism.

Additionally, the “film thickness” profile observed in the wake region in Figure 4.1b) is obviously not a real representation of any real thickness; it is the result of the re-calculation of the brightness of fluorescent light under the surface of the liquid in the pool. What can be extracted from the data in this region is the spatiotemporal trajectories of the edges of the bubbles, as shall be seen later. The edges appear in the images as bright rings due to total internal reflection of the laser light at the bubble circumference.

In Chapter 3, the method of converting the images acquired from the 3D-approach such as Figure 4.1a) into spatiotemporal records (2D-approach) for subsequent use in analysis was described. Figure 4.2 shows the evolution of the central portion of the artificial bubble with time for some examples of the liquid and gas flowrates tested (see Table 3.1 in Chapter 3). Through this tool, a greater focus can be directed towards a smaller section of the image, which provides a lot of insight in terms of observing a particular behaviour and keeps track of its evolution over time.

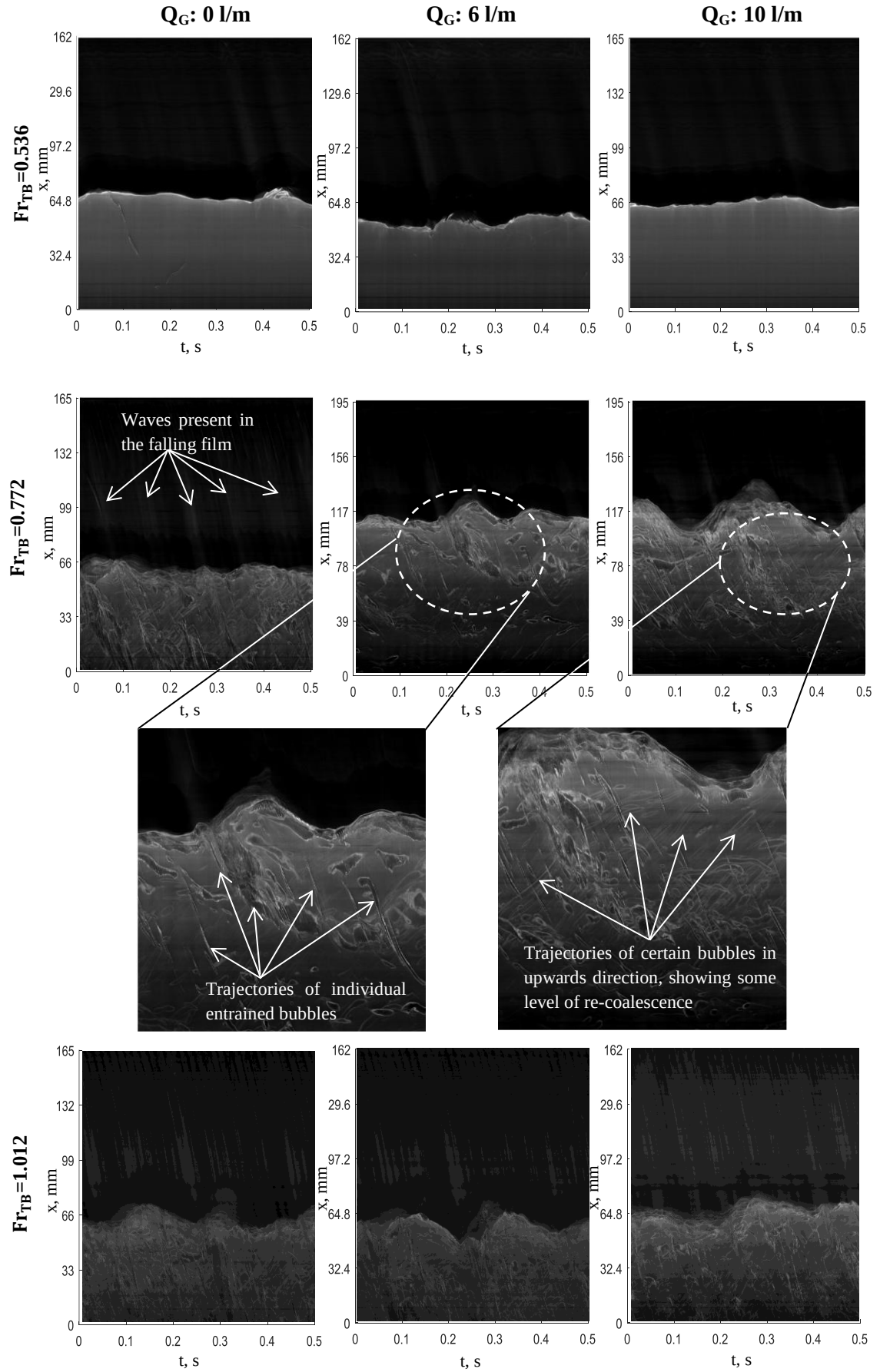


Figure 4.2: Spatiotemporal evolution of some of the gas and liquid flowrate conditions tested (with zoomed sections).

For instance, brighter spots present in the falling film region correspond to the waves present in the film, while the ‘thin lines’ in the wake region correspond to the bubbles that are entrained from the Taylor bubble. From the plots, it is apparent that with increasing liquid flowrate, the level of entrainment increases significantly. This is seen by the increasing number of bubbles present in the wake region. Conversely, no apparent difference can be seen with varying gas flow rate. These findings support the entrainment theory of Kockx et al. (2005), which correlates the entrainment rate to the falling film and wave behaviour, as observations of the paths of the small bubbles show that the velocity of the bubbles travelling downwards are very close to that of the waves (through their gradient).

Another observation that can be drawn from the plots is the presence of some bubbles that are moving in the upwards direction (‘edges’ going in the upwards rightwards direction), which correspond to the re-coalescence of some of the entrained small bubbles back to the artificial bubble. This phenomena has been visually observed in lesser detail by Abdulahi (2013) and quantified by Delfos et al. (2001a). Its impact on the hydrodynamics of the falling film and the entrainment behaviour will be discussed in Section 4.6.

In addition to the spatiotemporal plots, videos from the images recorded were made for all the data sets. These allowed for further observation of events that are less apparent when observing a still image. For instance, it allowed the identification of different entrainment mechanisms, as will be reported in Section 4.6. These are seen to occur very close to the wall, whereas towards the centre of the pipe, re-coalescence of the entrained bubbles back to the artificial bubble is observed. Therefore, due to the reduced effect that the falling film has at the centre of the pipe, their buoyancy is greater than the drag forces of the falling film, which leads the bubbles to travel back in the upwards direction.

Although these plots and videos provide a great insight in terms of observations of what is occurring in a slug flow situation, the quantification of the entrainment and re-coalescence rates and mechanisms still needs to be better understood. It is therefore important to quantify and characterize first the falling film and its waves, in order to establish a relationship between both, which is the purpose of the next sections.

4.2 Average film thickness, wave amplitude and wave amplitude to average film thickness ratio

Analysis of the film thickness profile obtained for instance, from one of the examples in Figure 4.2 for a particular axial location shows that there is some error present in the signal due to camera noise (unsmooth), as denoted by the blue line seen in Figure 4.3.

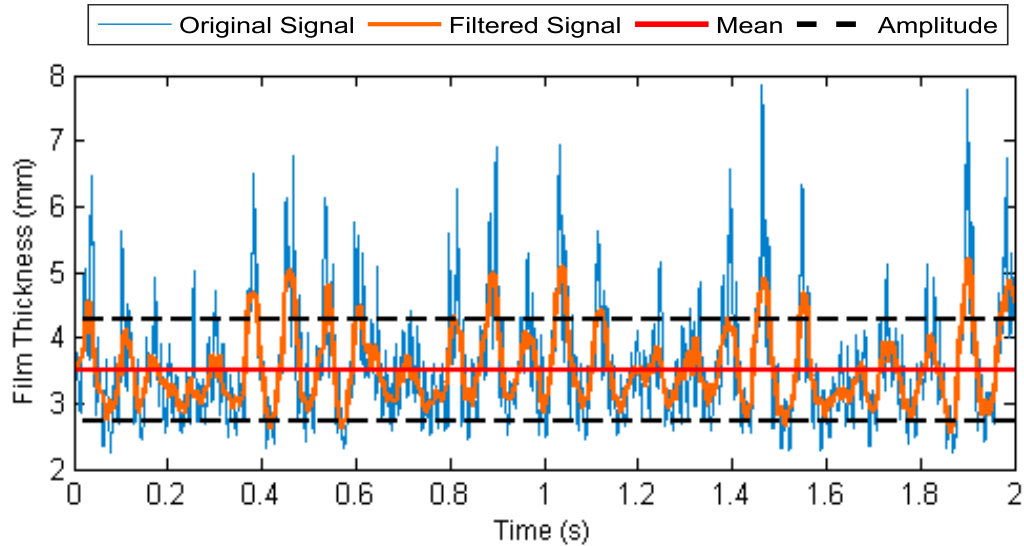


Figure 4.3: Signal processing stage performed to the film thickness time series for a particular axial location.

Therefore, to reduce it, 1D median filtering was applied for the film thickness profiles of every axial location measured, with a window size several times smaller than the wavelength of the oscillations present in the signal, resulting in the smooth profile denoted by the orange line in Figure 4.3.

With a corrected time series for each position over the x coordinate of the falling film for all the data sets obtained, the first parameter to be derived was the average film thickness over the length of the artificial bubble. This was simply measured by calculating the mean of the time series at each x coordinate position, which resulted in Figures 4.4 and 4.5, which show the evolution of the average film thickness with downstream distance for constant gas flowrates. As expected, the shape of the falling film surrounding the artificial bubble can be observed. Additionally, for any given gas flowrate tested, an increase in film thickness at any point of the x coordinate with increasing liquid flowrate (Figure 4.4) is observed, as more liquid is being injected into the system.

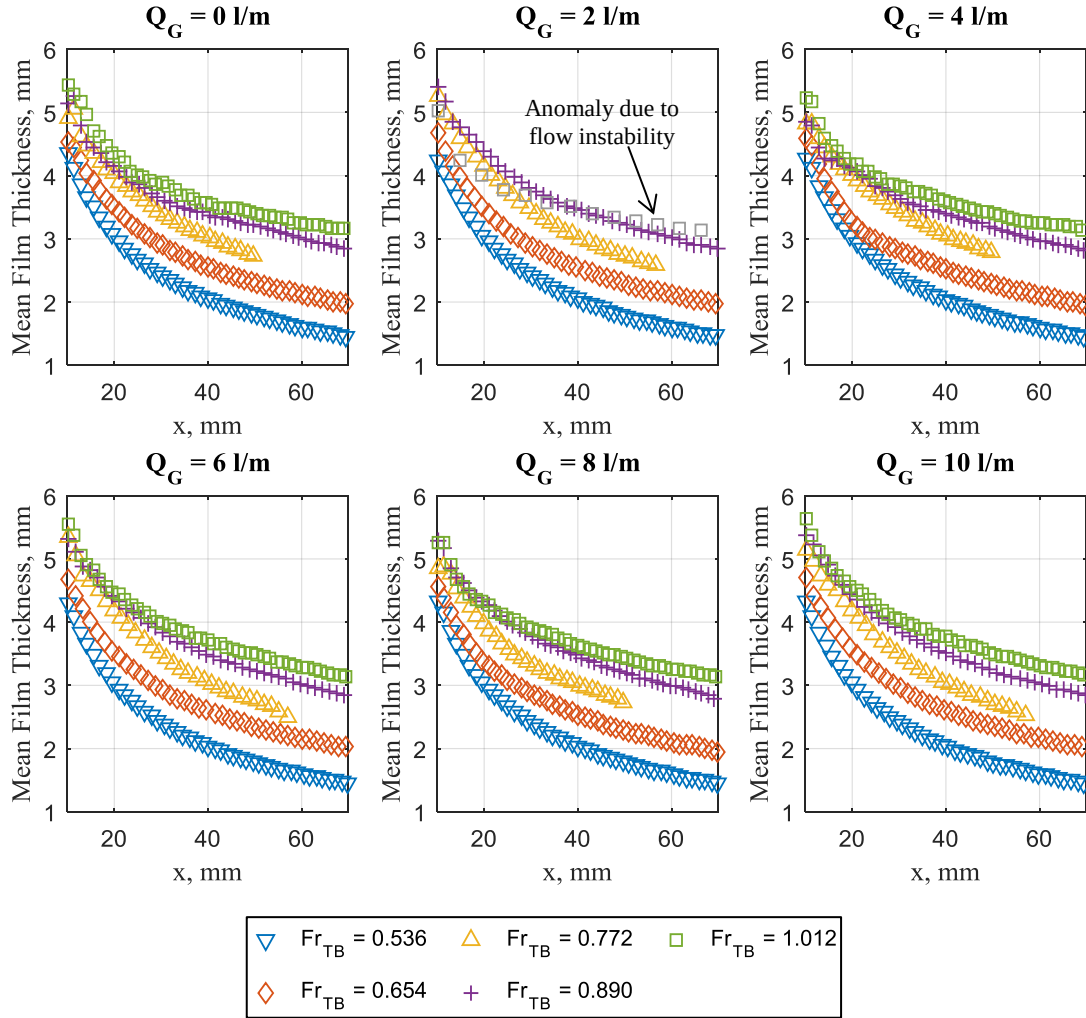


Figure 4.4: Average film thickness profiles for constant gas flowrates. The axial distance, x , refers to the distance from the bottom of the hemispherical cap.

Additionally, from Figure 4.5, it can be observed that the gas flux has no overall effect in the average film behaviour for the gas flowrates tested. This is because negligibly small shear stresses are present at the gas-liquid interface, and is a finding supported by previous authors (Kockx et al., 2005). This is a feature that will be seen in all measured parameters. For presentation purposes, only every tenth pixel is presented in both Figures 4.4 and 4.5.

It is worth noting that, in some cases, which are more evident in Figure 4.4, the film thickness profile for the case of $Fr_{TB}=0.772$ is shorter than the remaining ones. This is due to the fact that when the experiments for this particular case were conducted, the measurements were recorded when the artificial bubble was slightly shorter in comparison to the rest of the

flowrates measured and hence, the shadow effect is seen at a lower distance from the cap for this particular case. Nonetheless, it does not affect the overall behavioural trend.

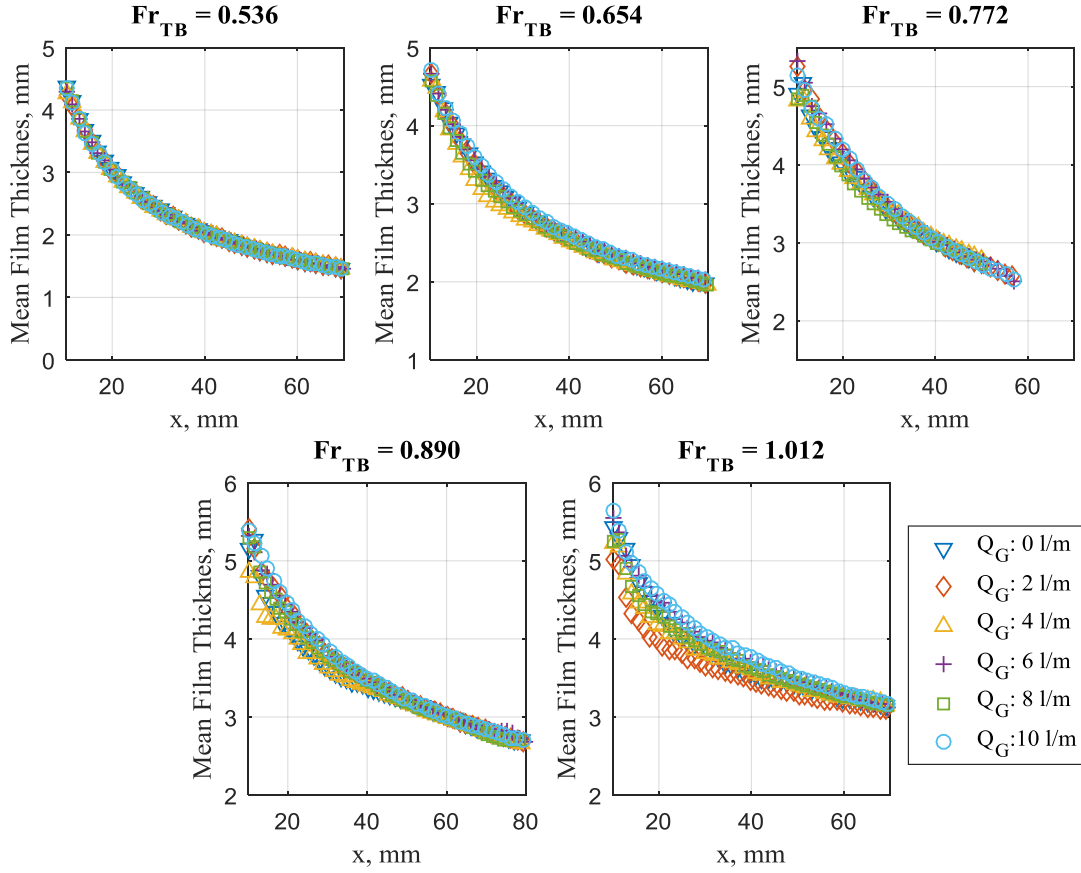


Figure 4.5: Average film thickness profiles for constant liquid flowrates.

The next step was to measure the amplitudes of the waves over the x coordinate of the falling film. This would theoretically provide information as to how the waves which are observed to be travelling down the falling film evolve with distance from the hemispherical cap until the skirt region of the artificial bubble. As in the work of Delfos et al. (2001b), for simplicity, it was assumed that the waves follow a sinusoidal waveform, which will be confirmed at a later stage. For a sine wave, the relationship between the root mean square (RMS) and peak-to-peak amplitude is given by the following equation:

$$Peak - to - peak = 2 \times \sqrt{2} \times RMS \quad (\text{Eq. 4.1})$$

In the description of physical events, the term ‘root mean square’ is often seen as a synonym for standard deviation when referring to the square root of the mean squared deviation of a signal from a given baseline or fit (Kenney and Keeping, 1962). This is the case, since

standard deviation is a measure of spread of the amplitude values of a signal. In other words, the standard deviation (std) is actually the RMS value of a signal calculated after the mean value has been removed.

Bearing this in mind, the amplitude for each axial position was calculated with the following equation using the corresponding time series for that axial position:

$$\text{Amplitude} = \sqrt{2} \times \text{std}(\text{time series}) \quad (\text{Eq. 4.2})$$

By doing so, it can be said that the corresponding measured amplitude for each axial position is an average of all the amplitudes recorded over the 2s period. This resulted in Figures 4.6 and 4.7, which show the evolution of the mean wave amplitude with downstream distance for constant liquid and gas flowrates, respectively.

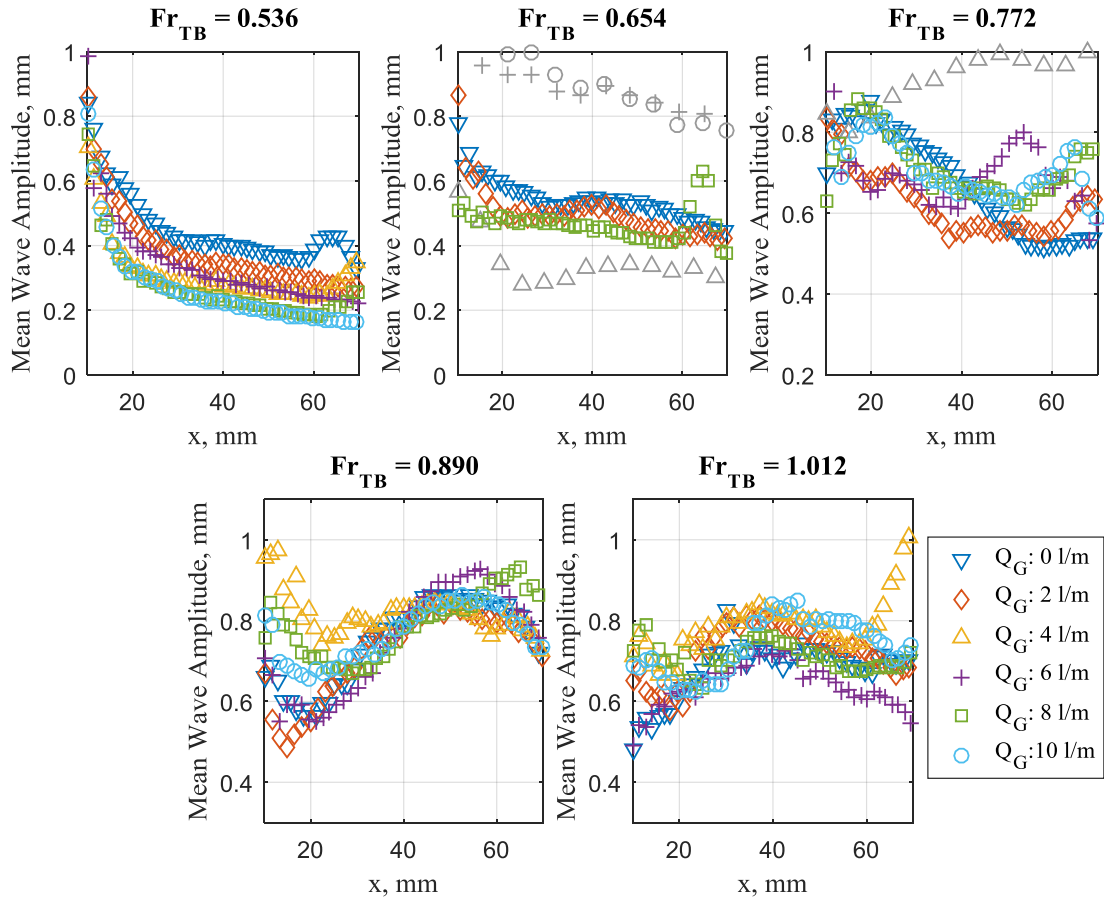


Figure 4.6: Mean wave amplitude for constant liquid flowrates.

For the lowest liquid flowrates tested ($Fr_{TB} = 0.536$ and 0.654), there is a decrease in the amplitude of the waves with downstream distance, which is expected given that through visual observation of the spatiotemporal plots of Figure 4.2, practically no waves were present in the falling film surrounding the artificial bubble. Moreover, except for the lowest liquid flowrate tested (unphysical condition), there is a negligible effect that the gas flowrate has on the overall variation of the wave amplitude with axial distance, as no distinct pattern is observed. The exception at the lowest liquid flowrate might be due to the fact that since very low liquid flowrates are being tested, with low/zero level of undulations, the gas flowrate is strong enough to suppress any wave action, but not strong enough to affect the overall mean film thickness (Figure 4.5).

For the cases close to and equal to a slug flow condition ($Fr_{TB} = 0.890$ and 1.012), fluctuations are observed between 10 - 25 mm from the bottom of the hemispherical cap. This is probably due to some instabilities that are present when the flow transitions from the cap region into the pure falling film region. After 25mm, a slight increase in the wave amplitude is observed, which then decreases as the skirt region is being reached, which is expected, as the falling film is becoming thinner due to the nature of the Taylor bubble shape. Furthermore, close to the end of the artificial bubble (around 70mm from bottom of cap), fluctuations can be seen in the wave amplitude profiles. This is due to the fact that as the wave and liquid film approach the skirt of the bubble and the wake region, instabilities are generated due to the interaction of both the incoming wave and the skirt interface. These are partly responsible for the gas entrainment and for the peaks that are observed in the right hand side of the graphs in both Figures 4.6 and 4.7.

The behavioural trends described above are also seen in Figure 4.7. However, in this representation of the data, it is more clearly seen that an increase in liquid flowrate for a particular gas condition, leads to an increase in wave amplitude. It is suggested that this is because the level of turbulence is increasing.

In Figures 4.4, 4.6 and 4.7 (and later in Figures 4.8 and 4.9), in some instances, particular gas and liquid flowrate conditions are displayed in grey symbols, as these were out of the

general trend displayed by the data. A possible explanation for this behaviour is the fact that all measurements were conducted when it was thought that the artificial bubble was under dynamic equilibrium (i.e the skirt level was fully stationary). However, there were always some slight movements of the skirt level (and hence size) and during testing, attempts were made to to be compensate by opening or closing the valve located at the bottom of the test section. As a result, these changing conditions have an effect on the turbulence present on the falling film, which are translated as the out of trend lines in Figures 4.6 and 4.7, but are mostly smoothed out when measuring the mean film thickness.

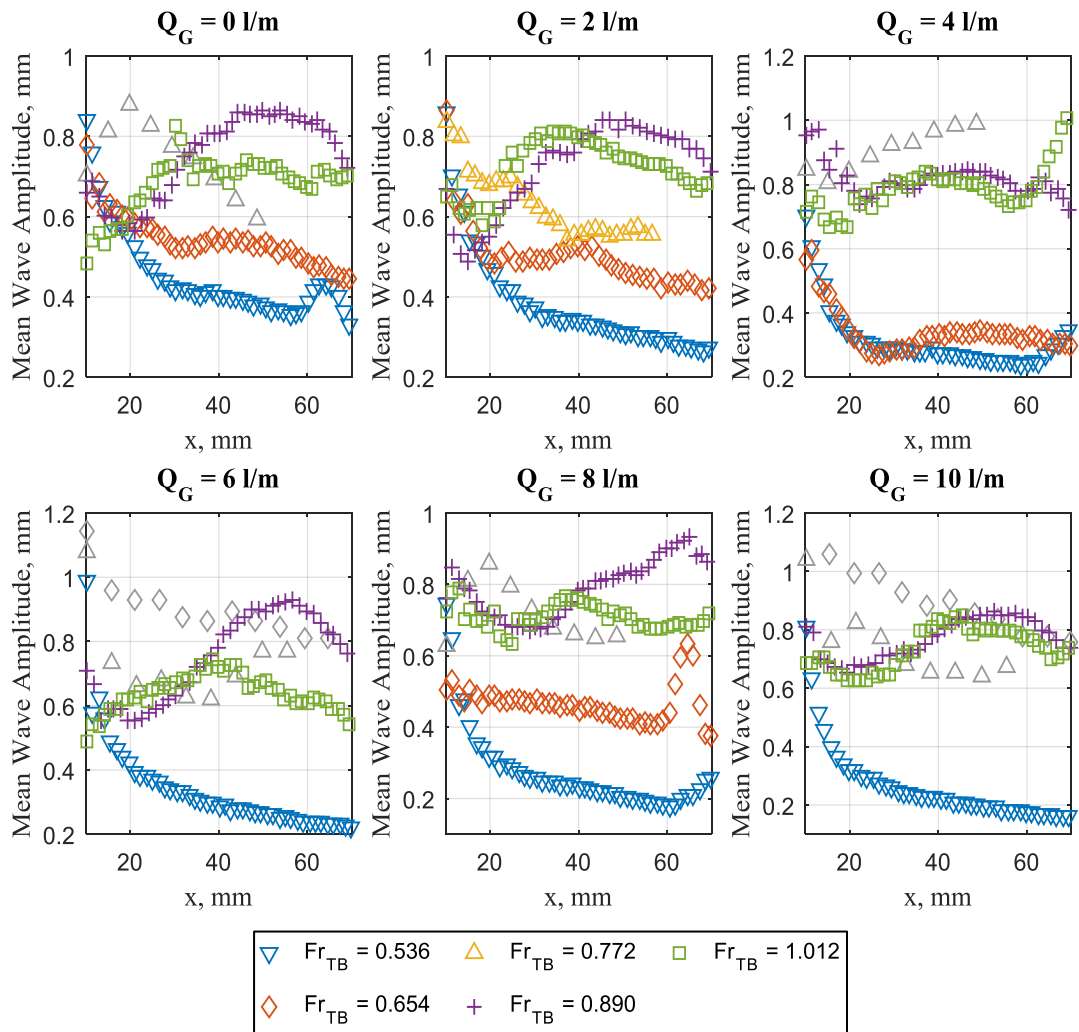


Figure 4.7: Mean wave amplitudes for constant gas flowrates.

Figures 4.6 and 4.7 show how the absolute mean wave amplitude varies with axial distance. Due to the characteristic shape of a Taylor bubble, with a decreasing film thickness profile as seen in Figures 4.4 and 4.5, it is important to assess the relative evolution of the amplitude of the waves to the mean film thickness profile of the artificial bubble. To this end, Figures 4.8

and 4.9 show the ratio of the averaged wave amplitude with the corresponding film thickness against the downstream position.

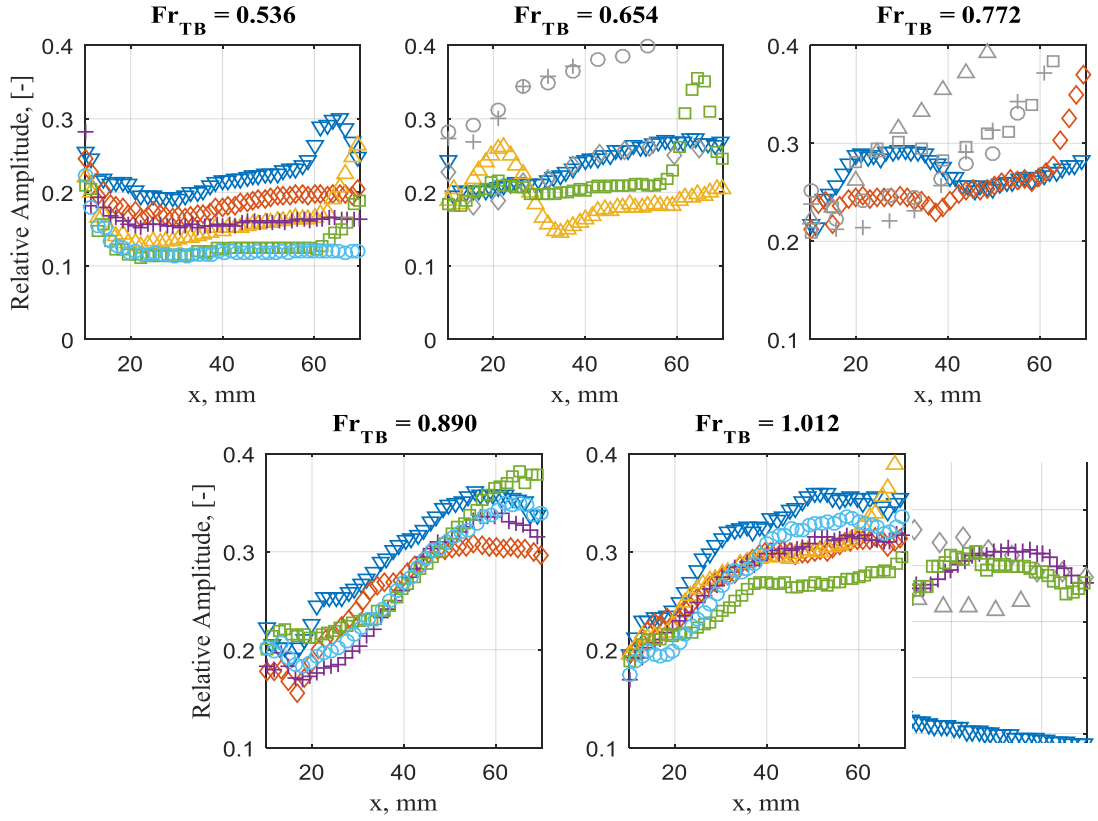


Figure 4.8: Average amplitude to film thickness ratio for constant liquid flowrates.

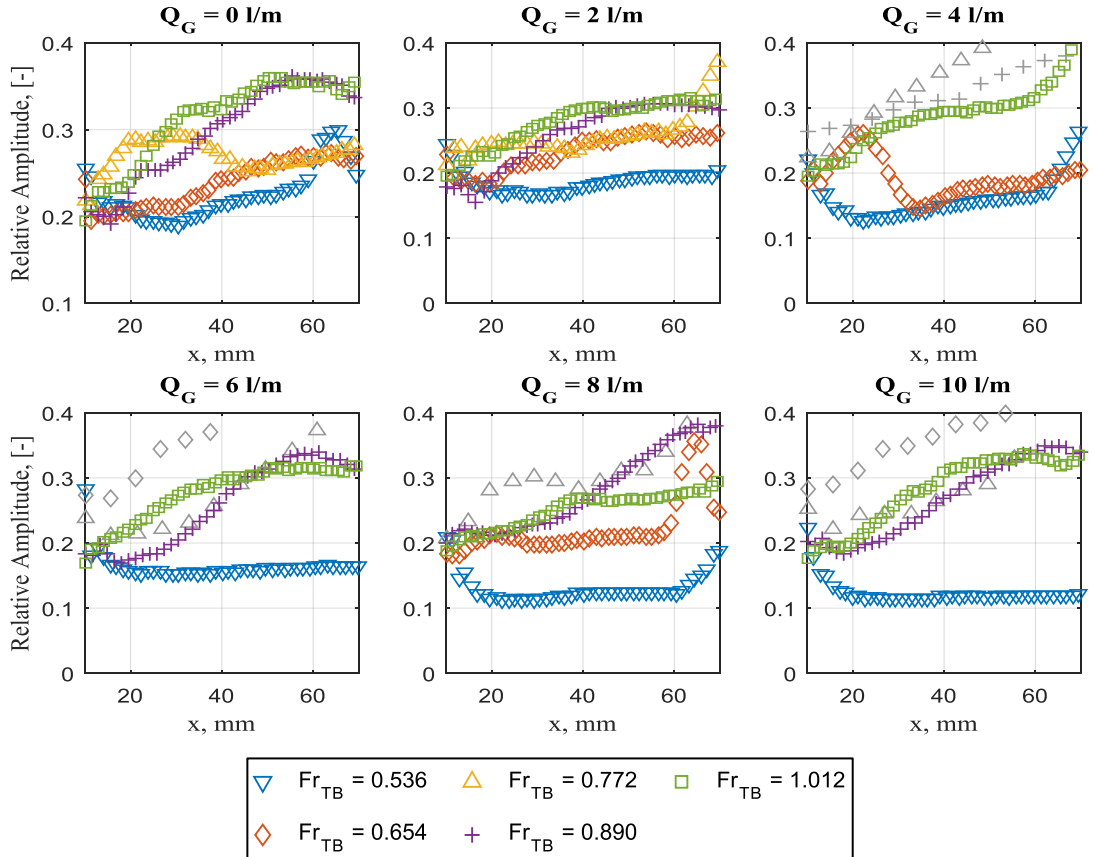


Figure 4.9: Average amplitude to film thickness ratio for constant gas flowrates.

In Figures 4.8 and 4.9, unlike the observed decrease in absolute wave amplitude as the skirt level is being reached, in relative terms to the film thickness, the general trend that is observed is a slight increase of the ratio with downstream position. This means that the wave structures present in the falling film increase slightly in size in relation to the film thickness as the skirt of the artificial bubble is being reached. This is of high importance since it gives further evidence that indeed the fluctuations present in the falling film might be partly responsible for the gas entrainment from the bubble into the wake region. The only exception is for the lowest (unphysical) case of $Fr_{TB} = 0.536$, which has been linked to a lack of enough liquid flow for perturbations to appear in the falling film.

Additionally, from Figure 4.9, as observed in Figure 4.7, it can also be seen that there is an increase of the ratio with increasing liquid flowrate, although this is much less evident in comparison to the effect that increasing liquid flowrate has on the absolute wave amplitude. Finally, it is seen that the ratios do not exceed the 40% liquid film height level.

4.3 Speed of waves present in the falling film

The next step of the analysis was to obtain the speed of the structures (i.e. waves) present in the falling film surrounding the artificial bubble. This was achieved by employing the cross-correlation function between consecutive film thickness time series, as described in Section 3.4.1 of Chapter 3. The results of this procedure can be seen in Figures 4.10 and 4.11. It is clearly seen from both figures that the wave speed tends to increase with axial distance. Additionally, from Figure 4.10, it can be seen that the wave velocity also increases with increasing liquid flowrate, which is to be expected. This further suggests that there might be some validation of the entrainment mechanism proposed by Kockx et al. (2005), as will be discussed in Section 4.6.

In the case of a typical slug flow simulation ($Fr_{TB} = 1.012$ in Figure 4.11), after the non-linear growth near the inlet, the increase in wave speed becomes linear. This also is observable at lower liquid flowrates, but in these cases, this linear growth stabilizes and plateaus much earlier. Similarly, the same plateauing feature is observed in the film thickness

plots in Figures 4.4 and 4.5 for the same conditions, as this will be analysed in the next section.

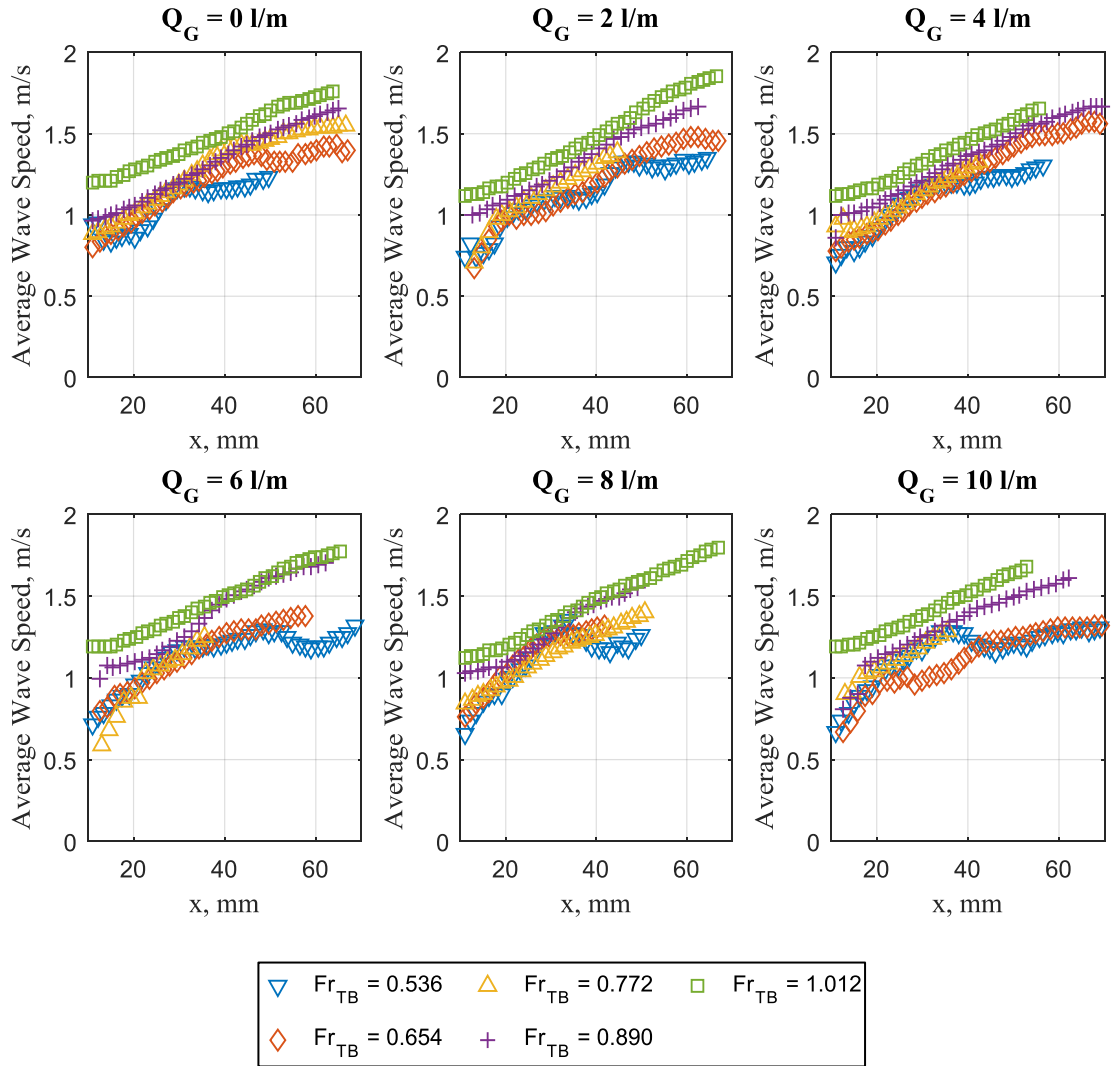


Figure 4.10: Average wave speed for constant gas flowrates.

Furthermore, the wave model states that an increase in the wave size (in terms of amplitude and wavelength), is translated into an increase in the wave speed. However, in absolute terms, the wave amplitude is not constantly increasing with axial location, as seen in Figures 4.6 and 4.7, although its speed is. As a result, it is important to investigate what is the factor or factors responsible for this increase in wave speed.

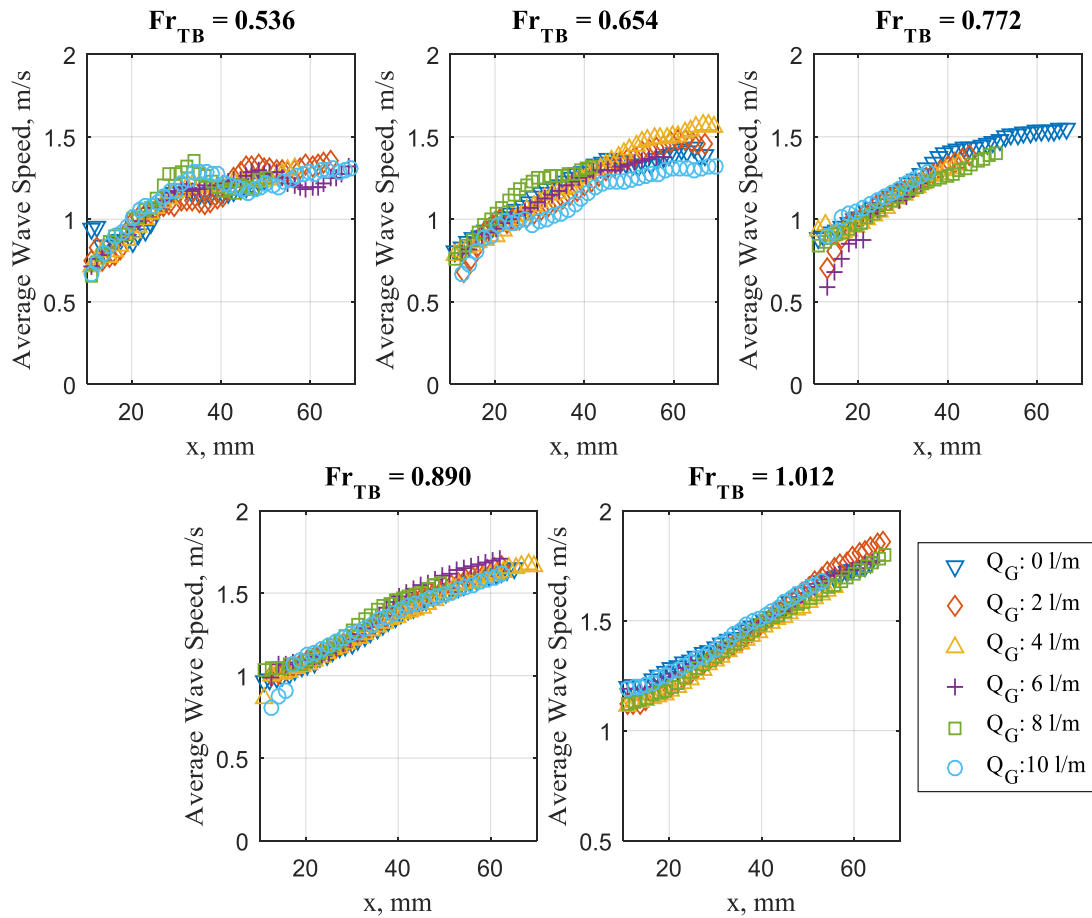


Figure 4.11: Average wave speed for constant liquid flowrates.

4.4 Wave velocity against average film height

Based on the profiles of the parameters observed in Figures 4.4 and 4.5 and Figures 4.10 and 4.11, further investigation was conducted in order to determine if there is a correlation between film thickness and wave speed.

A possible correlation between the wave speeds with the wave amplitude did not produce any distinguishable trend or relationship. This is in direct disagreement the work of Karapantsios and Karabelas (1995) in wavy falling films and of Pashniak (1969) and Azzopardi (1986) in annular flows, where a linear relationship is obtained when plotting the average wave velocity against the average wave amplitude for a particular axial location. The reason for this discrepancy can be possibly attributed to the difference in the flow dynamics between the falling film in a slug flow situation and in purely gravity-driven falling films or annular flows.

As described in Chapter 2, one of the distinctive characteristics of annular flows is the presence of high amplitude (of orders several times higher than the film thickness), fast moving waves, denominated as disturbance waves. These are intermittent and therefore non-periodical. The waves present in the falling film surrounding a Taylor bubble cannot be characterized in the same manner. As reported in Section 4.2, the wave amplitude to film thickness ratio does not exceed 40%, and as shall be demonstrated later, these waves are periodical and follow a sinusoidal waveform. Therefore it is suggested that different correlations are applicable to describe their behaviour.

A possible relationship can be seen in Figures 4.12 and 4.13, where the average wave velocity was plotted against the inverse square root of the average film height over the axial distance for different gas and liquid flowrates.

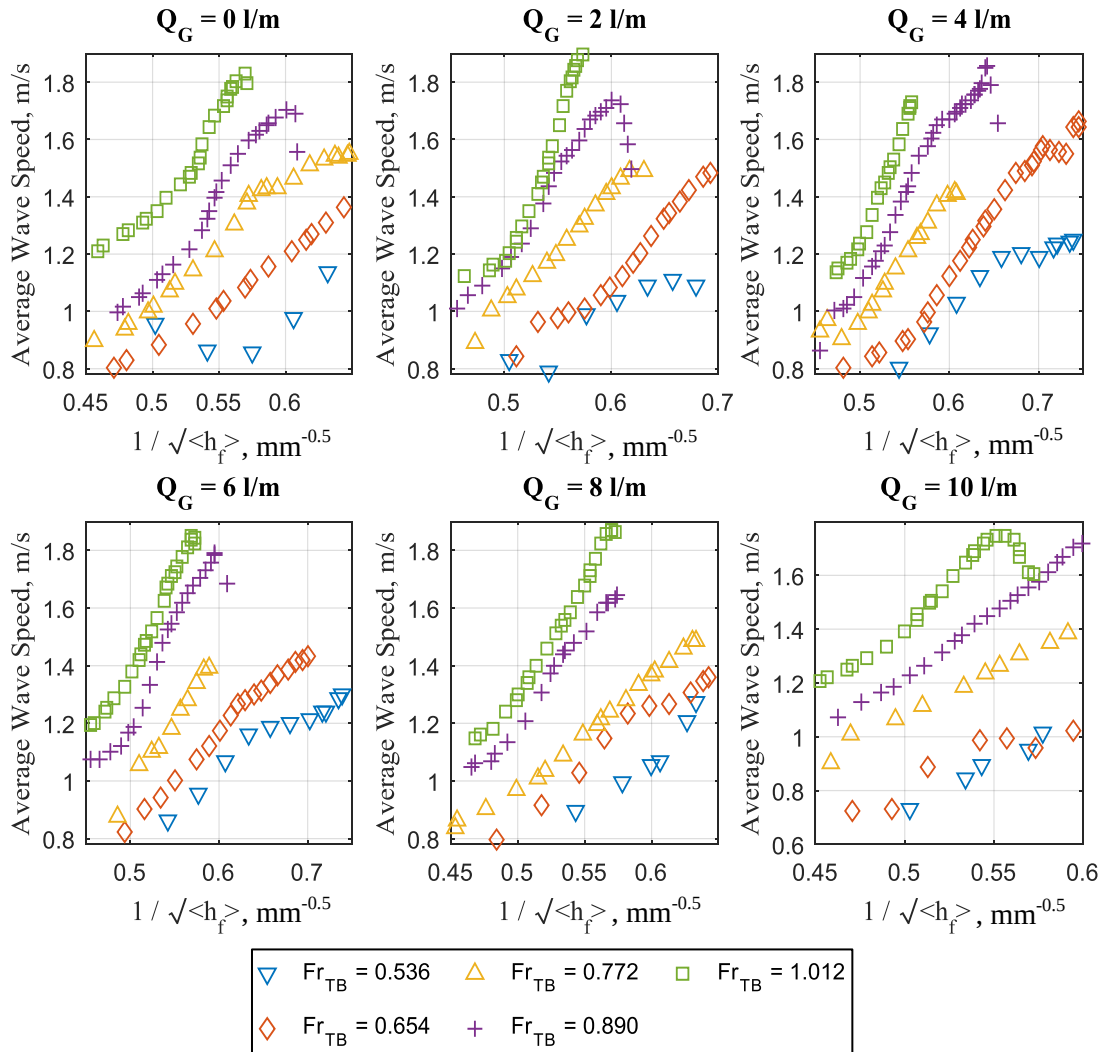


Figure 4.12: Wave speed as a function of film height for constant gas flowrates.

It can be seen that there is indeed a correlation between both parameters, where generally, with decreasing film height (or in other words, with increasing axial distance), the wave speed increases. As expected, higher speeds are observed for the same film thickness with increasing liquid flowrate, as seen in Figure 4.12. Discontinuities from the general linear trend can be observed at both ends in some plots in Figure 4.12 (for instance, for the case of $Fr_{TB} = 1.012$ at $Q_G = 0, 2$ and 10 l/m). It is postulated that these are either due to the turbulences generated near the hemispherical cap or the instabilities near the skirt, as discussed above. If these features are disregarded, a linear relationship between the wave speed and the inverse square root of film thickness is observed for each liquid flowrate tested. The gas flowrate has no effect in this parameter, as shown in Figure 4.13.

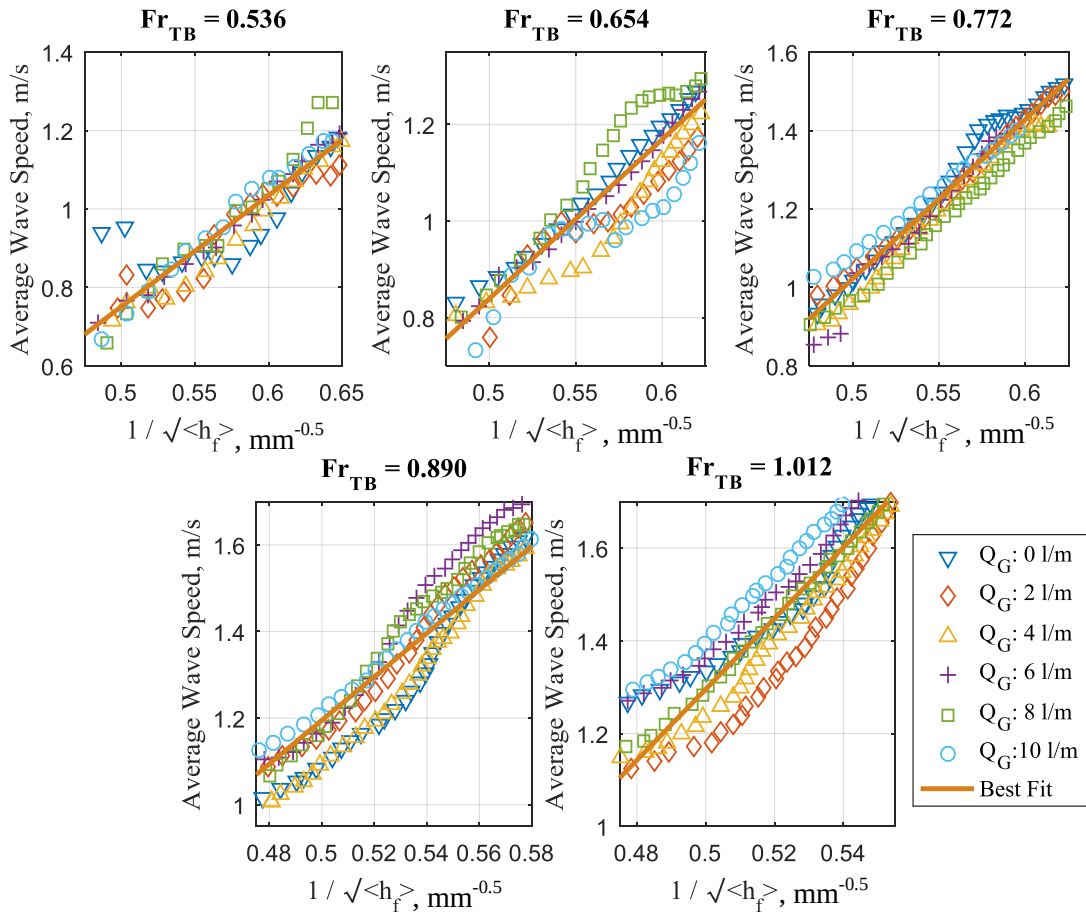


Figure 4.13: Wave speed against film height for constant liquid flowrates.

It is therefore suggested that in contrast to the annular flow regime, in a slug flow situation, the increase in wave speed is dependent on the film thickness. Kashinsky et al. (2008) states in their work on wall shear stress of a stationary bubble, that with increasing axial position, the gas bubble occupies a significant part of the tube cross section (i.e. the film thickness decreases), and the liquid velocity in its film is considerably higher. Therefore, due to mass conservation, the thinning of the film leads to the velocity of the film to increase, which is then translated to an increase in the speed of the waves present in the falling film. Hence the linear correlation between both parameters, as shown in Figure 4.13.

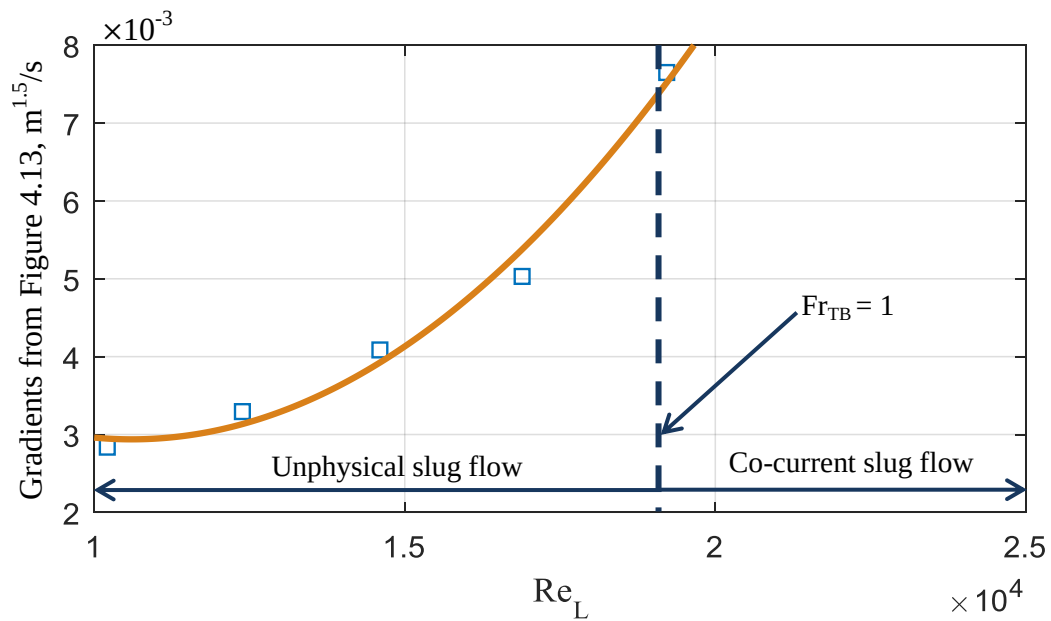


Figure 4.14: Evolution of the gradients obtained from the plots in Figure 4.13 with liquid Reynolds number. The blue points and the orange line correspond to the data points and best fit line respectively.

It is interesting to investigate how the gradients from these linear relationships evolve with liquid flowrates, which is shown in Figure 4.14. It also shows that the data is well fitted with a quadratic best fit line, with the gradient increasing with increasing liquid flowrate. It is important however, to stress that the majority of the simulated artificial bubbles were generated under unphysical conditions. These would not be encountered in typical slug flow conditions, with the exception of $Fr_{TB} = 1.012$. As result, by observation Figure 4.14, there is the possibility that in the region of co-current slug flow ($Fr_{TB} > 1.012$) that this relationship becomes linear.

4.5 Frequency and power spectral density

Next, a power spectral density (PSD) analysis was conducted on the film thickness time series data to investigate the downstream evolution of the frequency corresponding to the maximum power obtained (i.e. dominant wave frequency) from this analysis. In order to do so, a Fast Fourier Transform (FFT) was applied to the spatiotemporal plots for the different gas and liquid flowrates in the manner described in Section 3.4.2 of Chapter 3. Figure 4.15 shows the PSD plots obtained at different locations along the artificial bubble for increasing liquid flowrate cases at different gas flowrates. Varying the gas flowrate showed no significant changes in the profiles of these plots. From each graph, it can be seen that a dominant frequency is encountered, which is constant with downstream distance (circles in Figure 4.15), as the frequency of these waves does not change. This corresponds to the frequency of the waves present on the falling film as observed from the spatiotemporal records shown in Figure 4.2.

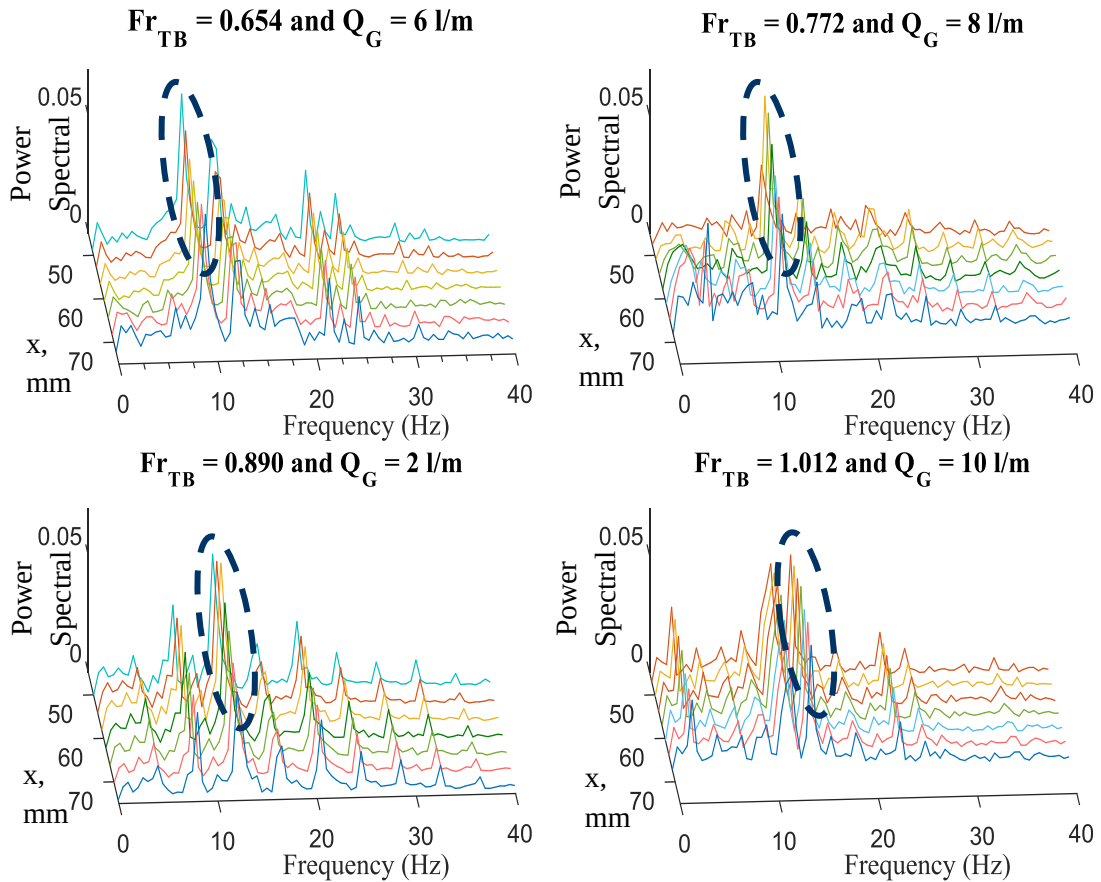


Figure 4.15: Power Spectral Density of increasing liquid flowrates cases for various gas flowrates over the longitudinal coordinate of the artificial bubble.

As seen from Figure 4.2, with increasing liquid flowrate, the number of perturbations (waves) present in the falling film increases perceptibly, and this feature is captured by the spectral analysis, where an increase in the dominant frequency is observed in Figure 4.15. The dominant wave frequencies of the PSD plots obtained for all flowrate combinations tested were measured and plotted in Figure 4.16. These are shown to linearly increase with increasing liquid flowrate regardless of the gas flowrate tested, as more waves are present in the falling film. It should be noted that the results for the lowest liquid flowrate tested are not displayed in Figure 4.16. This is due to the fact that in the analysis of the PSD plots for this condition, the absolute power of the dominant frequency obtained was several orders of magnitude lower than the absolute power of the dominant frequencies for higher liquid flowrates. From the spatiotemporal plots in Figure 4.2, it can be seen that the presence of waves in the falling film for this condition is almost negligible, and therefore it was concluded that the dominant frequency obtained is not representative of a wave frequency.

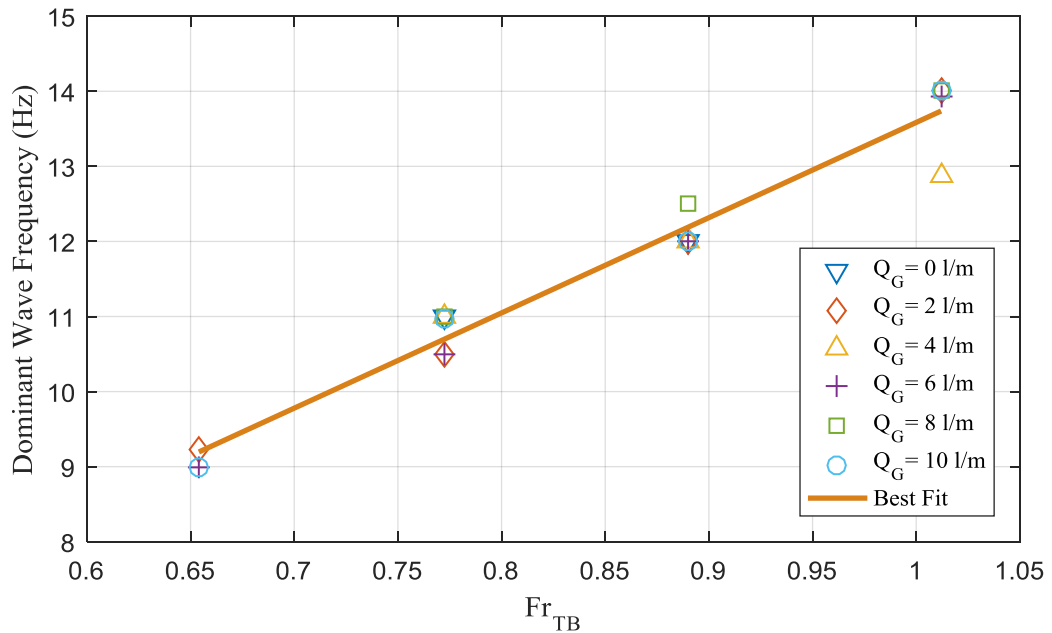


Figure 4.16: Dominant Wave Frequencies for different flowrate conditions.

With the information of the amplitude and frequency of waves measured from the spatiotemporal plots, it is now possible to demonstrate that the behaviour of the waves present in the falling film follows a sinusoidal waveform, as shown in Figure 4.17.

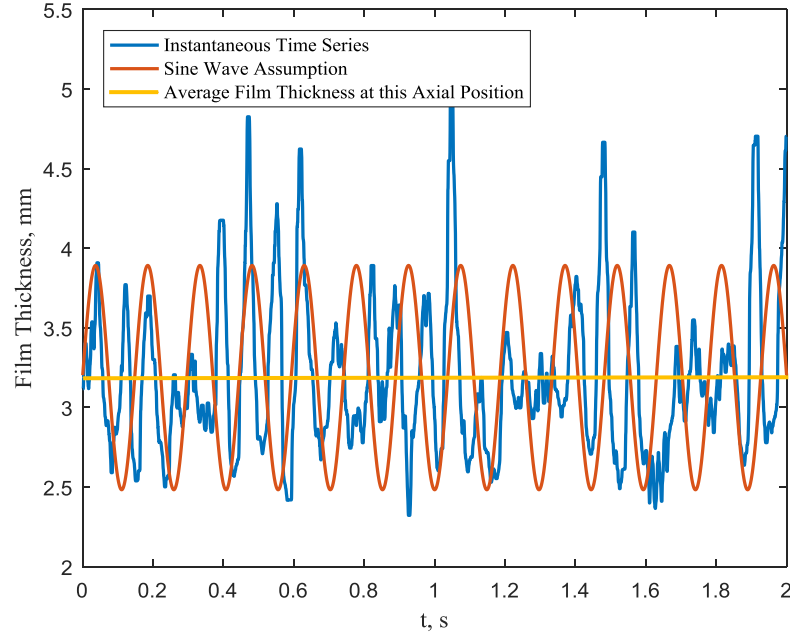


Figure 4.17: Time series of film thickness profile at a location close to the skirt of the bubble, with sinusoidal wave assumption employed at $Fr_{TB} = 1.012$ and gas flowrate of 10 l/m.

The blue line in Figure 4.17 represents the instantaneous time series of the film thickness at a location close to the skirt of the bubble, whereas the red line represents this data in terms of the sine wave sinusoidal assumption, given by the following relationship, assuming that there is no phase delay:

$$h_{fsine}(t) = \Delta h_w \cdot \sin(2\pi ft) \quad (\text{Eq. 4.3})$$

where $h_{fsine}(t)$ is the instantaneous film thickness assuming the sinusoidal waveform at a particular time, Δh_w is the average amplitude of the waves, obtained from the instantaneous film thickness time series using Equation 4.2 and f is the dominant wave frequency for a particular flowrate combination, obtained from Figure 4.16 in the frequency analysis section.

With the PSD analysis concluded, a full characterization of the falling film was achieved, not only in terms of its film thickness, but also in terms of the amplitude, speed and frequency of the waves present in the falling film.

4.6 Entrainment mechanisms and models

Following the numerical analysis, the focus of this work then shifted towards analysing the videos obtained from the BBLIF measurements in an attempt to elucidate how the entrainment of gas from the Taylor bubble to the wake region occurs. This would potentially allow for a confirmation of the generally accepted model of entrainment proposed by Delfos (1996).

As a recap from Chapter 2, when the slug flow regime is reviewed, it is generally accepted that the amount of air entrained corresponds to the amount of air that is trapped in between the crests and troughs of the waves present in the falling film. These waves are coherent around the pipe circumference, thus meaning that a full ‘rim’ of air will be potentially entrained once the falling film waves collide with the gravity waves generated at the skirt level upon their arrival. This is shown diagrammatically in Figure 4.18, which shows a 2D plane view of this phenomena and how the falling film parameters present in Equation 2.32 influence the rate of the entrainment event.

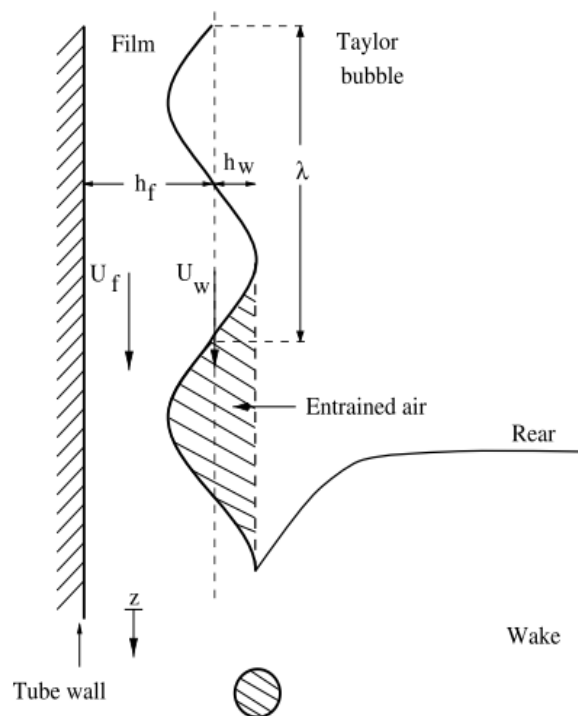


Figure 4.18: Diagram showing the entrainment mechanism proposed by Delfos (1996). The shaded area is the entrained air that is assumed to be entrained by the wave action (Kockx et al., 2005, Delfos et al., 2001b).

The application of the BBLIF technique is advantageous not only in terms of the large number of spatial film thickness results it offers over a multitude of locations along the pipe, but also the high definition images that can be obtained with a very high temporal resolution. This allows for the observation of phenomenological events with very high contrast between both phases in the wake region, such as for instance the re-coalescence events that were displayed in the spatiotemporal plots. Due to these visual advantages, the experiments were conducted at superficial velocities that without the artificial apparatus would not be encountered in conventional slug flow. This allowed for the gradual evolution of entrainment mechanisms to be observed and more easily identified until the case of $Fr_{TB}=1$ was achieved.

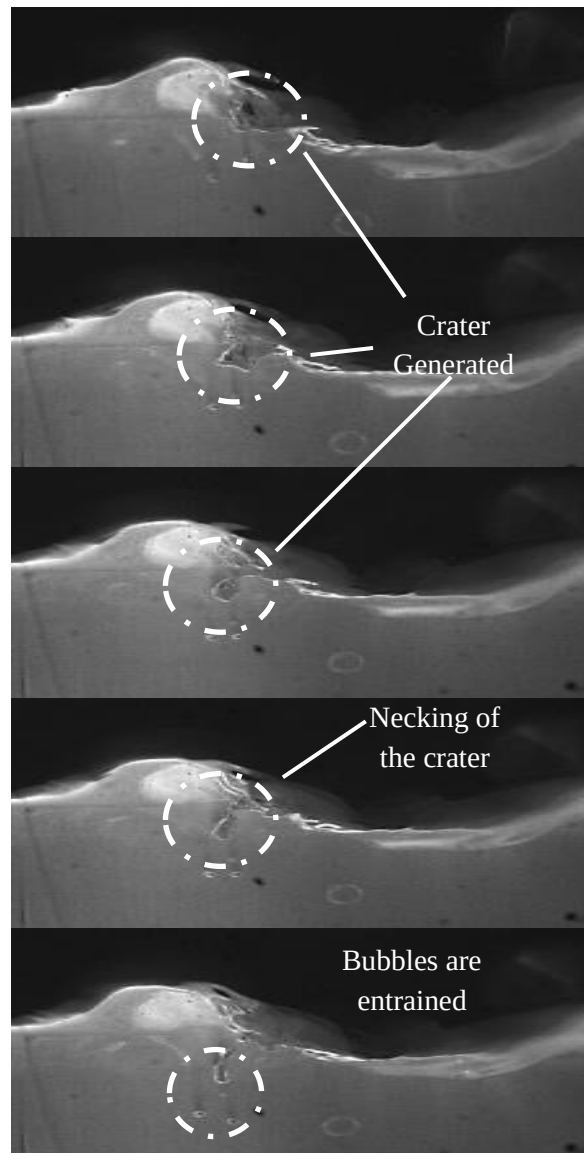


Figure 4.19: Zoomed view of the skirt level showing the evolution of the entrainment mechanism through crater generation at $Fr_{TB} = 0.536$; gas flowrate of 6 l/m.

The first mechanism observed at the lowest liquid flowrate, which was the predominant method of entrainment in this particular case is what we herein denominate as entrainment by *crater generation*. Whenever a transverse instability is seen at the skirt of the Taylor bubble, this is the location that is more likely for entrainment to occur, since it is in that particular location that the incoming waves of the falling film are more likely to cause a disruption. This results in the generation of a local crater ('pocket' of air) in the skirt. This crater then grows gradually in size as more air is being transferred to it and while it is sheared by the falling film action. Eventually it breaks down (necking) into bubbles that are impinged into the wake region, as shown in Figure 4.19. Riiser et al. (1992), in their pioneering work with stationary bubbles, reported from their observations of high speed video recordings, that perturbations at the bubble tail appear simultaneously with waves in the falling film, which according to them led to the formation of very thin fingers of gas at the perimeter of the bubble tail. These fingers were then elongated by shear and then broken up to be entrained by the wave. This is a clear description that substantiates the existence of entrainment through *crater generation*, which is the mechanism that most resembles the entrainment mechanism proposed by Delfos (1996). However entrainment is seen to be actually much more localised rather than an event that occurs coherently over the entire circumference of the pipe.

The second mechanism observed has never been reported previously in literature. It consists in the interaction of previously entrained bubbles (through *crater generation*) that are re-coalescing back to the Taylor bubble. Abdulahi (2013) reports that these entrained bubbles initially remain in the wake region, where some begin to move downwards, while a few start to move in the upwards direction (re-coalescing). The latter, usually occurs through the centre of the pipe, where the falling film's dragging action is less pronounced, as shown in Figure 4.20 from the work of Delfos et al. (2001a). Figure 4.20 shows the variation of the probability of bubble re-coalescence with radial and axial position. As it can be seen, closer to the centre of the pipe, the probability of re-coalescence is higher, and it also increases with decreasing axial position in the wake region.

However, in certain cases, the bubbles do not fully re-coalesce back to the Taylor bubble, but instead remain stuck to the skirt region. Eventually they change their radial position, shifting closer to the wall of the pipe, where the action of the falling film is more pronounced.

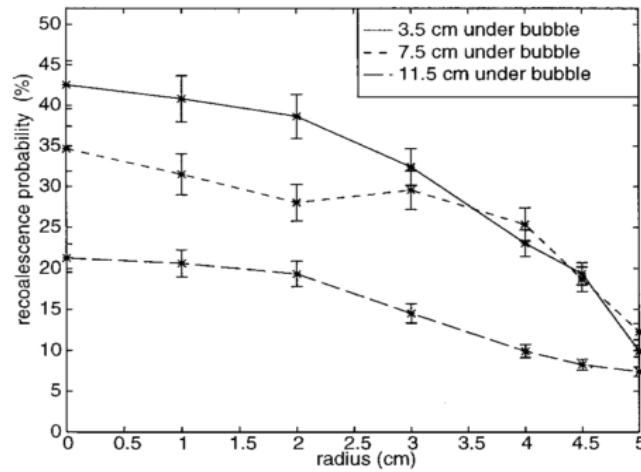


Figure 4.20: The radial coalescence probability distribution at various axial positions (Delfos et al., 2001a).

When this occurs, the attached bubble causes an instability at the skirt that further enhances the entrainment rate, as seen in Figures 4.21 and 4.22. This mechanism is herein defined as *self enhancement of entrainment due to the action of re-coalescing bubbles*.

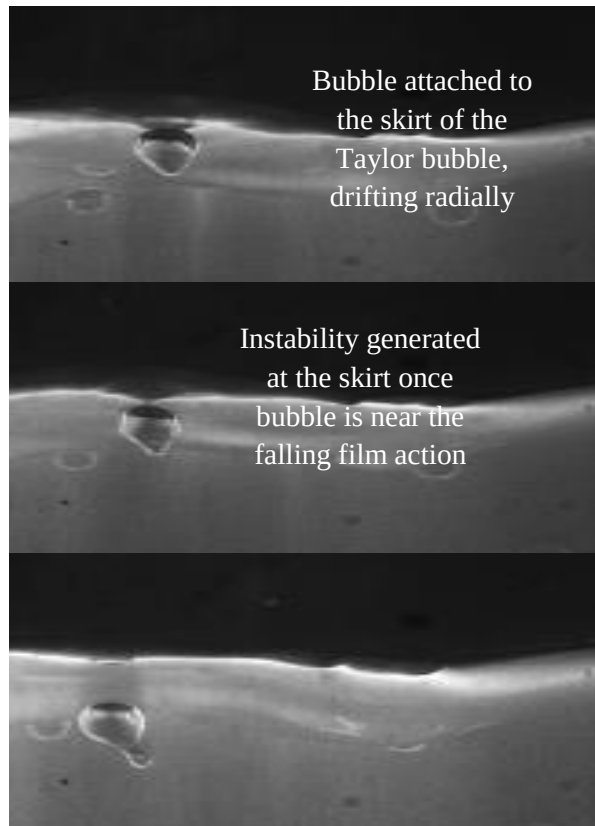


Figure 4.21: Re-coalescing bubble drifting radially and eventually causing an instability at the skirt level at low liquid velocities at $Fr_{TB} = 0.536$; gas flowrate of 2 l/m.

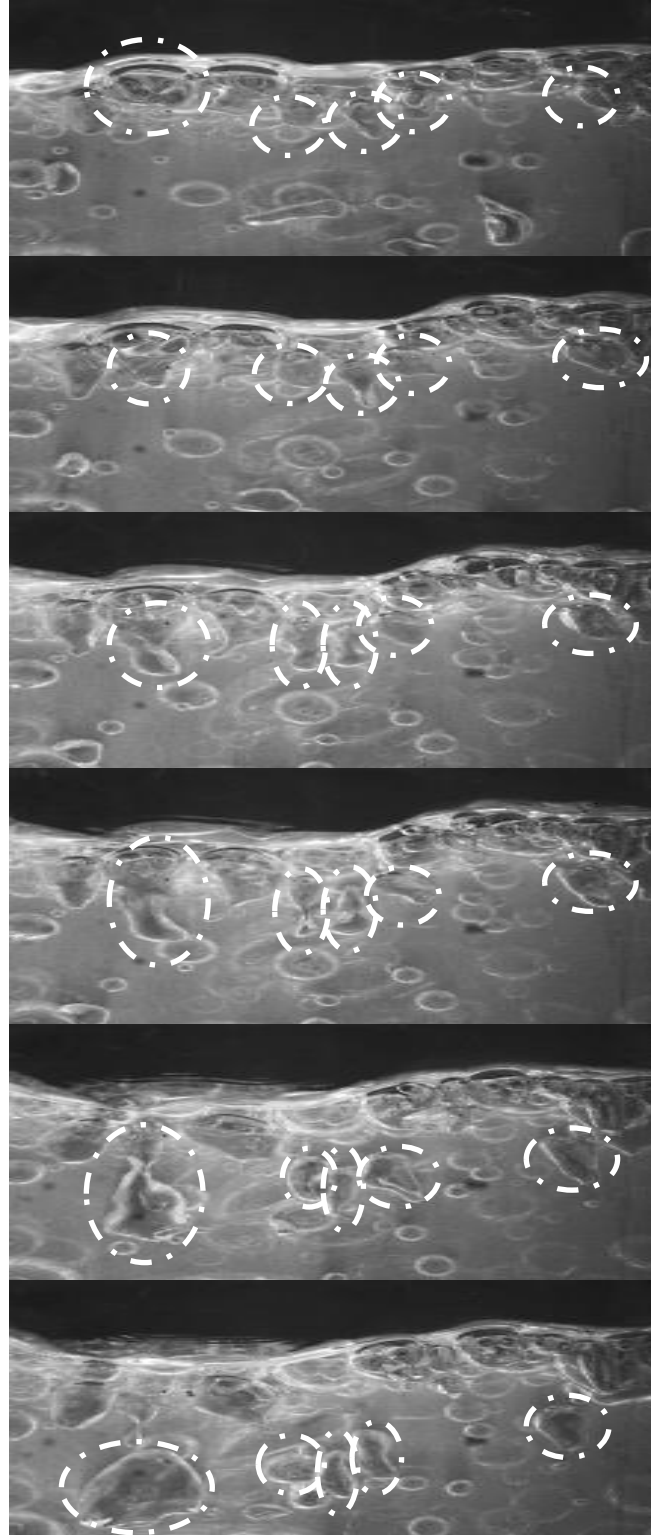


Figure 4.22: Entrainment mechanism through self-enhancement due to interaction of re-coalescing bubbles at higher liquid velocities at $Fr_{TB} = 0.654$; gas flowrate of 8 l/m (circles representing tracking of entrainment events).

With increasing liquid flowrate, the entrainment events increase perceptibly, as expected. This thus leads to more bubbles to be available to re-coalesce back to the Taylor bubble, leading to a cycle of *self-enhancement of entrainment*.

The locations where re-coalescing bubbles are present in the skirt of the Taylor bubble are more prone to instability generation due to the small interface that exists between both (small rim of liquid), as opposed to the interface between the Taylor bubble and the bulk of liquid if no small bubbles are present at that particular location. As a result, it is in these regions that entrainment will be mostly localised, as incoming waves will disrupt these small interfaces and transfer the volume of air that is located between its crests and troughs into the small bubbles. As seen from Figure 4.22, the small bubbles gradually increase in size as more air is being transferred into these ‘pockets’. An easier way to visualise these event is to relate it the situation where a balloon is being filled. It increases in volume as more air is being injected, until it reaches a disruptive point. The same happens with these small bubbles, where at some point, they become big enough to be greatly affected by the dragging forces of both the waves and falling film, leading them to break up and disconnect from the skirt of the Taylor bubble and consequently entrain air into the wake region. In some cases, this occurs in a similar fashion to the necking event seen in Figure 4.19 during the *crater generation* entrainment mechanism.

There is a possibility that it is through this mechanism that re-coalescence of air actually occurs, since from the observations of the videos, no bubble has ‘disappeared’ back into the Taylor bubble once it gets attached to it. It is more likely that whenever the interface between the small bubble and the Taylor bubble is broken, some of the air contained in the small bubble is transferred back to the Taylor bubble.

Finally, it can be seen in Figures 4.23 and 4.24 that by further increasing the liquid flowrate to the condition of typical slug flow ($Fr_{TB}=1$), the level of entrainment is of a chaotic nature, with multiple events occurring simultaneously, which makes the identification of the mechanisms at play an arduous enterprise. The first observation to be made from Figures 4.23 and 4.24 is the high volume of bubbles present in the wake region, covering the whole radial section of the pipe. From the images, and more easily from the observation of the videos recorded, it is possible to attest that most of the entrainment occurs close to the pipe wall.

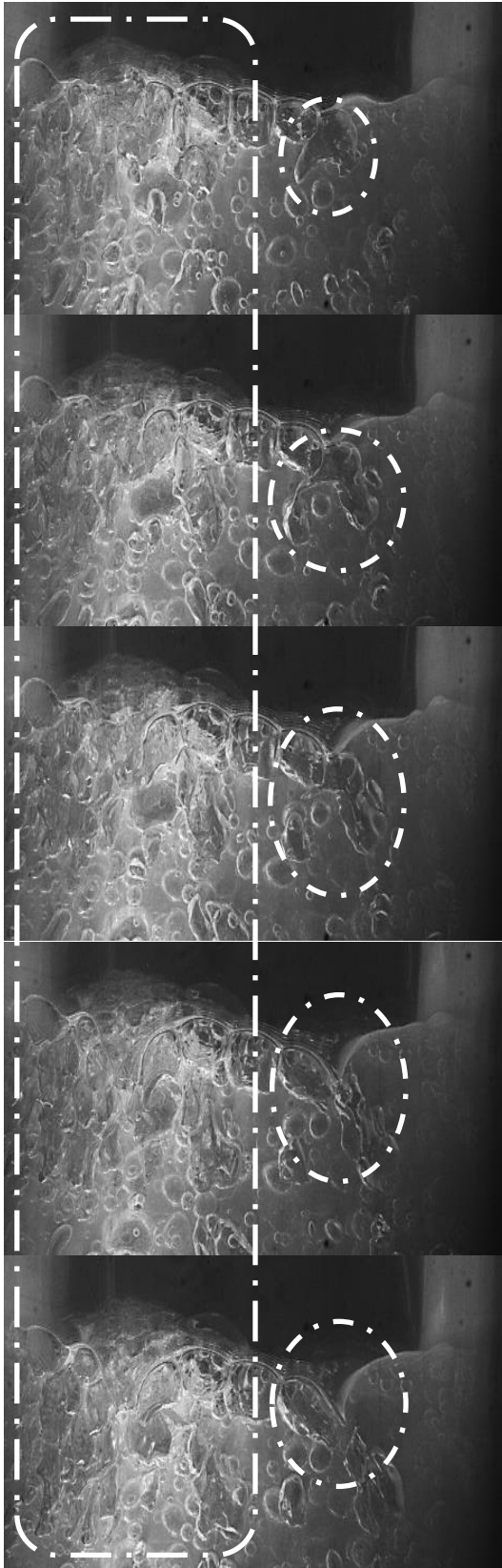


Figure 4.23: Combination of entrainment mechanisms in a typical slug flow condition, where a crater is generated in the re-coalescing bubble ($Fr_{TB} = 1.012$; gas flowrate of 10 l/m).

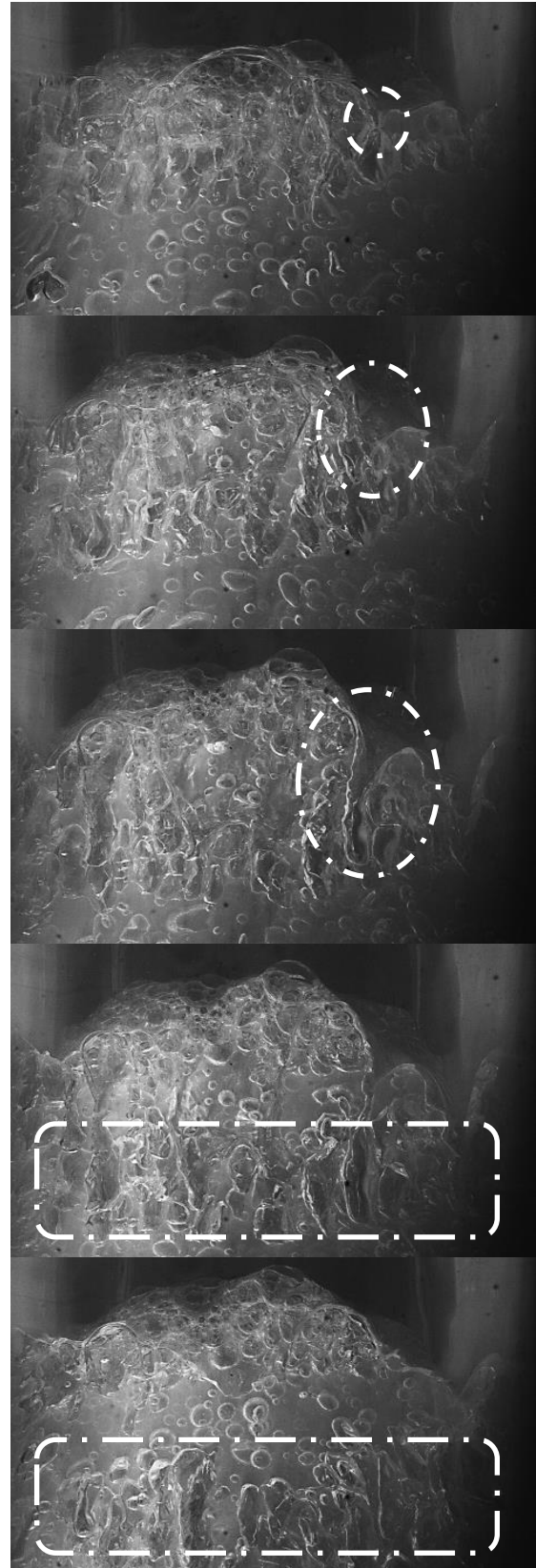


Figure 4.24: Impact of large wave on the entrainment mechanisms in a typical slug flow condition, where a large crater is observed ($Fr_{TB} = 1.012$; gas flowrate of 10 l/m).

Furthermore, it can be seen that both entrainment mechanisms identified occur simultaneously. In the left region of Figure 4.23, a large number of entrainment events are seen, most of them resembling the *self enhancement mechanism* displayed in Figure 4.22, where pockets of air are created in the bubbles that are attached to the skirt region, until entrainment occurs when these pockets break up. Additionally, a lot of the bubbles attached to the skirt are dragged downwards due to the continuous action of the falling film. The area represented by the circles in Figure 4.23 shows the case where such a high concentration of air is being injected into a single bubble, the bubble breaks in a fashion similar to the way seen in a *crater generation* in the skirt of the Taylor bubble. Furthermore, the instability that it generates at the skirt level initiates a *crater generation* event, as shown in the final stages of Figure 4.23.

Figure 4.24 shows more specifically how unstable the skirt region is in typical slug flow conditions, with transverse movements present which are originated once a large wave passes through, which poses large disruptive effects. This is made more evident by the huge crater generated in the area to the right side of Figure 4.24 (circle), where the skirt interface is highly unstable, since it does not show a flat profile. Additionally, another feature that shows how disruptive a large wave can be is the large number of huge bubbles that de-attach simultaneously with the bubble generated from the crater, as seen from the last stages of Figure 4.24 (denoted with the white rectangular box).

An aspect that is worth considering is that in a case of pure slug flow, where the Taylor bubble is moving in relation to the wall of the pipe, the amount of bubbles that manage to re-coalesce back to the Taylor bubble and hence, give rise to the *self-enhancement mechanism* is expected to be lower. This is due to the fact that since the Taylor bubble is moving in the upwards direction, it would be less likely for re-coalescing bubbles to catch up with it, unless strong vortices were present. As a result, in such cases, *entrainment through crater generation* would be a more active mode of entrainment. This is especially valid given the fact that with increasing pipe diameter, Taylor bubbles start becoming more asymmetrical and irregular, thus meaning that more transverse instabilities would be observed at the skirt level, which

would enhance the *crater generation mechanism*. As a result, both mechanisms here identified are expected to be occurring in a typical slug flow situation, but their probability of occurrence would possibly be different.

These examples provide a flavour of how chaotic the entrainment events are, thus explaining why literature was scarce with mechanisms that describe the dynamics of how these phenomenological events are initiated and how they develop.

It is apparent that there is some validity to the entrainment mechanism proposed by Delfos (1996), where the effect that the increasing falling film velocity, wave velocity and wave amplitude have on the frequency of entrainment events has been shown. However, it is also clear that entrainment is a localised process, where it is not only the waves that are responsible for its occurrence, but also, and very importantly, the re-coalescing bubbles have a large role in further enhancing the entrainment events. This is a feature that has not been previously reported and should in the future be taken into consideration.

4.7 Summary and conclusions

This chapter reported on the full characterization of the falling film surrounding an artificial Taylor bubble, and how its dynamics affect the entrainment process between the Taylor bubble and the wake region. The findings provide a reliable comparison with a typical upwards slug flow.

More specifically, the following conclusions were drawn:

- The merits of employing such a high spatial and temporal resolution technique have been shown in the study of artificial Taylor bubbles, since the interaction between the falling film dynamics and entrainment of gas from the bubble to the wake region has been visually demonstrated. From the observation of the spatiotemporal plots, entrainment increases perceptibly with increases in liquid flowrate and a pattern is observed between the wave dynamics and entrainment events. Furthermore, the re-coalescence mechanism at the centre of the pipe was observed;

- With increasing liquid flowrate, an increase is observed in the film thickness of the falling film and in the relative amplitude, speed and frequency of the waves present in the falling film. The speed of the waves is also seen to increase with axial position from the nose of the artificial bubble. In particular, a linear relationship is seen between the wave frequency and the liquid Reynolds number, whereas the wave velocity increases linearly with the inverse square root of the film thickness along the axial coordinate. Changing the gas flowrate shows almost no change in the aforementioned parameters;

- Through the manipulation of the liquid flowrate used to replicate the falling film surrounding the Taylor bubble, the gradual evolution of entrainment mechanisms could be observed, even if this represented unphysical typical slug flow conditions ($Fr_{TB} < 1$). Two new modes of entrainment have been identified and characterized: (i) through crater generation, (ii) through self enhancement of entrainment by action of re-coalescing bubbles, with both occurring simultaneously in slug flow conditions ($Fr_{TB} = 1$). It was concluded that the action of re-coalescing bubbles has been previously disregarded in terms of its impact on the entrainment. This mechanism is important and it was observed that these bubbles once present near the skirt of the Taylor bubble, cause a great number of instability events.

Chapter 5. Upwards and Downwards Annular Flow Experiment in a 11.7mm Pipe

As discussed in Chapter 2, despite the large number of studies in the open literature that attempt to characterize the disturbance wave behaviour under various conditions, there has not been a clear focus on how the flow orientation (in vertical flow) for a constant set of pipe diameters, phase flowrates and properties affects their behaviour. The work presented in this Chapter fills this gap by reporting on experiments conducted in an 11.7 internal diameter pipe in both upwards and downwards annular flow situations. The details of the experimental campaign employed to obtain the results below are provided in Section 3.3.2 of Chapter 3. Through the analysis of spatiotemporally resolved film thickness measurements acquired with BBLIF, a high level of characterization of the interfacial wave phenomena present in such conditions will be provided. This will be of great assistance in the improvement of existing analytical models, and provides validation data for potential computational fluids dynamics (CFD) simulations that aim to predict such flows.

5.1 Liquid film characterization close to the inlet

Although considerable effort has been expended in the past to study the behaviour of liquid films in a fully developed region (typically 2 – 4m downstream of the inlet), very few detailed measurements have been made of the phenomena in the developing flow stage, more specifically in the first 100 mm downstream of the inlet. The knowledge of the flow parameters in such conditions is considered important for industrial design and useful for the improvement of existing analytical models and for finding empirical correlations to aid in predicting flows (Hazuku et al., 2008).

5.1.1 Spatiotemporal plots

Figure 5.1 shows some examples of spatiotemporal plots obtained between 0 – 121mm from the inlet section for the upwards orientation of the flow.

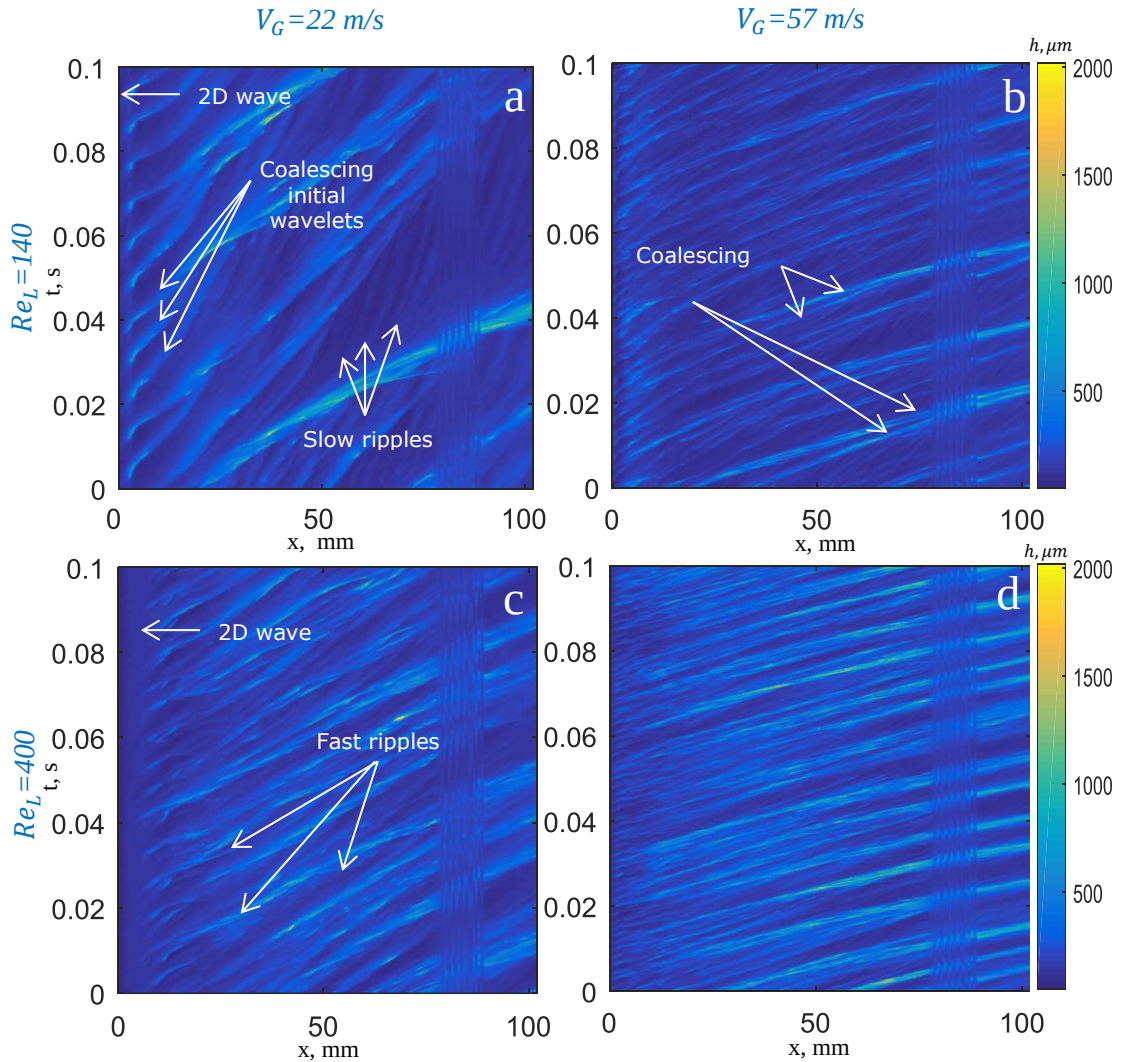


Figure 5.1: Examples of spatiotemporal records obtained close to the inlet for various gas and liquid flowrate combinations in upwards flow.

The spatiotemporal results obtained are in good agreement with the work of Alekseenko et al. (2015), who performed BBLIF measurements in the same measurement area in a 15mm internal diameter pipe in downwards flow. Moreover, qualitatively, no significant behavioural difference is seen between the upwards and downwards configuration at this stage from the spatiotemporal plots.

From Figure 5.1, it can be seen that the liquid phase exits the slot of the inlet section as a 2D structure. This is almost immediately broken down into high frequency, small wavelets due to the shearing action of the gas phase. These are presumably periodic waves of maximum growth appearing due to the Kelvin-Helmholtz instability, where the interface becomes wavy due to the shearing action of the gas phase on the liquid phase (Alekseenko et al., 2015, Lamb, 1975, Levich, 1962). These initial wavelets are irregular in terms of their individual velocity, which ultimately leads to coalescence of neighbouring wavelets. This yields new waves with different properties and spatiotemporal behaviour.

With increasing liquid, but especially, gas flowrate, the frequency of these wavelets and their velocity increases significantly. In these scenarios, the 2D-waves are seen to be broken down much faster (closer to the inlet). With increasing frequency of the wavelets, their separation time is greatly reduced and the absolute scatter in their velocity is seen to increase. This leads to a shorter axial distance being required for the coalescence of neighbouring waves.

It should be noted that in the absence of coalescence, the initial wavelets tend to decelerate, losing their amplitude (dimmer intensity in the images) and changing in shape. The waves resulting from the coalescence of the small initial wavelets are seen to be larger in terms of their amplitude and velocity, and, as reported for the first time by Alekseenko et al. (2015), this is the mechanism leading to the formation of disturbance waves. A confirmation of the validity of such a mechanism is the presence of fast ripples on top of these newly formed waves (see Figure 5.1) that leads to droplet entrainment, which is a main characteristic of a disturbance wave.

Examination of the spatiotemporal plots close to the inlet provides invaluable insight into the phenomenological events that can help researchers to qualitatively obtain a better understanding of the behaviour of annular flows. Furthermore, they allow for the extraction of information that can quantify the different parameters observed. These can range from film thickness profiles, wave velocity profiles, temporal and spatial acceleration of waves and their frequency, which are discussed in the following subsections.

5.1.2 Film thickness profiles

The variation of time-averaged film thickness with axial distance for both flow orientations is shown in Figure 5.2. The examples shown refer to the lowest and highest liquid flowrates tested, while varying the gas flowrate.

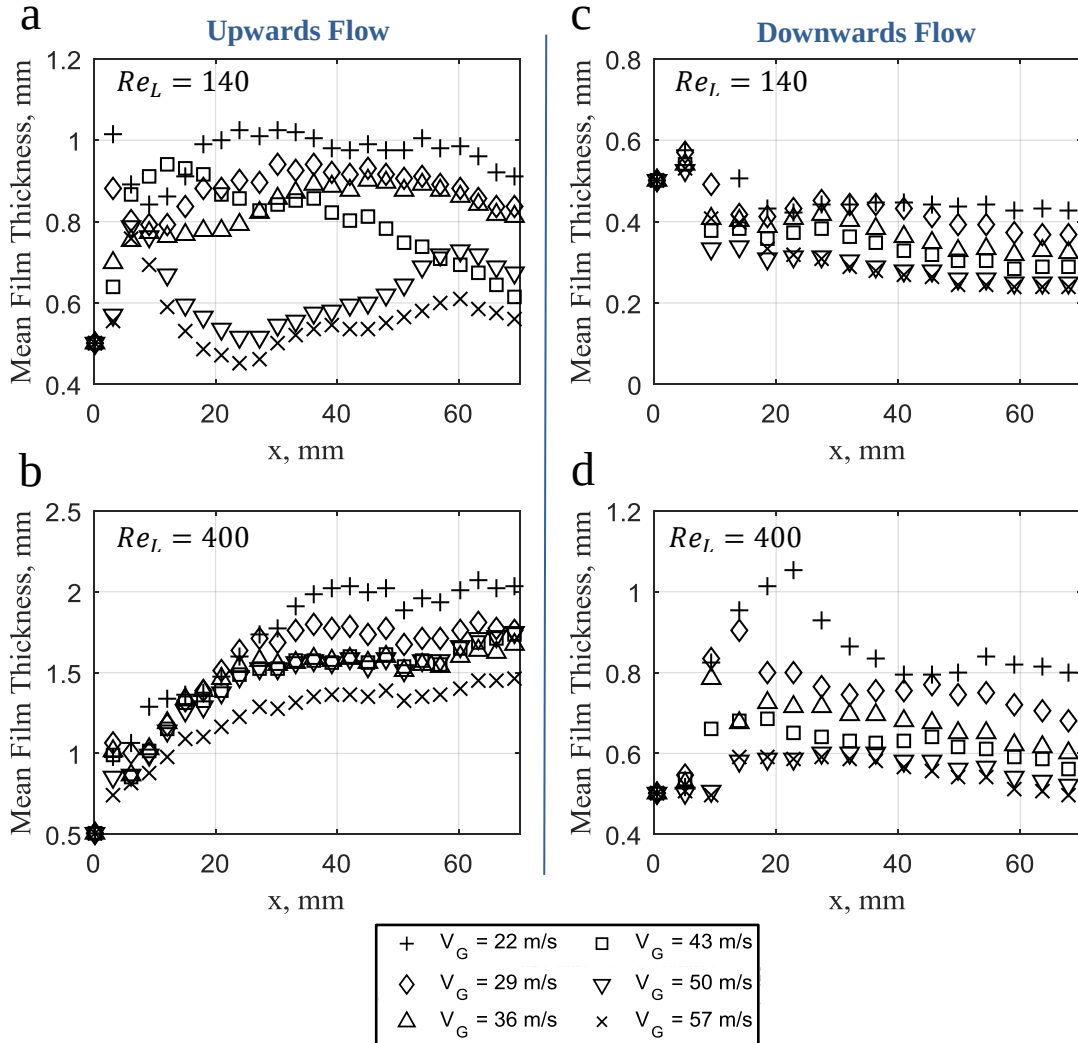


Figure 5.2: Variation of the film thickness with axial distance for both upwards (a, b) and downwards (c, d) flows. Figures a) and c) refer to the case of $Re_L = 140$ while varying the gas flowrate, whereas Figures b) and d) refer to the case of $Re_L = 400$.

It can be seen that in all cases, close to the inlet, an increase in film thickness is observed, which was also observed in the work of Wolf et al. (2001), which studied the flow development using conductance probes located at various axial intervals. This can be attributed to a transition from laminar to turbulent flow as the liquid phase exits the tangential slot of the inlet section, as the turbulent flow is thicker. Furthermore, the coalescence of the

wavelets reported in the previous section leads to some level of disorder in the film profile (around 5-20mm). After this stage, as the waves are being developed, a thinning of the film thickness is observed due mostly to the action of the gas shear, where the gas velocity and the interfacial shear stress increase as the flow develops due to the pressure gradient in the axial location (Alekseenko et al., 2015, Hazuku et al., 2008). A further validation of this occurrence is given in the fact that for all cases, with increasing gas velocity, a lower film thickness profile is observed. Another factor that can contribute to some extent to the thinning of the film thickness is some entrainment that can occur at this stage (Wolf et al., 2001). However, as seen from Figure 5.1, the level of entrainment is quite low as the disturbance waves have not fully developed at this stage.

Naturally, increasing the liquid flowrate leads to thicker film thickness profiles, since more liquid is being injected into the system.

Lastly, it can be also seen that the flow orientation has an effect on the film thickness profiles at this stage, since thicker film thickness profiles are observed in the upwards configuration, where the gravitational action is against the flow direction. This results in the liquid phase being ‘pushed’ together, making it thicker. A feature that supports this is the fact that the thinning of the film thickness profile is much less chaotic in the downwards flow configuration. Additionally, an exception to the thinning of film thickness is seen for the case of $Re_L=400$ for the upwards flow configuration (Figure 5.2c), where in the measurement area, the film profile is only seen to be plateauing. This is due to both the gravitational action and to the higher liquid flowrate being injected into the system, where the thinning of the film takes a longer axial distance to start occurring.

5.1.3 Wave velocity profiles of initial waves

In order to obtain the average velocity of the structures present in the film close to the inlet, the cross-correlation method described in Section 3.4.1 of Chapter 3 was applied to all the spatiotemporal plots recorded. The results are shown in Figure 5.3, again for the lowest and highest liquid flowrates tested while varying the gas velocity for both flow orientations.

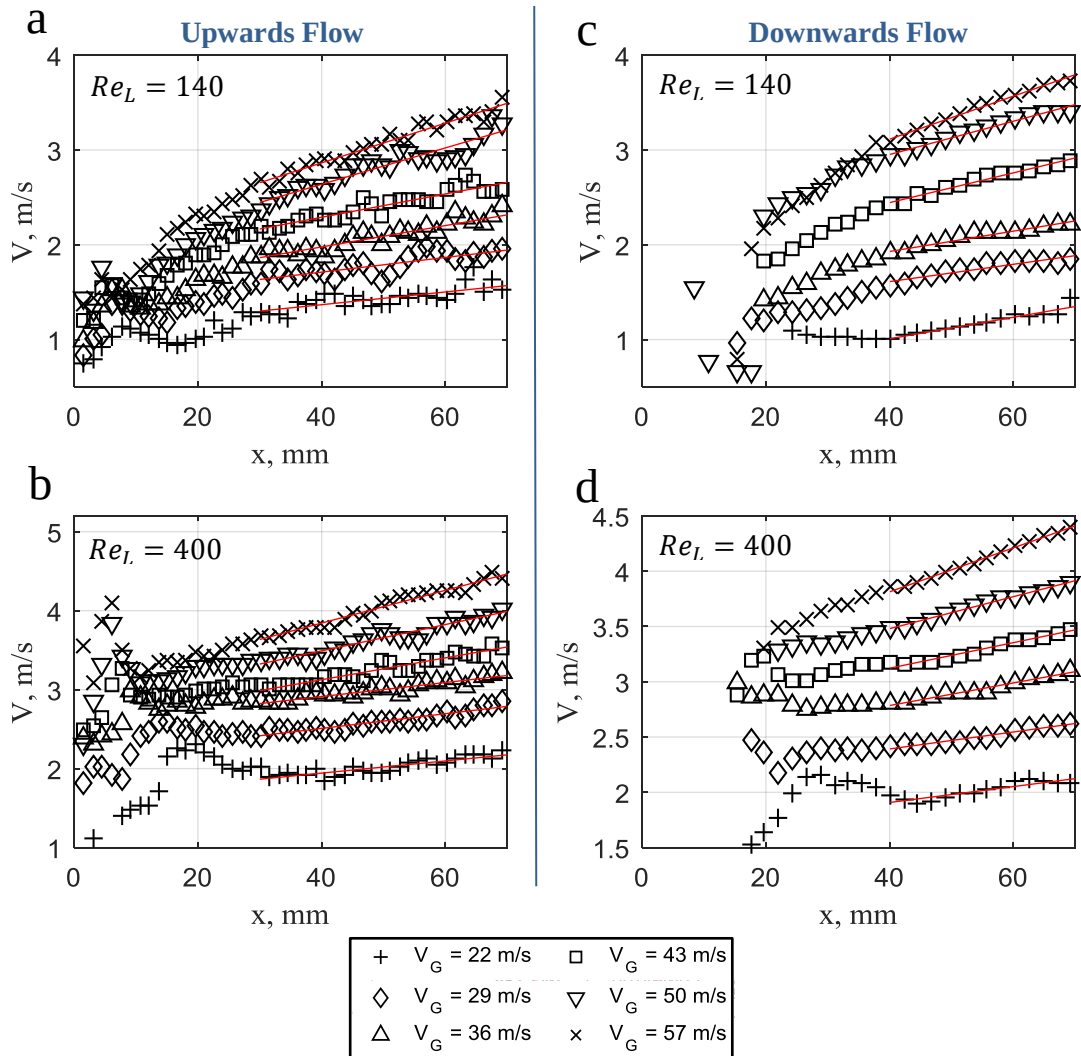


Figure 5.3: Evolution of cross-correlation velocity of waves with axial distance for both upwards (a, b) and downwards (c, d) flows. Figures a) and c) refer to the case of $Re_L = 140$ while varying the gas flowrate, whereas Figures b) and d) refer to the case of $Re_L = 400$. The red lines denote the region where the increase in velocity with axial distance is linear.

It can be seen that for all cases, the velocity increases generally with downstream distance, which can be related to the thinning of the film and the increasing shearing action that the gas phase has on the developing disturbance waves, which accounts for their acceleration. As expected, increasing both the liquid and gas flowrates leads to an increase in the velocity.

Close to the inlet, there is a rapid increase in the velocity as the liquid phase exits the tangential slot and is subjected to the shearing action of the gas-phase. This jump in velocity is slightly more pronounced in the upwards configuration since as seen in Figure 5.2, the film is thicker than in the downwards configuration and therefore prone to greater shearing action of the gas. This is followed by a short deceleration, which in their work in downwards annular flow in a 15mm pipe, Alekseenko et al. (2015) related to the decay of the initial wavelets that were formed due to the Kelvin-Helmholtz instability and that did not coalesce, as discussed in Section 5.1.1.

Finally, after this stage (around 30-40mm), the newly formed disturbance waves start developing and their velocity is seen to increase linearly with axial distance (denoted by the red lines in Figure 5.3, where the slope of this dependence increases with gas velocity. At this stage, the wave velocity for both upwards and downwards configuration appears to be similar. The study of the gradient of the linear approximation shown by the red lines in Figure 5.3 corresponds to the spatial acceleration of the waves, a_x , which is discussed in the next section.

5.1.4 Spatial and temporal acceleration of waves

The spatial acceleration of the waves, a_x , or in other words, $\Delta V / \Delta x$, for all regime points is shown in Figure 5.4a).

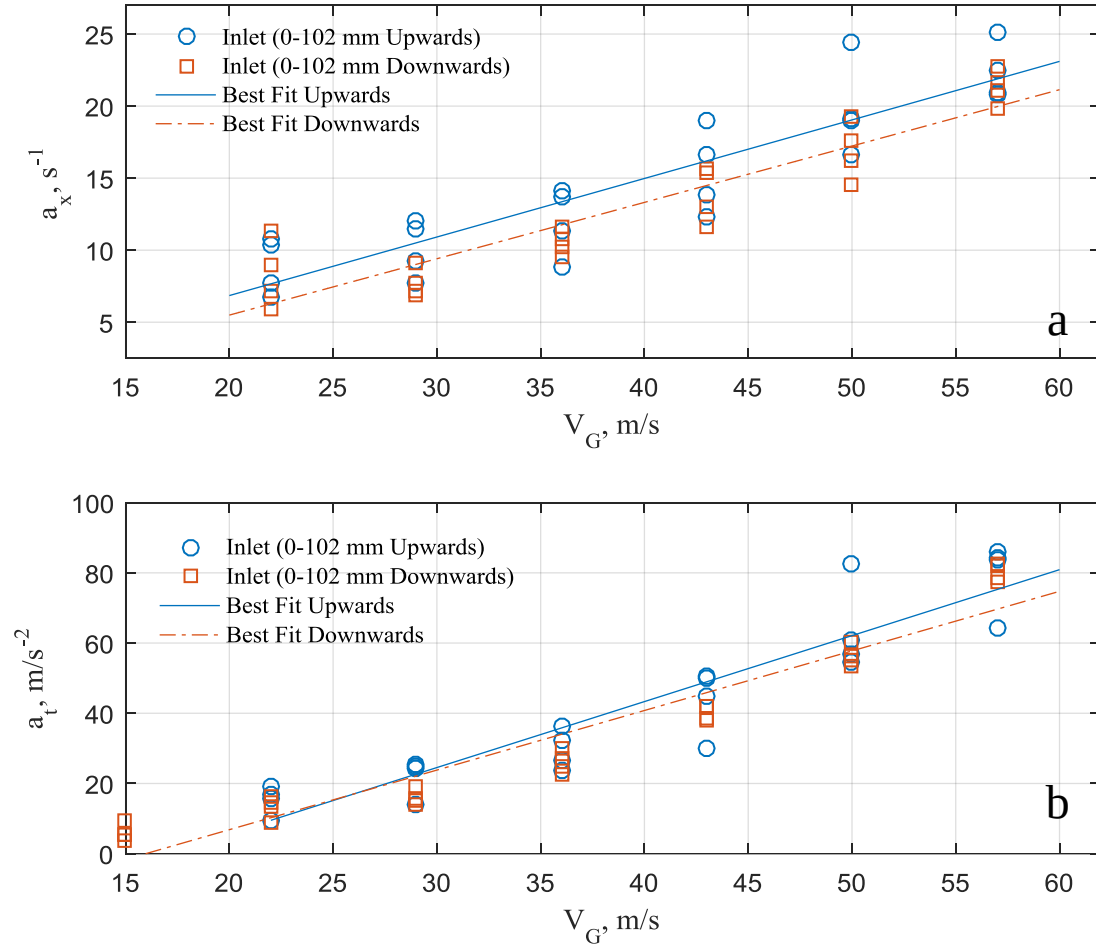


Figure 5.4: a) Spatial and; b) Temporal acceleration of disturbance waves obtained from analysis of the velocity profiles in Figure 5.3.

The spatial acceleration is shown to grow linearly with gas velocity for both upwards and downwards configurations, being slightly higher for the upwards case. However, through function *confint* in MATLAB, which returns the 95% confidence bounds associated with the best fit lines plotted, it was observed that the uncertainty of both the upwards and downwards best fit lines to be within the same bounds. Furthermore, varying the liquid flowrate has no effect on the overall spatial acceleration, as no particular trend has been identified.

Additionally, it is interesting to relate the acceleration in space with the change of wave velocity in time, a_t , since the latter is expected to be linked to the forces (such as interfacial

shear stress) acting on the disturbance waves (Alekseenko et al., 2015). The temporal acceleration, a_t , or in other words, $\Delta V / \Delta t$, was obtained from the following expression:

$$a_t = \Delta V / \Delta x \times \Delta x / \Delta t = \Delta V / \Delta t \quad (\text{Eq. 5.1})$$

Where $\Delta x / \Delta t$, the average velocity, is simply the average of data points in each individual velocity profile in the linear region.

The application of such method is seen in Figure 5.4b). Likewise to the spatial acceleration, there is a linear increase in the temporal acceleration with gas velocity, with no identifiable effect of the liquid flowrate on this parameter. At low gas superficial velocities, $V_G < 36 \text{ m/s}$, the temporal acceleration is the same for both upwards and downwards configurations. Above this value, the accelerations start to diverge, being higher for the upwards case, although, as with the previous case, the uncertainties of the best fit lines plotted are within the same bounds.

The study of the spatial and temporal accelerations of disturbance waves during their development stages can be therefore seen as a useful extra parameter that can be used in the validation of the CFD models that attempt to simulate annular flow conditions.

5.1.5 Spatial evolution of normalized power spectra

The next step was to perform a spectral analysis on the spatiotemporal records to investigate the downstream evolution of frequency of maximum power in the power spectral density. This was achieved through the application of the Fast Fourier Transformation procedure described in Section 3.4.2 of Chapter 3. The application of such procedure can be illustrated by Figure 5.5. The graphs correspond to the power spectral density obtained for particular axial locations, whereas the subfigures above correspond to the graphical representation of the power spectral density obtained for all the axial locations of the measurement area, viewing from the XZ plane. The objective of such an approach is to measure the frequency of the wavelets that lead to the formation of disturbance waves and to infer the evolution of the coalescence mechanism described in previous sections.

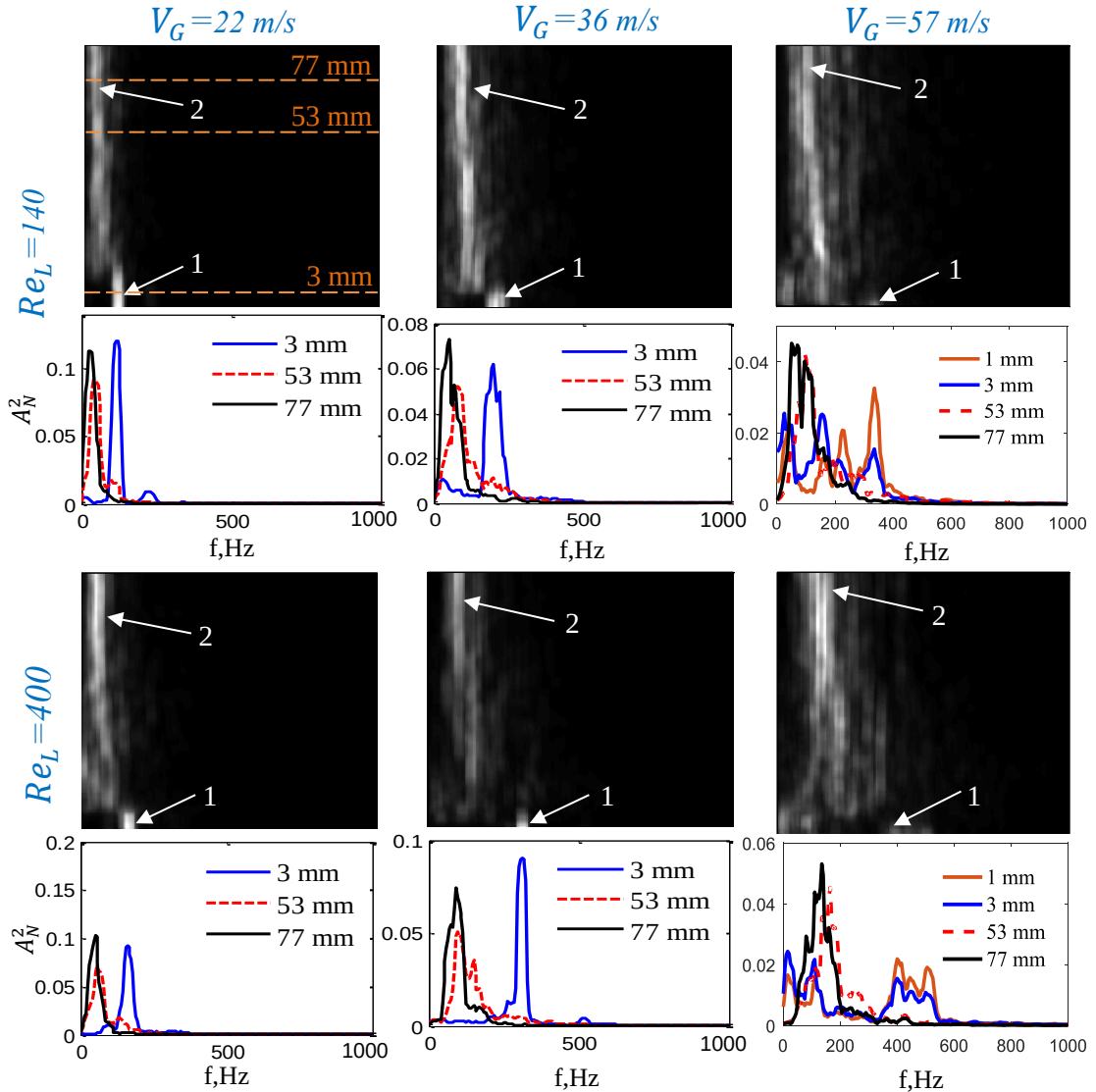


Figure 5.5: Spatial evolution of normalized power spectra for the upwards configuration.

For the cases of low to moderate gas superficial velocity (<36 m/s), the PSD close to the inlet (at 3mm) has one well pronounced peak, which is also marked as point (1) in the graphical subfigure. The pronounced peak corresponds therefore to the frequency of the wavelets that lead to the subsequent formation of disturbance waves. From the graphical subfigure it is possible to then observe that the PSD gradually shifts towards lower frequency values with downstream distance, after which stage the PSD does not undergo major changes in its shape (seen at 53 and 77mm from the inlet). This is due to the coalescence mechanism of the wavelets described above, where disturbance waves start to being formed. The position of the frequency peak at this stage is denoted by point (2) in the graphical subfigure. At higher gas superficial velocities (>36 m/s), the downstream evolution of the PSD is somewhat different. Close to the inlet (1-3 mm), between 0 and the point of the maximum frequency, the PSD shape is seen to be stretched. Due to the higher shearing action of the gas phase, the high frequency peak is actually seen closer to the inlet than in previous cases (1mm), as the wavelets are more easily generated. The PSD is also seen to not reach zero values, which can be related to the irregular characteristics of the wavelets, in particular, to their large variation in amplitude and time separation (Alekseenko et al., 2015). Likewise to the previous cases, there is a shift in frequency towards lower values, although the PSD is more decayed and there is a wider variation of frequency of the waves.

In general terms, it is worth noticing that with increasing liquid flowrate, there is an increase in the initial frequency of the wavelets formed. However, this increase in wavelet frequency is much more strongly affected by an increase in gas superficial velocity.

Lastly, in the case of the downwards configuration, the same patterns are observed, with the only difference being that the distance at which the initial wavelets are formed is slightly further from the inlet (between 5-10 mm for high and low gas superficial velocity cases respectively). This difference is obviously due to the effect that the gravitational action has on the liquid film thickness, leading to slightly higher interfacial shear stresses at this stage.

The actual frequency values of the initial wavelets for both upwards and downwards configurations were analysed and are described in the next section.

5.1.6 Frequency of wavelets that lead to the formation of disturbance waves

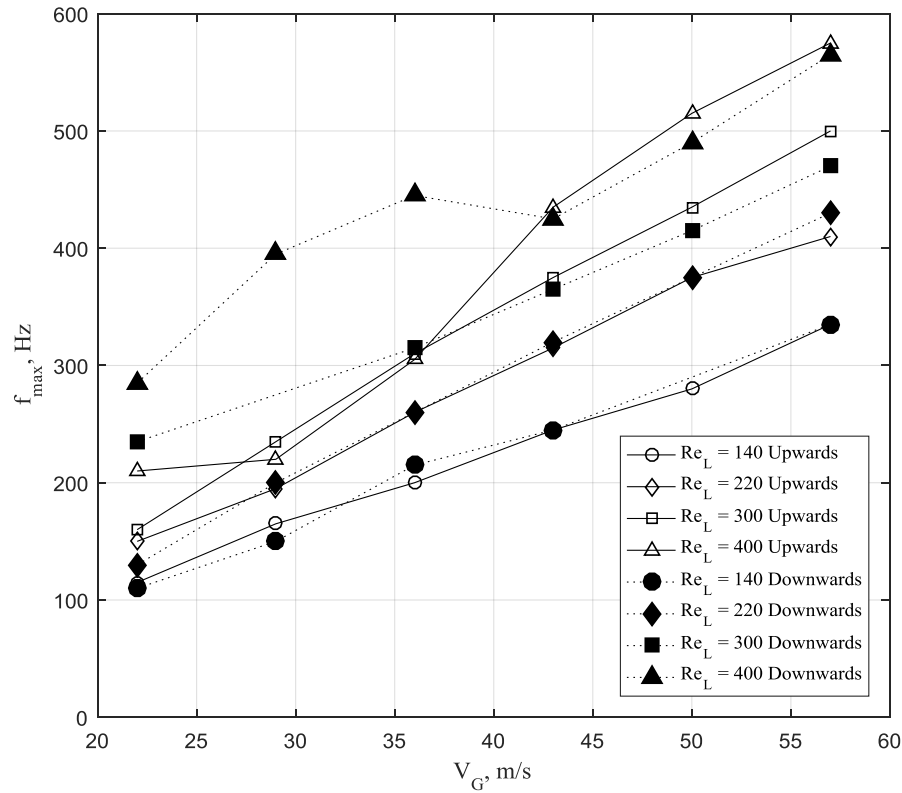


Figure 5.6: Frequency of initial wavelets for both upwards and downwards flows.

Figure 5.6 shows the values of the peaks in the PSD close to the inlet for all gas and liquid flowrates combinations tested for both upwards and downwards flow configurations. Similarly to what Chu and Dukler (1975), Azzopardi (1986) reported in their study of disturbance waves, the frequency of the wavelets that lead to their subsequent formation is also seen to increase linearly with increasing gas superficial velocity. An increase in liquid Reynolds number also leads to an increase in the frequency of the wavelets. This is expected since both waves are directly linked, since during the mechanism of coalescence, there is an energy transfer from the high-frequency initial wavelets to the lower-frequency disturbance waves.

It is worth mentioning that the trends seen in Figure 5.6 are obtained by taking into consideration that the particular axial location at which the wavelets are initially formed varies slightly depending on the flowrate conditions being tested. Otherwise, as in the work of

Alekseenko et al. (2015), frequency values that are out of the general trend could be obtained, where extrapolation of the data would be required in such cases.

Lastly, an important feature that can be captured from Figure 5.6 is that despite the different axial location at which the wavelets are formed, particularly for different flow orientations; for the same flowrate conditions, the frequency of the initial wavelets is seen to be the same for both upwards and downwards flows. The only exceptions can be seen at the lowest gas superficial velocities in the case of $Re_L = 400$, which can be attributed to the uncertainty associated with the application of the FFT procedure, which is detailed in Appendix C.

With a full description of the behaviour of annular flows in both orientations close to the inlet given in the previous subsections, the focus shifted towards studying the spatiotemporal records of film thickness further downstream. More specifically, the characterization of the disturbance wave behaviour is of particular interest, where the flow is assumed to be close to fully developed. This is the topic of the next sections.

5.2 Liquid film properties under the disturbance wave regime further downstream

5.2.1 Spatiotemporal plots

Figure 5.7 shows examples of spatiotemporal records of the film thickness, $h(x,t)$, obtained at 330–430 mm from the inlet.

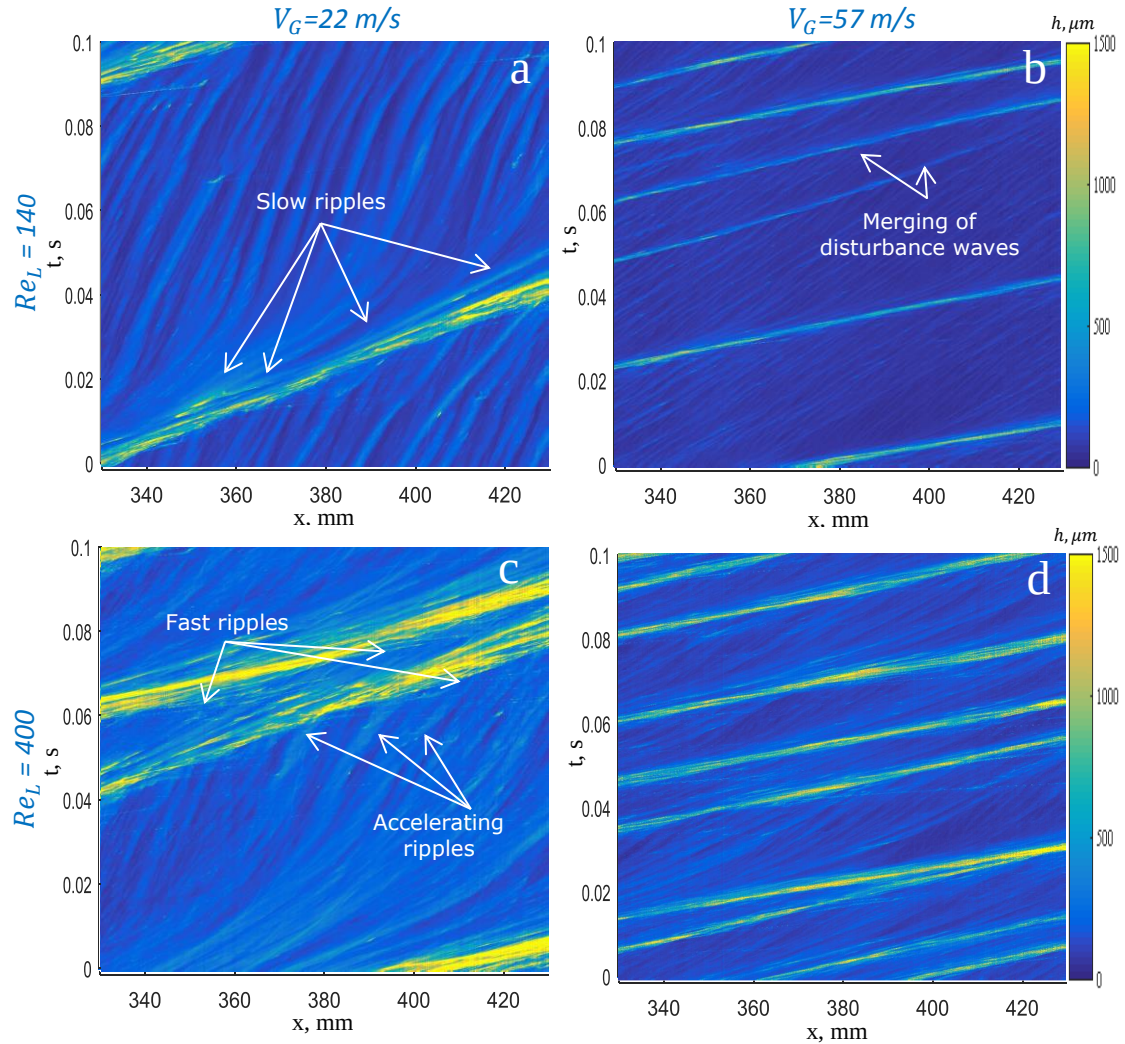


Figure 5.7: Examples of spatiotemporal records obtained at 330 – 430mm from the inlet for various gas and liquid flowrate combinations in upwards flow.

Many qualitative events can be identified from the observation of such spatiotemporal plots, which aid researchers to better understand and characterize the behaviour of disturbance and ripple waves in a close to developed condition. This has been extensively detailed in the

work of Alekseenko et al. (2012a), Alekseenko et al. (2014) and Alekseenko et al. (2015), which serve as the backbone of this annular flow study.

As discussed in Chapter 3, the local brightness of the spatiotemporal plots is directly proportional to the value of film thickness. Therefore, in Figure 5.7, the brightest points correspond to the trajectory of the disturbance waves present in the film, which can be seen to be several orders higher in terms of their amplitude and width. These are seen to have their individual velocity, which in certain cases leads to the coalescence of consecutive disturbance waves, such that the resultant wave possesses the velocity of the faster former individual wave. The base film is seen to be covered with ripples with velocity much lower than that of the disturbance waves. These are seen to be generated at the rear slopes of the disturbance waves, where they typically slide back to the base film behind the parent disturbance wave and travel at a relative constant velocity until the following disturbance wave absorbs them. Close to this stage, the ripple wave can accelerate. However, depending on the relative position of origin, the ‘new born’ ripples can also travel faster than the parent disturbance waves, more specifically travelling at the disturbance wave crest toward its front and disappearing there. This is due to the disruption of the fast ripple by the gas shear into droplets through the ligament break-up mechanism.

Finally, it can be seen that the disturbance wave trajectory is close to linear, thus meaning that they are travelling at a constant velocity, which is one of the pre-requisites to satisfy the fully developed condition. It is worth mentioning that unlike the wavelets, which it was demonstrated that they are formed from, disturbance waves exhibit a high level of non-periodicity. As a result, this requires for the application of a tracking algorithm discussed in Section 3.4.3 of Chapter 3, whose successful application is denoted by the red lines in Figure 5.7d. With this tool, a full characterization of the disturbance waves can be obtained not only in terms of averaged values of parameters such as frequency, velocity, time and distance separations, but also by their distribution, given that the spatiotemporal location of each individual wave has now been obtained. This is the topic of the next sections.

5.2.2 Disturbance wave velocity profiles

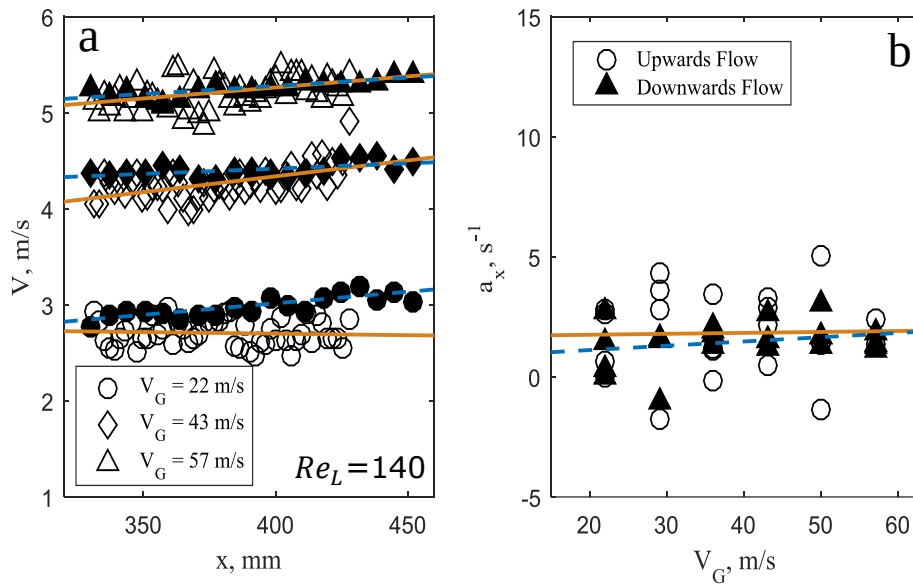


Figure 5.8: Evolution of velocity of disturbance waves with downstream distance (hollow and full symbols representing upwards and downwards flow respectively); b) spatial acceleration of disturbance waves for all cases tested. In both plots, full (orange) and (blue blue) dotted lines correspond to the best fit lines plotted for the upwards and downwards annular flow cases respectively.

Observation of the evolution of disturbance wave velocity for the case of $Re_L = 140$ obtained with the cross-correlation method described in Section 3.4.1 of Chapter 3, as seen in Figure 5.8a, shows only a slight increase in wave velocity with axial distance, independent of the flow orientation. The same trend is seen with variation of the liquid Reynolds number. This indicates that the waves are close to reaching a fully developed state, since their velocity is almost constant.

Additionally, the distance required for full development does not appear to be dependent on the orientation of the flow, as both upwards and downwards plots show no apparent difference. This is further substantiated by investigating the spatial acceleration of the disturbance waves of all flowrates combinations tested, as shown in Figure 5.8b. As in the calculation of the spatial acceleration of waves close to the inlet, discussed in Section 5.1.4, this was achieved by simply obtaining the gradient of the best fit lines plotted for each data set in Figure 5.8a. Figure 5.8b shows that the spatial acceleration of the disturbance waves shows no variation with increasing gas flowrate, and is close to zero as a constant velocity is close to being achieved. Furthermore, there is no noticeable trend of the influence of liquid Reynolds number on the overall spatial acceleration of disturbance waves.

5.2.3 Average velocity and frequency of disturbance waves

As extensively reported in literature (Chu and Dukler, 1975, Azzopardi, 1986), increasing the gas superficial velocity results in a linear increase in disturbance wave velocity and frequency, which is confirmed in Figure 5.9. An increase in liquid Reynolds number also leads to an increase of both parameters.

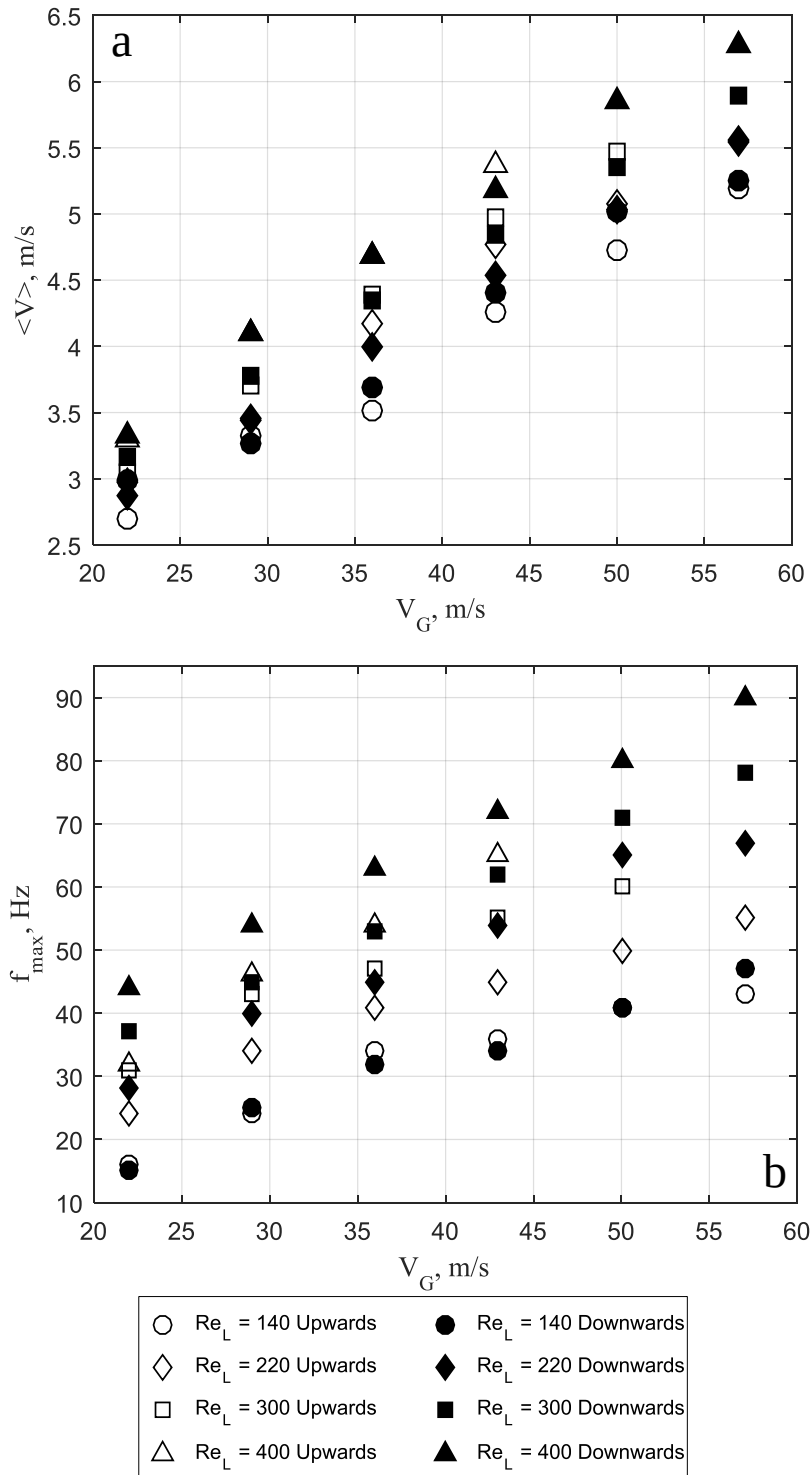


Figure 5.9: a) Average disturbance wave velocity; b) Frequency of disturbance waves measured with tracking algorithm.

The average disturbance wave velocity was measured by averaging the velocity values at each axial location and is shown in Figure 5.9a. This is in agreement with the velocities obtained by averaging the velocity of each individual wave obtained from the tracking algorithm. The latter was achieved by calculating the gradient between the points where each disturbance wave was first and last observed. The frequency of the waves, shown in Figure 5.9b, was calculated by counting the number of waves detected by the tracking algorithm and dividing by the time of capture.

Although, there is no significant difference in the disturbance wave velocity between upwards and downwards flow, it can be observed that this is not the case for the frequency of the disturbance waves. With exception to the lowest liquid Reynolds number tested, Figure 5.9b shows that despite having the same velocity, the frequency of disturbance waves is higher in downwards flow than in upwards flow for the same conditions tested. This is an indication that the gravitational action has an impact on the number of disturbance waves present in the film at 37D from the inlet, promoting a higher level of disturbance wave coalescence in the upwards configuration at this stage. In the case of $Re_L=140$, the amount of liquid present in the system is not large enough for the gravitational action to affect the number of waves created. However, this difference in wave frequency with flow orientation has implications in parameters such as distance and time separation between disturbance waves, and possibly on the intermittency and width of these disturbance waves, which is covered in the following sections.

5.2.4 Average time and distance separation of disturbance waves

As discussed in Section 3.4.3 of Chapter 3, the time separation and the distance separation between consecutive waves can be obtained, since the spatiotemporal location of each individual disturbance wave is known through the tracking algorithm. The resultant measured time and distance separation between the disturbance waves between 330 – 430 mm from the inlet is shown in Figure 5.10 for both flow orientations.

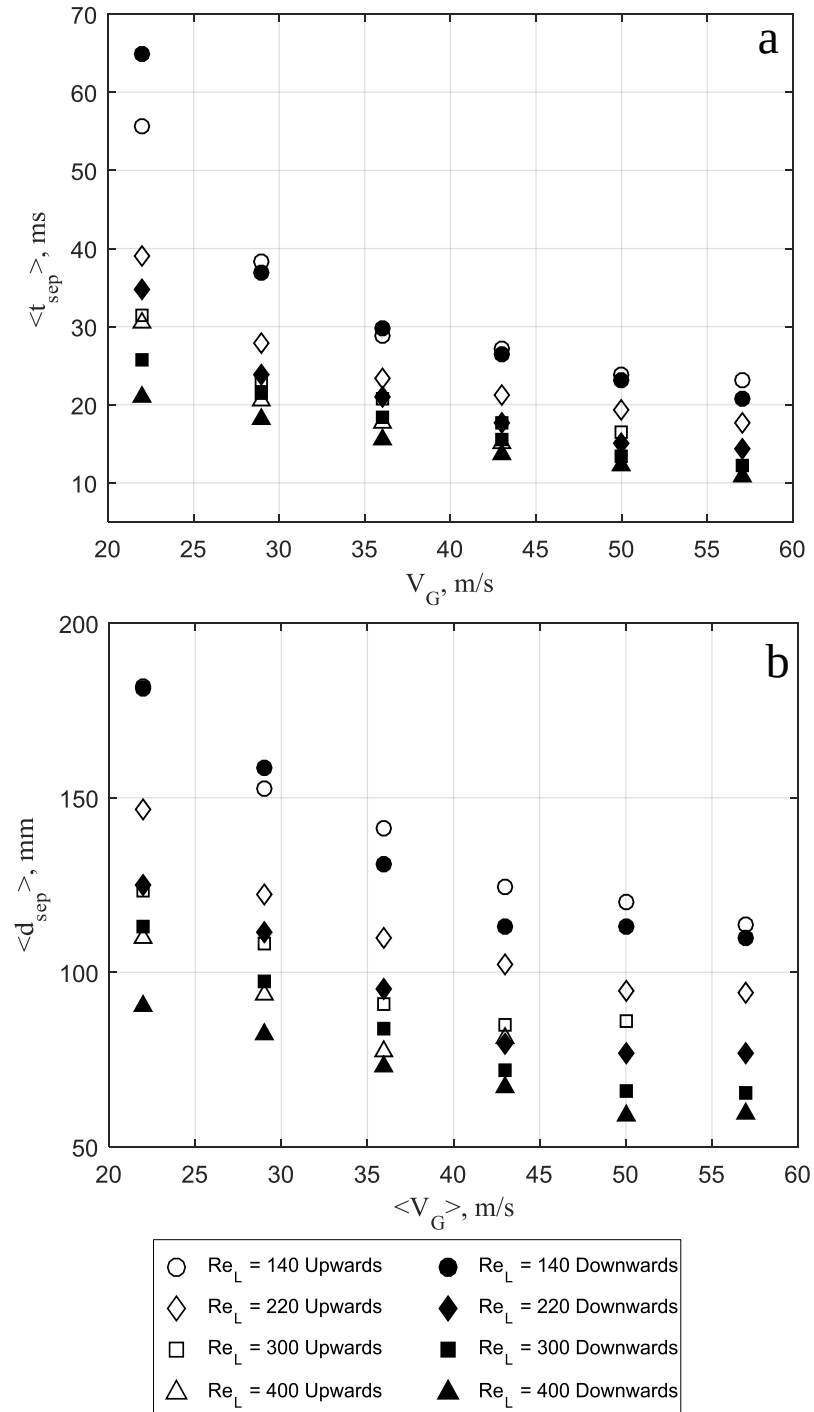


Figure 5.10: Average a) time and b) distance separation of disturbance waves.

As expected, both mean time and distance separation between disturbance waves decrease with increasing both the gas and liquid flowrates, since, as shown in Figure 5.9b, the frequency of the waves increases with both these parameters. Since the frequency of disturbance waves for the lowest liquid Reynolds tested is independent of the flow orientation, it can be seen from Figure 5.10 that the time and distance separation values are almost the same for both orientations at this Reynolds number. However, for the remaining cases, due to the higher number of disturbance waves in the downwards configuration, these parameters are lower for the downwards case.

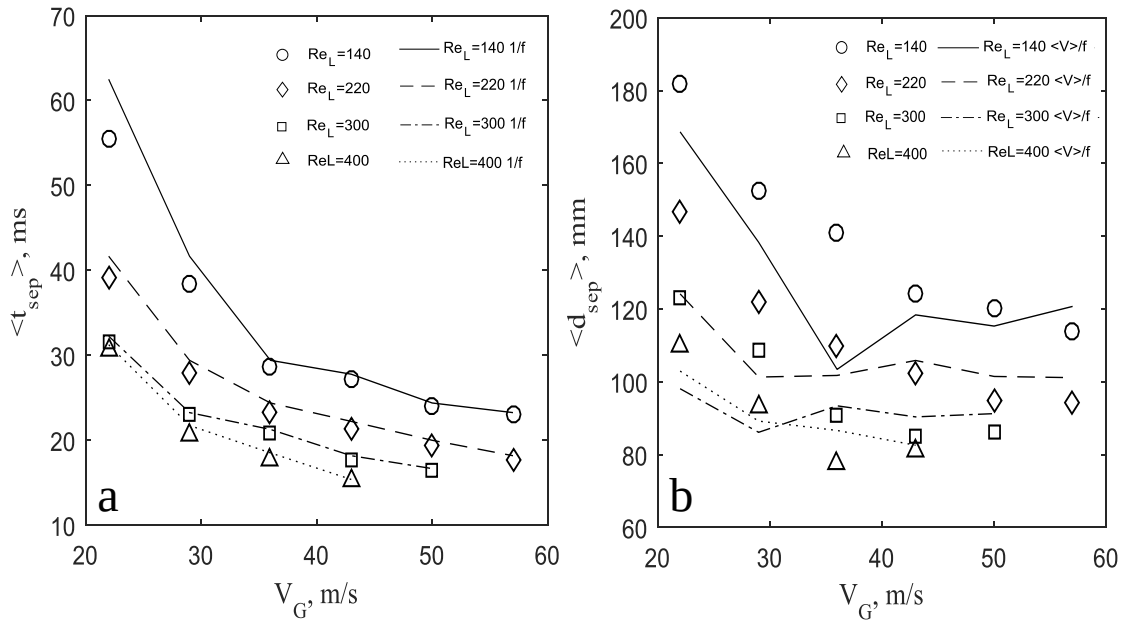


Figure 5.11: Comparison of the measured time separation of disturbance waves between the values obtained from the tracking algorithm and theoretical values for the upwards configuration.

Additionally, it is important to acknowledge that these parameters change with downstream location, since disturbance waves possess their own individual velocity. As discussed in Section 3.4.3 of Chapter 3, the results obtained come from an average of the calculation of these parameters at every 50 pixels of the spatiotemporal plot. As a result, there is a slight discrepancy between the values for the time and distance separation obtained with the tracking algorithm, and the theoretical ones, obtained with the following relationships:

$$t_{sep,theoretical} = 1/f \quad (Eq. 5.2)$$

$$d_{sep,theoretical} = \langle V \rangle / f$$

This is illustrated in Figure 5.11.

5.2.5 Normalized distributions of velocity, time and distance separations of disturbance waves

As discussed in the previous sections, the tracking algorithm allows for the spatiotemporal location of each individual disturbance wave to be obtained, thus allowing not only for the measurement of the parameters to be measured in this study in terms of their mean values, but also for the normalized distribution of these parameters to be obtained, which is shown in Figure 5.12. This is the kind of statistics that is of vital importance to CFD modellers, since it provides the ability to fully validate the results obtained from their simulations.

Figure 5.12a) and b) show that the normalized velocity obtained with a bin width of 0.75 m/s displays velocity distributions with a shape similar to one found in a normal distribution. Additionally, it can be seen that with increasing superficial gas velocity, the variation in individual wave speed increases slightly, as the plots start displaying a wider profile, probably due to the increased level of turbulence occurring at these conditions. This is the case irrespective of the liquid Reynolds number.

Conversely, the normalized time separation in Figure 5.12c) obtained with a bin width of 20 ms shows that the variation in time separation between individual waves is higher for the lowest superficial gas velocities, since the number of the disturbance waves present in the base film is lower and due to the inherent lack of periodicity of these same disturbance waves. With increasing superficial gas velocity, the frequency of disturbance waves increases perceptibly across the entire base film, and therefore the time separation between waves decreases, resulting in the shifting of the plots towards the left hand side. This is more evident in the case of the lowest liquid Reynolds tested (Figure 5.12c). In the case of the highest liquid Reynolds tested (Figure 5.12d), since the frequency of the waves is also affected by this parameter, the variation in time separation does not exceed 50 ms. This is further substantiated with the resultant distance separation distribution (Figure 5.12 e and f), which starts shifting towards the left hand side with increasing liquid Reynolds number. Finally, it is important to mention that the same general trends are observed for the downwards orientation.

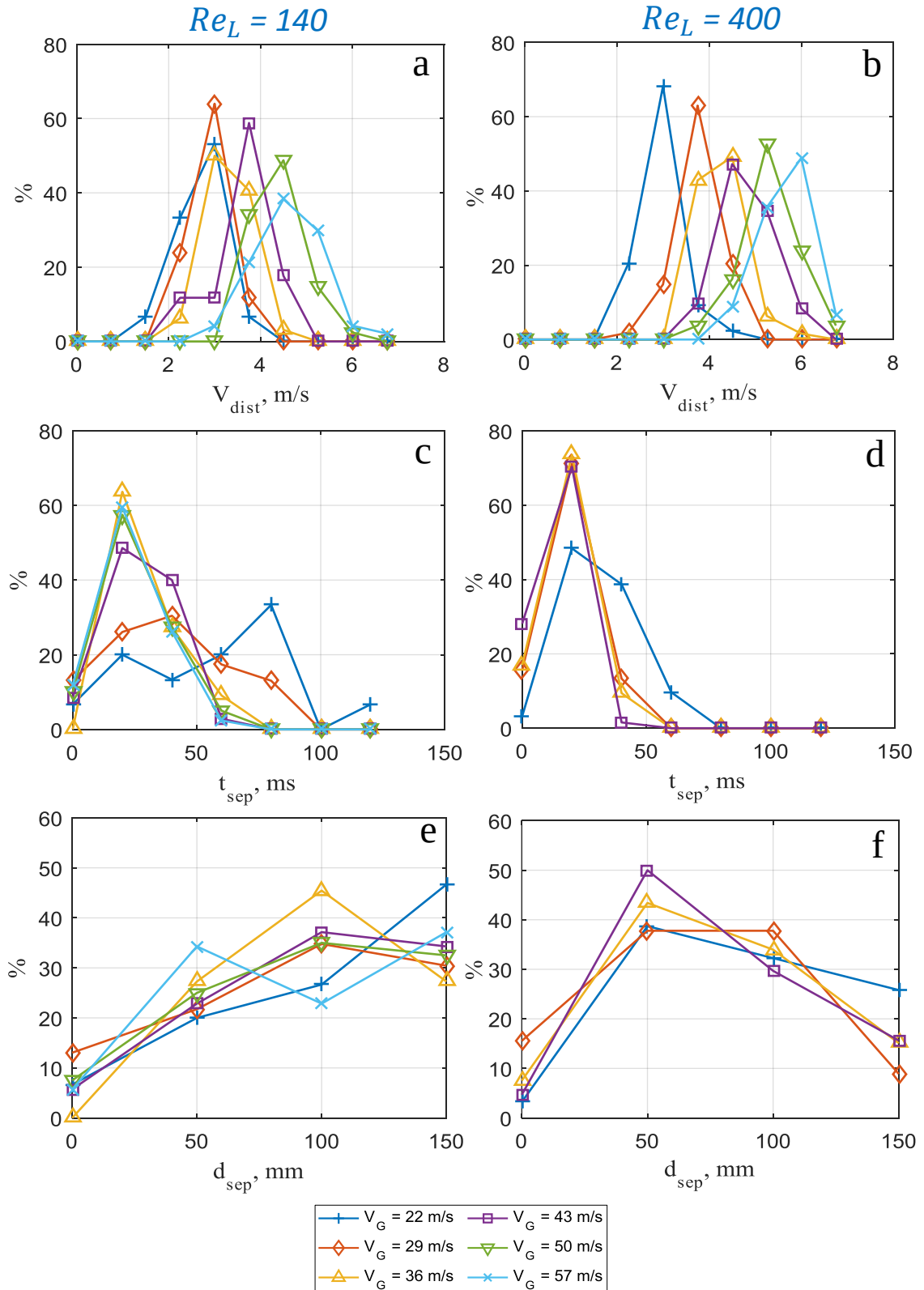


Figure 5.12: Normalized distribution of velocity (a and b), time separation (c and d) and distance separation (e and f) of disturbance waves for the upwards case.

5.2.6 Intermittency, ratio of time spent per disturbance wave, and disturbance wave width

In Section 3.4.4 of Chapter 3, the method employed to measure the intermittency of disturbance waves, or in other words, the total time that the disturbance waves are present in the signal over the total length of the time series record, was detailed. Figure 5.13 shows the resultant intermittency of disturbance waves obtained for both upwards and downwards orientations.

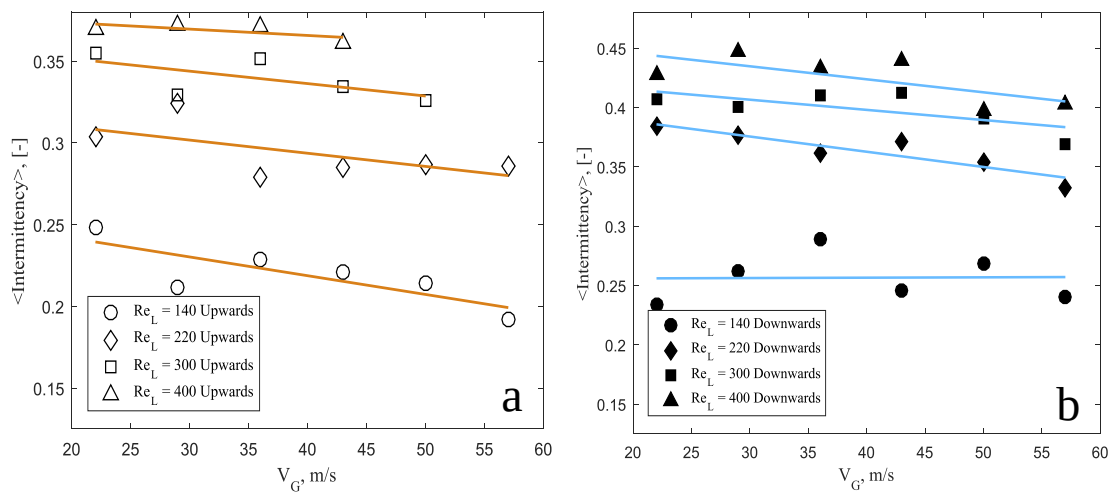


Figure 5.13: Intermittency of disturbance waves for: a) upwards and; b) downwards orientations.

A common feature in both graphs is the strong increase in intermittency of disturbance waves with increasing liquid Reynolds number, as the frequency of disturbance waves increases with this parameter. However, since as shown in Figure 5.9b, the frequency of disturbance waves is higher for the downwards orientation (for the higher liquid Reynolds numbers), the intermittency is slightly higher for the downwards case. Additionally, it can be seen that the variation in intermittency with increasing superficial gas velocity is almost linear. Interestingly however, with increasing superficial gas velocity, there is a slight decrease in the intermittency levels, although the frequency of the disturbance waves increases with this parameter. This is an indication that although more waves are present in the film with increasing superficial gas velocity, that they are becoming shorter in terms of their wave width, as it is evident that they spend less time in the film.

The intermittency values are in slight disagreement with the empirical correlation developed in the work of Schubring et al. (2010b), who studied upwards annular flow. The correlation only reflects on the effect that the liquid flowrate has on the overall wave intermittency, where it is assumed that the gas phase plays no role in this parameter, as shown by the following relationship:

$$INT_w = 0.1 + Re_L / 40,000 \quad (\text{Eq. 5.3})$$

The application of Equation 5.3 to this study's configuration yielded lower values. A possible reason for this is the fact that it was developed based on data obtained for an upwards annular flow configuration in a 23.7mm pipe, more than twice the diameter of the current study. Additionally, the results obtained are based on the extraction of information from high-speed recordings, and therefore there is an inherent level of ambiguity present when applying such techniques. Lastly, since it is empirically based, the correlation does not take into consideration the effect that the gravitational action induces on the overall intermittency of the waves, and therefore it is not built to predict annular flows in downwards configurations. Therefore, in order to attest to the fact that disturbance waves become shorter in terms of their width with increasing gas superficial velocity, firstly, the intermittency values were simply divided by the corresponding wave frequency ones, as shown in Figure 5.14a. It shows that the percentage of the time that each disturbance wave is present in the base film is inversely proportional to the superficial gas velocity. This decrease in the ratio is also seen with increase in liquid Reynolds number. An important observation that can also be made from Figure 5.14a is that except for the cases of the lowest liquid Reynolds number, the time that each wave is present in the base film is the same regardless of the flow orientation. This is an indication that despite the fact that the wave frequency is different for both flow orientations, the wave width is not. To further validate this conclusion, the width of the waves was estimated based on a theoretical relationship which shows that the intermittency of the waves, INT_w , is a function of frequency of the waves, f_{wave} , the wave width, $wave_{width}$ and the wave velocity, V_{wave} , as shown by the following equation (Schubring et al., 2010b):

$$INT_w = \frac{f_{wave} \times wave_{width}}{V_{wave}} \quad (\text{Eq. 5.4})$$

The application of Equation 5.4 can be seen in Figure 5.14b.

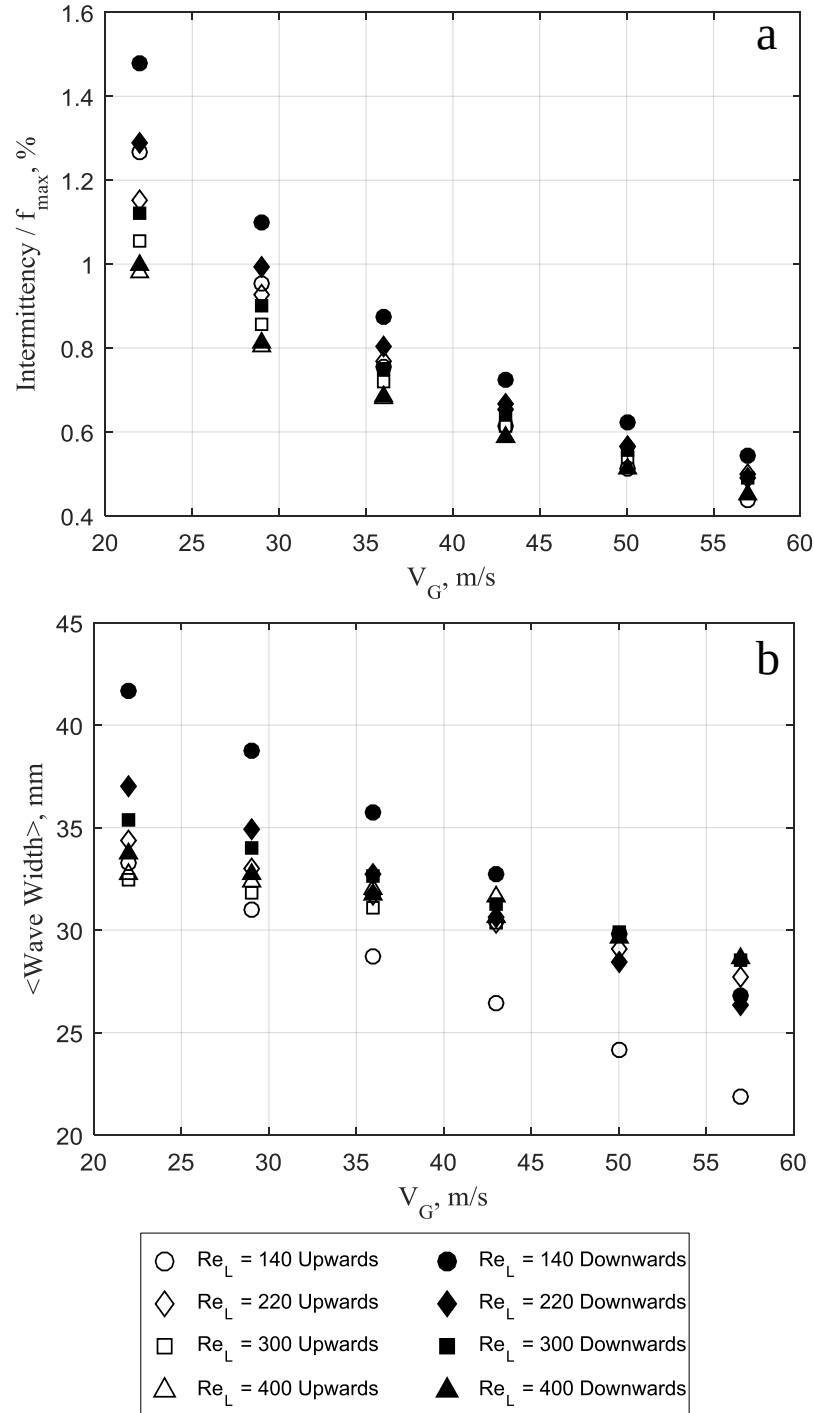


Figure 5.14: a) Ratio of intermittency over disturbance wave frequency; b) Disturbance wave width based on the theoretical relationship between wave intermittency and wave width.

Since the velocity of the disturbance waves was shown in Figure 5.9a to be independent of the flow orientation at this axial location, Figure 5.14b shows that indeed the width of the

disturbance waves is the same for the same flow conditions regardless of the flow orientation (with exception to the lowest liquid Reynolds number), and that the waves become shorter with increasing superficial gas velocity.

It is important then to consider that if the number of disturbance waves is higher for the downwards orientation but the wave width is the same for both orientations under the same flowrate conditions, where is this extra amount of liquid that is in the form of more waves in the downwards flow located in the upwards flow scenario. A possible explanation can be indirectly provided through the observation of the average ripple velocity for both flow orientations, which is shown in the next section.

5.2.7 Ripple to disturbance wave velocity ratio from the Omega-K analysis

An Omega-K analysis was applied to all spatiotemporal plots, as described in Section 3.4.5 of Chapter 3. In some cases, no significant feature could be detected from the Omega-K plots. In those cases, as detailed in Chapter 3.4.5, the average ripple velocity was measured by manually calculating the gradient of 10 randomly selected ripple waves present across in each spatiotemporal plots. This resulted in the trends shown in Figure 5.15:

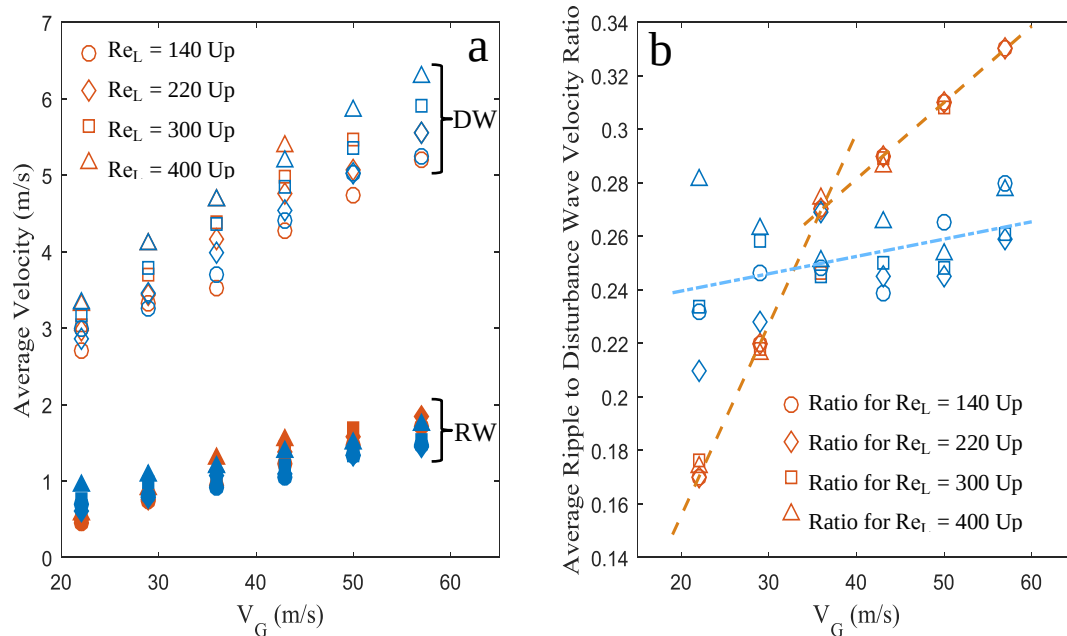


Figure 5.15: a) Absolute average disturbance (DW) and ripple (RW) wave velocities for all cases; b) Average ripple to disturbance wave velocity ratio. Orange and blue symbols refer to upwards and downwards cases respectively.

Figure 5.15a shows the resultant absolute mean velocities for both the disturbance and ripple waves. It is evident that increasing the superficial gas velocity leads to an increase in the velocity of both the disturbance waves (as previously shown in Figure 5.9a) and the ripple waves, which travel at a much slower speed in the base film in between consecutive disturbance waves. However, this rate of increase is less pronounced for the downwards flow. The absolute values were plotted as a ratio of average ripple to disturbance wave velocity, as shown in Figure 5.15b, which allows for a better characterization of the flow behaviour. Figure 5.15b shows that with increasing superficial gas velocity, the ripple to disturbance wave velocity ratio increases linearly for the upwards flow, with the ratio being independent with the liquid Reynolds number. There is however a change in the rate of this increase at a superficial gas velocity around 36 m/s, where the ripple waves are increasing in velocity in relation to the disturbance waves, but at a slower pace. This might be due to an increased level of entrainment that occurs at higher superficial gas velocities, where more droplets are being deposited in the base film. Although they can initially lead to a sudden acceleration of the liquid film upon impact, as shown in Figure 3.12, a crater is generated at the impact point, which can have a dissipative effect on the ripple wave motion. Additionally, upon impacting onto the base film, bubble entrainment into the liquid phase is enhanced, in which the entrained bubbles can possibly be further ‘slowing’ down the ripple waves.

It is very interesting however when comparison is established between flow orientations, since Figure 5.15b also shows that this level of increase in ripple to disturbance wave velocity ratio is not present in downwards flow. In this case, the where the ratio is close to constant with increasing superficial gas velocity, irrespective of the liquid Reynolds number. This constant profile for the downwards case is in agreement with the results obtained by Alekseenko et al. (2014) in their work in a downwards flow in a 15 mm pipe. Additionally, the ratio is shown to be higher than the upwards case up to a superficial gas velocity of 36 m/s, after which the upwards ratio surpasses the downwards one with further increases in superficial gas velocity.

As a result, if one considers where the amount of liquid that is located in the form of additional disturbance waves for the downwards case is in the case of the upwards configuration, three initial options are available. These are: in the form of higher disturbance wave amplitude, in the form of higher entrainment rate and/or in the form of a thicker base film due to gravitational action. Since the disturbance wave speed was shown to be the same for both flow orientations, it is unlikely that the disturbance waves have higher amplitudes in the upwards case, as this would be translated into a higher shearing action from the gas stream, leading to higher disturbance wave velocity. Additionally, it is not evident that the flow orientation has any substantial effect on the likelihood of liquid entrainment from the disturbance waves into the gas core. However, if one considers the effect that the gravitational action has upon the base film, where in the upwards case it is acting against the flow, the result might be that this amount of liquid is translated into a thicker base film. Conversely, in the downwards case, the gravitational action acts on the same direction as the flow, which theoretically leads to an acceleration of the film, yielding a thinner base film thickness. Therefore, at low superficial gas velocities (< 36 m/s), the gas stream acting against gravity might not be sufficient to shear the ripples at a fast pace, but after this stage, due to an increased base film thickness in the upwards configuration, the ripple waves are more prone to the shearing action of the gas and therefore move at a faster rate than the ripple waves in the downwards configuration.

5.2.8 Base and mean film thickness

In order to attest for the validity of the hypothesis discussed above, where it is assumed that the base film thickness is higher for the upwards configuration due to the opposite effect that the gravitational action has on the flow, both base and mean film thickness measurements were calculated from the spatiotemporal plots obtained at 330-430 mm from the inlet. These were calculated based on the definitions detailed in Section 2.6.3 of Chapter 2. Additionally, the overestimations in the film thickness measurements inherent in the application of the BBLIF technique in the study of annular flows, where total internal reflection can induce an

error to the measurements were taken into consideration. This was achieved by setting a threshold, where values above 1.5mm were cut-off by that level for both upwards and downwards configurations. Figure 5.16 shows an example of a time series record for a single axial location for the case of $Re_L = 140$ and $V_G = 22 \text{ m/s}$, where the implementation of the thresholding procedure can be seen.

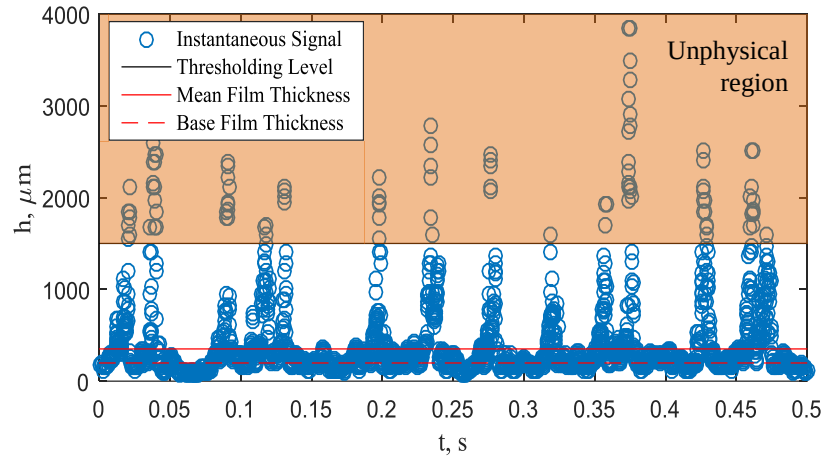


Figure 5.16: Example of the thresholding of the instantaneous film thickness being applied to overcome overestimation of the film thickness due to total internal reflection of laser light under high-slopes of the gas –liquid interface. This example refers to $Re_L = 400$ and $V_G = 22 \text{ m/s}$ in upwards flow.

As a result, the following relationships were obtained, as shown in Figure 5.17. Variations on the thresholding level between 1.5mm and 2.5mm did not lead to significant variations in the measured parameters. Moreover, as shall be seen in Chapter 6, the fact the new proposed correlation for mean film thickness successfully predicts the values of this study, along with reported values within different system configurations, substantiates the validity of the thresholding method here employed.

It can be seen from Figure 5.17 that as expected, both the base and mean film thickness increase with increasing liquid Reynolds number for both flow orientations, as more liquid is being inputted into the system. Additionally, due to the increasing shearing action of the gas both parameters decrease linearly with increasing gas superficial velocity, since the liquid film is increasing in velocity and getting thinner. Additionally, with increasing gas superficial velocity, the level of liquid entrainment into the gas core increases significantly, thus leading to further thinning of the liquid film. The trends reported in Figure 5.17 are in accordance to

what was expected from the mass and momentum balances that exist when both the liquid and gas flowrates are increased (Belt et al., 2009, Belt et al., 2010).

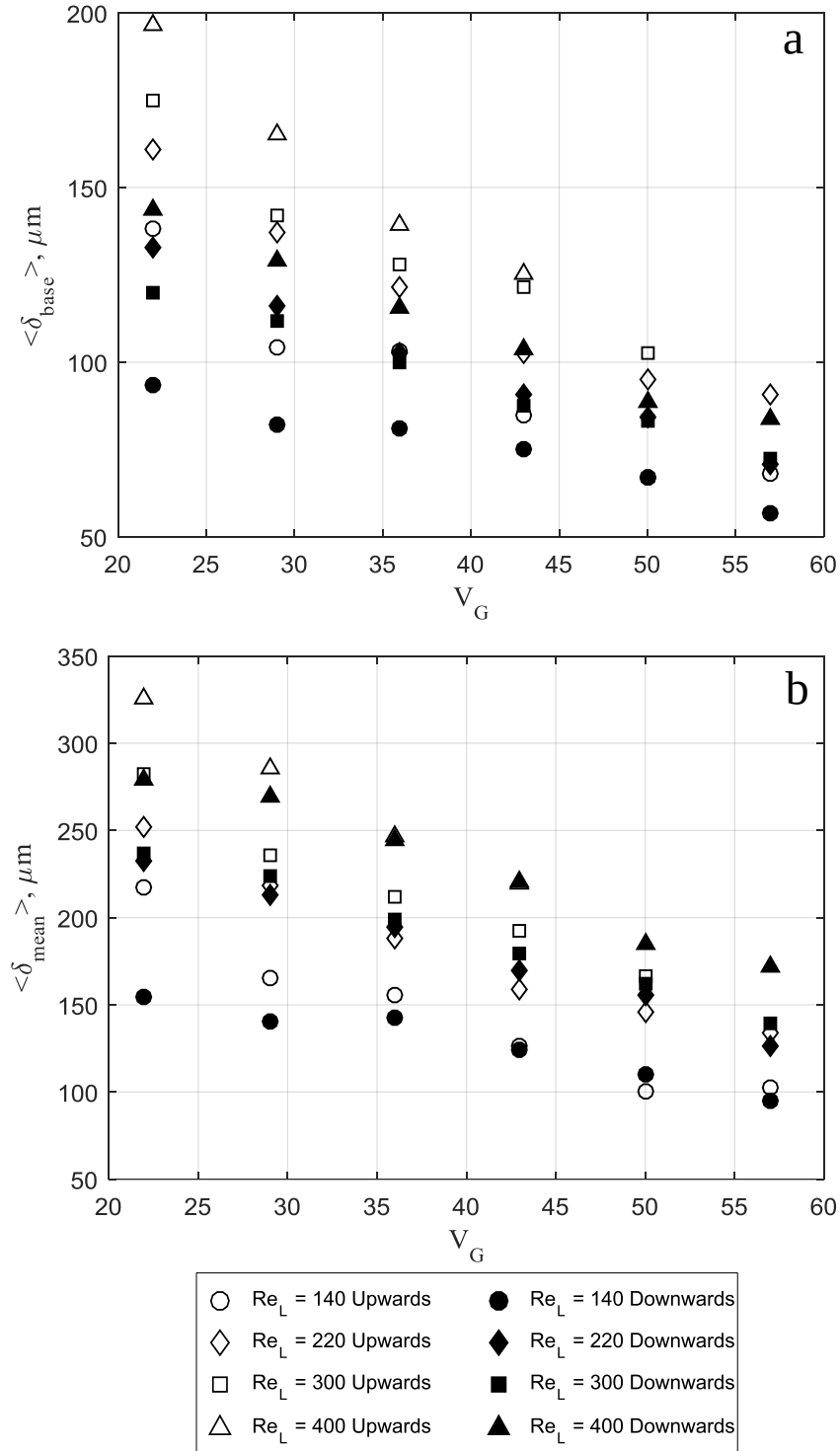


Figure 5.17: Base and film thickness for both flow orientations.

Moreover, as theorized in the previous section, it can be seen in Figure 5.17a, that indeed the gravitational action has an effect on the base film thickness, since the base film thickness for the upwards configuration is higher than the downwards case. Interestingly, this is not the

case when one considers the effect that the flow orientation has on the mean film thickness. Despite the fact that the gravitational action leads to a thicker base film in the upwards configuration, it can be observed from Figure 5.17b that the mean film thickness is similar for both flow orientations, which is not entirely surprising. If one considers the mass balance in the system, and assuming that the entrainment rate is the same for both flow orientations, it was seen that an extra amount of liquid is present in the base film for the upwards case. However, since the same flowrates are being tested, it is important to notice that the number of disturbance waves present in the film is higher for the downwards case (Figure 5.9b). Therefore, this extra amount of liquid in the form of waves for the downwards configuration potentially balances the extra amount of liquid present in the base film for the upwards case. As a result, this will yield in the same mean film thickness for both flow orientations.

5.3 Summary and conclusions

This chapter reported on how the flow orientation in vertical annular flow affects the dynamics of the regime, where the direct comparison for the same flowrate conditions was reported for the first time. The effect of flow orientation on the disturbance wave behaviour was investigated (where a full characterization was provided), in addition to its influence on the behaviour of ripple waves and finally the base and mean film thickness. Moreover, due to the versatility of the BBLIF technique, the evolution of the formation of disturbance waves was investigated in great detail, with measurements obtained at various axial locations, namely between 0 – 100mm and 330 – 430mm from the inlet. In the latter case, it was shown that the disturbance waves can be considered to be in a developed stage.

More specifically, the following conclusions were drawn:

- Close to the inlet, the flow orientation has an effect on the mean film thickness, since as the flow is developing, the mean film thickness was observed to be higher for the upwards configuration;
- Due to the mass and momentum balance, the film thickness increases with increasing liquid Reynolds and decreases with increasing gas superficial velocity.

- It was demonstrated that disturbance waves are generated from the coalescence of high-frequency small wavelets. These are originally formed close to the inlet section due to the Kelvin-Helmholtz instability, where the interface becomes wavy due to the shearing action of the gas phase on the liquid phase;
- It was seen that the velocity and frequency of the wavelets increase with both gas and liquid flowrates, as this is consistent with what is suggested from momentum balance. This will also be the case for the disturbance waves, as discussed below;
- After 30mm from the inlet, the waves in the film are seen to increase in velocity in a linear fashion. From this, both spatial and temporal acceleration of these waves were obtained, being both slightly higher in the upwards case;
- The evolution of normalized power spectra of the film thickness data was studied, where it is seen that the high frequency wavelets shift towards lower frequency values, thus validating the coalescence mechanism discussed above;
- From this, the initial frequency of the wavelets was measured, which was shown to be independent of the flow orientation at this stage;
- At 330 – 430 mm it was shown that the disturbance waves present in the film are travelling at a constant speed, thus allowing for the assumption that the flow is in a developed condition;
- The increase in wave frequency with both liquid and gas flowrates, as discussed above, consequently leads to a decrease in the average time separation between the disturbance waves;
- With the exception of the lowest liquid Reynolds tested, the frequency of the disturbance waves is higher for the downwards orientation, although they travel at the same velocity;
- This difference has an impact on the resultant time and distance separation between disturbance waves, which are shorter for the downwards configuration;

- Additionally, this leads to higher intermittency values for the downwards configuration, since they are seen to be present in the signal for a longer period of time. For both configurations, the intermittency increases with increasing liquid Reynolds number and decreases with gas superficial velocity;
- Despite the higher number of waves present in downwards flow, the wave width is the same for both flow orientations. It was also seen that with increasing gas superficial velocity, the width of the waves is reduced;
- The Omega-K analysis shows an increase in the ratio between the ripple and disturbance wave velocities with increasing gas flowrate for the upwards case, whereas for the downwards case, the ratio is constant under the same conditions. It was postulated that this is an indication of a difference in terms of the base film thickness with flow orientation;
- This was confirmed when both the base and mean film thickness were measured from the film thickness time series. It was observed that the base film was thicker for the upwards configuration, although the mean film thickness is seen to be similar for both configurations. This is an indication that the gravitational action has an effect on base film thickness, whereas the extra number of disturbance waves present in the downwards case leads to a balance of the values of mean film thickness between both configurations.

Many attempts have been made in order to derive correlations that predict the different parameters that characterize the annular flow regime when in a fully developed condition. These include correlations for the mean film thickness, disturbance wave velocity and frequency. These will be covered extensively on Chapter 6, where the experimental data here reported will be compared against existing correlations. Additionally, correlations that universally predict these different parameters in a multitude of air-water systems will be reported for the first time. These will ultimately lead to a better understanding and prediction of the annular flow regime.

Chapter 6. Prediction of Annular Flow Parameters

In modelling of annular flows, it is necessary to understand the forces that are important during the physical phenomena that take place under such conditions. Once understood, the ratios of these forces are then related to dimensionless groups such as Reynolds, Froude or Weber numbers in an attempt to classify the flow behaviour. Ideally, and as adopted widely in the published literature, this is performed using the known input parameters used in the different experimental campaigns, typically in some form of velocity parameter of both the gas and liquid phases. The reason for this is that it presents to be the most simple way of scaling for different system configurations, theoretically without the need of experimental data to attest for the validation of the models, and therefore it can be quickly adopted at an industrial level. Berna et al. (2014) provide an extensive review of most of the open set of correlations published that attempt to predict various flow parameters that characterize the annular flow regimes in this manner. By documenting the various expressions in literature, together with the experimental data, their aim was to reveal the lack of knowledge that still exists in the annular flow regime.

Not only has full knowledge of the important forces involved in the behaviour of the different parameters in annular flow has not been achieved by the multiphase flow community, which affects the decision of the relevant dimensionless groups chosen in their prediction, but also, as shown in Chapter 5 and more extensively by Wolf et al. (2001), there is a variation of the parameters with axial location. The latter severely hinders the application of correlations that rely only in the input parameters of the experimental campaign, as they presume that a developed flow is present (whose definition itself has not received universal consensus), and therefore cannot take into account the variability of the values of the parameters with downstream distance.

In this Chapter, the parameters of mean film thickness, disturbance wave velocity and frequency obtained in Chapter 5 will be tested against previous correlations published in the open literature, which are documented in the work of Berna et al. (2014). This will be followed by a discussion of what basic factors are important in the determination of the three annular flow parameters discussed above and how these are intertwined with each other.

From the discussion, correlations for the interfacial shear stress, disturbance wave frequency and velocity and mean film thickness will be reported. As will be shown, the effect of flow conditions, orientation and dimensions of the ducts were considered to determine common monotonic relationships that can be used for generic classification of these parameters.

6.1 Prediction of disturbance wave parameters from the open literature

6.1.1 Prediction of disturbance wave velocity

This section is devoted to discussing the different correlations available in the open literature for the prediction of the disturbance wave velocity. These are summarized in Table 6.1.

Table 6.1: Summary of correlations for the disturbance wave velocity.

Reference	Correlation
(Kumar et al., 2002)	$V_{dist} = \frac{\psi U_{SG} + U_{SL}}{1 + \psi} \quad (\text{Eq. 6.1})$ $\psi = 5.5 \sqrt{\frac{\rho_G}{\rho_L}}$
(Marmottant and Villiermaux, 2004)	$V_{dist} = \frac{\sqrt{\rho_G} U_{SG} + \sqrt{\rho_L} U_{SL}}{\sqrt{\rho_G} + \sqrt{\rho_L}} \quad (\text{Eq. 6.2})$
(Schubring and Shedd, 2008)	$V_{dist} = 0.41 \frac{U_{sg}}{\sqrt{x_G}} Re_G^{-0.25} \quad (\text{Eq. 6.3})$
(Al-Sarkhi et al., 2012)	$\frac{V_{dist}}{U_{SL}} = 1.942 X^{-0.91} \quad (\text{Eq. 6.4})$ For inclination of 45-90°, where $X = \sqrt{\frac{\rho_L U_L^2}{\rho_G U_G^2}}$

The set of correlations presented in Table 6.1 were tested against the experimental values obtained from the experimental campaign conducted in a 11.7mm diameter pipe, which were discussed in Chapter 5. The following graphs will show the comparison of the experimental values with the two best performing correlations of the entire set, namely from the work of Kumar et al. (2002) and Schubring and Shedd (2008). In the model of Kumar et al. (2002), the wave velocity is related to the interfacial friction factors based on both the gas and liquid velocities (f_{iG} and f_{iL} respectively), which is given by the following relationship:

$$\psi = \sqrt{\frac{\rho_G f_{iG}}{\rho_L f_{iL}}} \quad (\text{Eq. 6.5})$$

Due to the difficulty of estimating these parameters, they proposed an empirical correlation to estimate ψ , which is shown in Equation 6.1.

The empirical correlation of Schubring and Shedd (2008) was derived based on the experimental data obtained in an horizontal flow configuration, where the effect of the liquid velocity is given through the gas quality parameter, x_G , obtained using Equation 2.2. The performance of both correlations against the current study's experimental data is shown in Figure 6.1.

Figure 6.1.

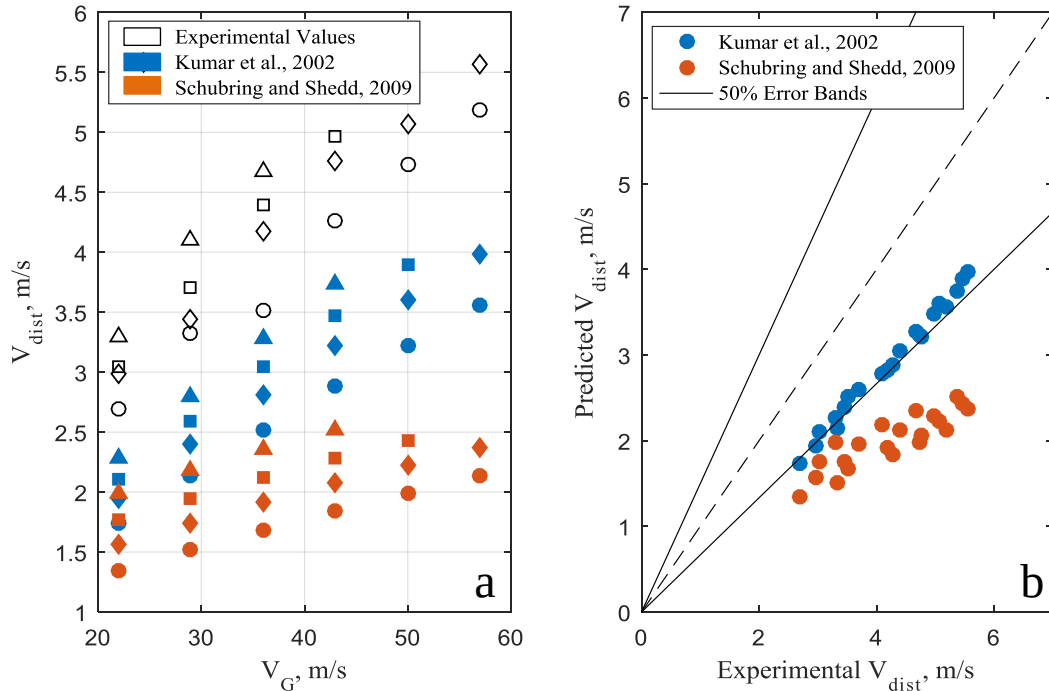


Figure 6.1: a) Variation of disturbance wave velocity with gas superficial velocity and liquid Reynolds number for both the experimental and modelled values; b) direct comparison between experimental and predicted values. In a), circle, diamond, square and triangle symbols refer to $Re_L = 140, 220, 300$ and 400 , respectively.

As can be seen from Figure 6.1a, both correlations successfully predict the effect that both the gas superficial velocity and the liquid Reynolds number have on velocity of the disturbance waves, where an increase in both results in an increase on the wave velocity. However, from Figure 6.1b it can be seen that they both under predict the experimental data, this being by just under 50% in the case of the correlation from Kumar et al. (2002), whereas in the case of the model from Schubring and Shedd (2008), the under prediction exceeds the 50% error. In both cases (and the same applies for the remaining parameters here reported), the discrepancy between predicted and experimental values far exceeds the experimental uncertainty, which is detailed in Appendix C. The remaining correlations present in Table 6.1 result in predictions that far exceed the 50% error (by more than 70%, although they capture the influence of both liquid Reynolds and gas velocity on this parameter) and are therefore not considered here.

One of the reasons for the discrepancy between the experimental and the predicted values is the fact that these correlations were derived based on experimental data obtained at axial distances considerably higher than in the current experimental campaign. These can surpass 100D whereas the current case corresponds to axial distances between 28 – 37D. Consequently, if one was to obtain measurements of the disturbance wave velocity in an 11.7mm pipe further downstream ($\geq 100D$), the measured velocities would be expected to be lower, as the gravitational action would have an effect on the waves (decelerating in the upwards case and conversely, accelerating in the downwards case). Furthermore, as shall be demonstrated in later sections, further downstream ($\geq 100D$), the rate of entrainment is substantially higher, thus having a further effect on the resultant disturbance wave velocity. Due to a higher amount of droplets present in the gas core, there is a change in momentum between gas phase and the disturbance waves, where the shearing action of the gas phase upon the disturbance waves is expected to be reduced. Although predicting lower disturbance wave values, the correlations from literature here tested do not directly take these factors into consideration. Their input experimental parameters are related to the experimental data by simply fitting coefficients that are empirically determined using regression analysis. As a result, a better understanding of the behavioural change of the annular flow regime with axial

distance is still to be obtained. Section 6.2 aims at enlightening researchers on the importance that this factor has on a successful prediction of this regime.

6.1.2 Prediction of disturbance wave frequency

The next parameter to be compared with existing correlations is the disturbance wave frequency, whose published correlations are summarised in Table 6.2.

Table 6.2: Summary of correlations for disturbance wave frequency.

Reference	Correlation
(Azzopardi, 2006)	$St_L = 0.25X^{-1.2}$ $St_L = \frac{f_{dist}D}{U_{SL}}$ (Eq. 6.6)
(Sekoguchi et al., 1985)	$St_G = \frac{f_{dist}D}{U_{SG}} = f_1(Eo)f_2(Re_L, Fr_G)$ $Eo = \frac{gD^2(\rho_L - \rho_G)}{\sigma}$ $f_1(Eo) = Eo^{-0.5}[0.5 \ln(Eo) - 0.47]$ $f_2(Re_L, Fr_G) = 0.0076 \ln\left(\frac{Re_L^{2.5}}{Fr_G}\right) - 0.051$ (Eq. 6.7)
(Sawant et al., 2008)	$St_G = 0.086 Re_L^{0.27} \left(\frac{\rho_L}{\rho_G}\right)^{-0.64}$ (Eq. 6.8)

In the case of the disturbance wave prediction, the two best performing correlations are from the work of Sekoguchi et al. (1985) and Azzopardi (2006). It is of particular interest to examine the performance of the correlation from Sekoguchi et al. (1985) since the set of flowrates and pipe diameter tested in this study's experimental campaign are within the same

range studied in their work. The performance of both correlations against the current study's experimental data is shown in Figure 6.2.

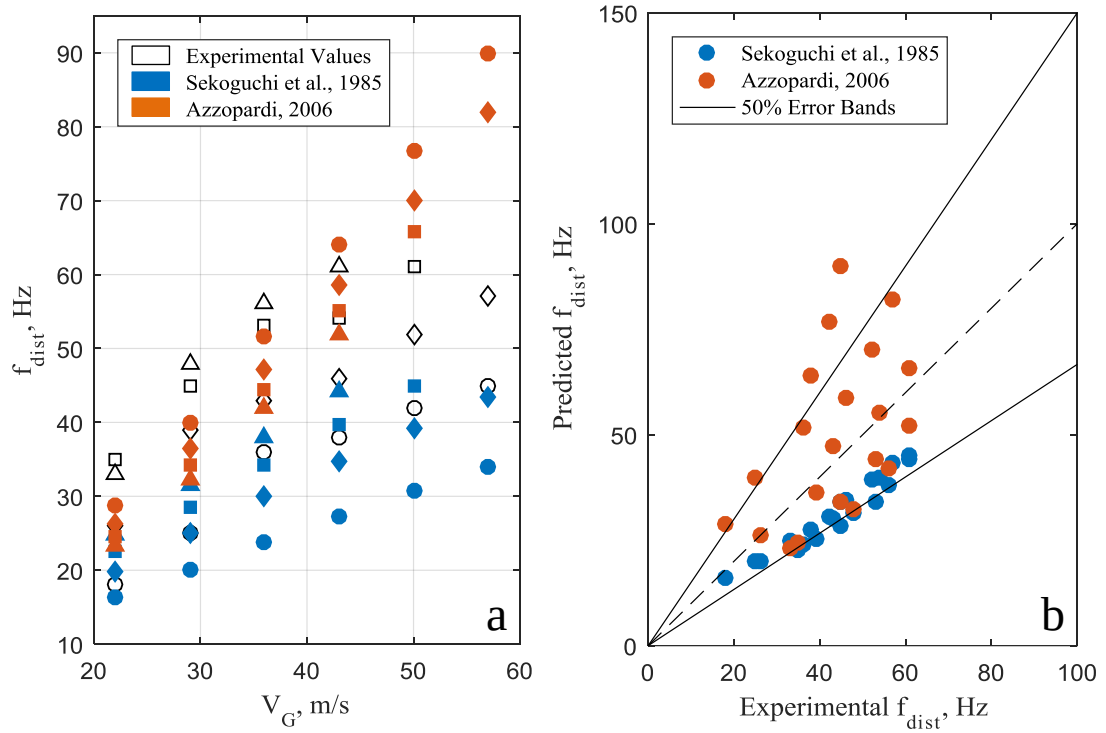


Figure 6.2: a) Variation of disturbance wave frequency with gas superficial velocity and liquid Reynolds for both the experimental and modelled values; b) direct comparison between experimental and predicted values. In a), circle, diamond, square and triangle symbols refer to $Re_L = 140, 220, 300$ and 400, respectively.

The model from the work of Sekoguchi et al. (1985) establishes a complex set of relationships between dimensionless numbers such as the Reynolds number of the liquid, the Froude number of the gas and the Eötvös number to empirically predict the disturbance wave frequency. It also under predicts the values for the disturbance wave frequency, as it was derived based on the measurements performed at 2.16m from the inlet, whereas the results for the current experimental campaign were obtained between 330 – 430mm from the inlet. At 2.16m from the inlet, due to the fact each wave travels with its own individual velocity (as seen in Chapter 5), a considerable amount of coalescence of the disturbance waves has occurred, thus leading to lower measured disturbance waves, from which the data was empirically derived. As a result, it can be seen from Figure 6.2b, the error in the performance of this correlation is close to 50%. From Figure 6.2a, the correlation of Sekoguchi et al. (1985) successfully captures the feature of increasing wave frequency with increasing both the

gas superficial and the liquid Reynolds number. On the other hand, as seen in Figure 6.2b, the prediction of results using the correlation of Azzopardi (2006) shows a better performance in terms of predicting frequency but the trend of increasing frequency with increasing liquid Reynolds number is not captured. From Figure 6.2a it can be seen that the disturbance wave frequency is inversely proportional to the liquid Reynolds number, which is not correct. Additionally, the correlation of Azzopardi (2006) relates the Lockhart-Martinelli parameter, which was given in Equations 2.36 – 2.39, with the liquid Strouhal number. In the derivation of both parameters, the liquid superficial velocity, U_{SL} is present, and therefore it is not the best engineering practice to equate parameters with the same variables with each other.

Due to the issues discussed above, a better prediction for the disturbance wave frequency is required, which will be covered in Section 6.2.2.

6.1.3 Prediction of the mean film thickness

Finally, the last parameter to be compared with existing correlations is the mean film thickness. As can be seen from Table 6.3, there has been an extensive amount of effort aimed at predicting this parameter over the years, as this is one of the key parameters required for the successful prediction of the pressure drop in the annular flow regime. One observation that can be made regarding the correlations below is the high level of empiricism that is associated with the prediction of this parameter. This can be seen from the fact that multiple physical effects are attempted to be taken into consideration by means of dimensionless numbers with various empirically derived exponents, which are combined into a complex expression. In addition, in some instances, there is some lack in the level of mathematical meaning in the expressions proposed. An example of this can be seen in Equation 6.12, where the in F parameter, the denominator contains multiple variables of Re_G with different exponents that could be combined into a single entry. This demonstrates that as a research community, there is still a high level of understanding that is required to be obtained regarding the annular flow regime.

Table 6.3: Summary of correlations for the mean film thickness in the annular flow regime.

Reference	Correlation
(Ambrosini et al., 1991)	$\delta^+ = \frac{\rho_L \delta u_L^*}{\mu_L} = \begin{cases} 0.34 Re_{lf}^{0.6} & \text{if } Re_{lf} \leq 1000 \\ 0.0512 Re_{lf}^{0.875} & \text{if } Re_{lf} > 1000 \end{cases}$ $u_L^* = \sqrt{\frac{\tau_I}{\rho_L}}$ $f_i = \frac{2\tau_i}{\rho_G U_G^2}$ (Eq. 6.9)
(Fukano and Furukawa, 1998)	$\frac{\delta}{D} = 0.0594 \exp(-0.34 Fr_G^{0.25} Re_L^{0.19} x^{*0.6})$ $x^* = \frac{U_{SG} \rho_G}{U_{SG} \rho_G + U_{SL} \rho_L}$ (Eq. 6.10)
(Hori et al., 1978)	$\frac{\delta}{D} = 0.905 Re_G^{-1.45} Re_L^{0.90} Fr_G^{0.93} Fr_L^{-0.68} \left(\frac{\mu_L}{\mu_{L,ref}} \right)^{1.06}$ (Eq. 6.11)
(Henstock and Hanratty, 1976)	$\frac{\delta}{D} = \frac{6.59F}{(1 + 1400F)^{0.5}} \quad \text{for vertical flows}$ $\frac{\delta}{D} = \frac{6.59F}{(1 + 850F)^{0.5}} \quad \text{for horizontal flows}$ $F = \frac{1}{\sqrt{2}} \frac{Re_L^{0.5}}{Re_G^{0.4}} \frac{\mu_L}{\mu_G} \frac{\rho_G^{0.5}}{\rho_L^{0.5}}$ (Eq. 6.12)
(Tatterson et al., 1977)	$\frac{\delta}{D} = \frac{6.59F}{(1 + 850F)^{0.5}} \quad \text{for horizontal flows}$ $F = \frac{\gamma(Re_{lf})}{Re_G^{0.9}} \frac{\mu_L}{\mu_G} \frac{\rho_G^{0.5}}{\rho_L^{0.5}}$ $\gamma(Re_{lf}) = \left[(0.707 Re_{lf}^{2.5})^{2.5} + (0.0379 Re_{lf}^{0.9})^{2.5} \right]^{0.4}$ (Eq. 6.13)

Reference	Correlation	
(Roberts et al., 1997)	$\delta = 846 \frac{D}{D_{ref}} \frac{Re_{lf}^{0.44}}{Re_G^{0.59}}$	(Eq. 6.14)
(Okawa et al., 2002)	$\delta = 0.25 \sqrt{\frac{f_w \rho_L}{f_i \rho_G}} \frac{U_{lf}}{U_{SG}} D$	(Eq. 6.15)
(Ishii and Grolmes, 1975)	$\frac{\delta}{D} = 0.347 Re_{lf}^{2/3} \sqrt{\frac{\rho_L \mu_L}{\tau_i \rho_L}}$	(Eq. 6.16)

The experimental results were compared with the existing correlations from Table 6.3 that rely directly on the input parameters that were measured in this experimental campaign. As a result, parameters that require the knowledge of the interfacial friction factor or the interfacial shear stress, such as the case of the works of Ambrosini et al. (1991), Okawa et al. (2002) and Ishii and Grolmes (1975) were not considered. The reason for this is that they required pressure drop measurements, which were not performed in this experimental campaign, and therefore these parameters cannot be derived. Furthermore, employing empirical correlations for the estimation of these parameters based on input values was not attempted as there is not full consensus on the application of those correlations themselves. Once more, the performance of the two best correlations for the prediction of the mean film thickness is shown in Figure 6.3. These consist of the correlations developed by Fukano and Furukawa (1998) and Hori et al. (1978). It can be seen from Figure 6.3a, that both correlations capture the effect of increasing film thickness with increasing liquid Reynolds number, as more liquid is present in the system. Furthermore, the thinning of the film with increasing gas superficial velocity due to a faster moving film and higher liquid entrainment is also predicted by both correlations.

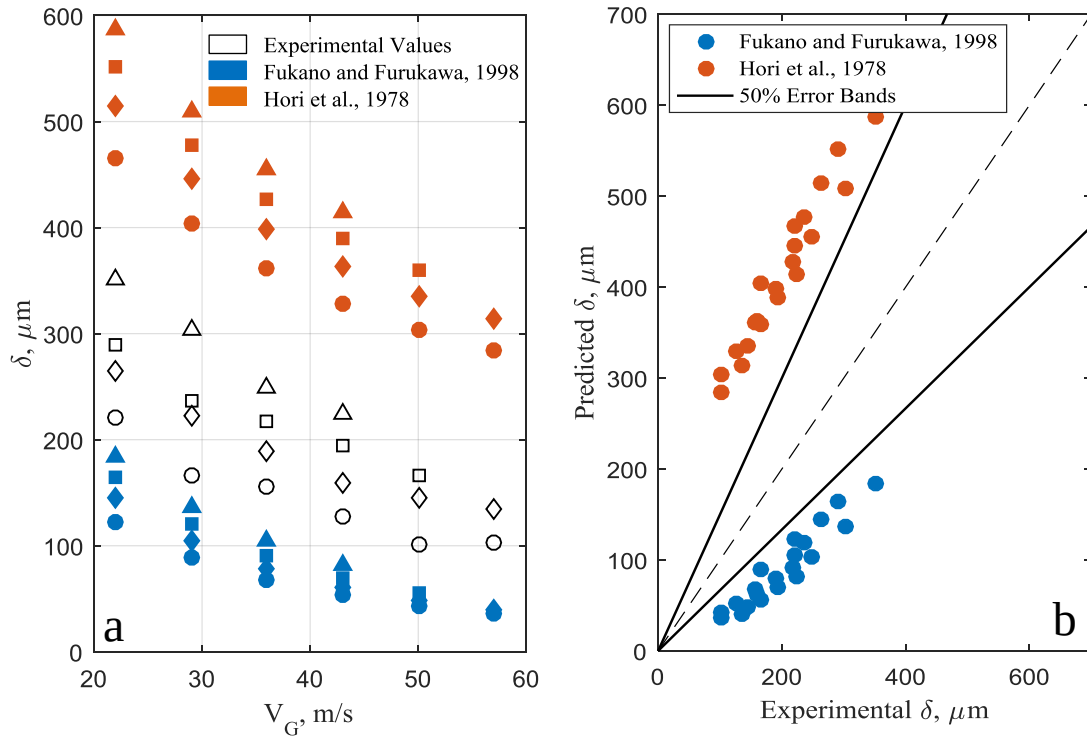


Figure 6.3: a) Variation of mean film thickness with gas superficial velocity and liquid Reynolds for both the experimental and modelled values; b) direct comparison between experimental and predicted values. In a), circle, diamond, square and triangle symbols refer to $Re_L = 140, 220, 300$ and 400 , respectively.

However, as seen more clearly in Figure 6.3b, the accuracy of the prediction for both correlations is not satisfactory, since the predictions are off the actual experimental value by more than 50%, with the correlation of Fukano and Furukawa (1998) under predicting the actual values, where the opposite occurs when applying the correlation of Hori et al. (1978). A possible explanation for the considerable discrepancy between both predictions can be the fact that the correlation of Hori et al. (1978) was developed based on data in the ripple region of annular two-phase flow, where the physics that govern this region differ greatly from the disturbance wave dominated region here reported (as is the case of Fukano and Furukawa (1998)).

From the comparisons of the predictions of the three parameters discussed in the previous subsections, it can be concluded there is an inherent lack of understanding of which forces govern the evolution of the different parameters here tested. A clear example of this was given by Table 6.3, where multiple dimensionless numbers are attempted to be combined into a complex expression in order to predict the mean film thickness. Furthermore, no correlation

described above takes into consideration the effect that the axial location has on the variation of the parameters here discussed. The importance that this factor has on the annular flow regime has been demonstrated in Chapter 5, and is complemented by the work of Wolf et al. (2001) and Hazuku et al. (2008). Lastly, although its importance is somewhat less than the previous factors discussed above, it is important to take into consideration the effect that the gravitational action has on the flow orientation of the annular flow regime. The following section aims at covering to some extent these factors, where correlations for the prediction of the disturbance wave velocity and frequency, together with mean film thickness are presented.

6.2 Proposed correlations for the prediction of the annular flow regime

In order to achieve the goal of generating predictive correlations for two of the main annular flow parameters, (i.e. wave frequency and mean film thickness), the basic underlying physical components that are believed to govern these parameters were considered. From this, more simplified relationships (in comparison with previous published correlations) have been established. The main drawback of the correlations proposed next is the fact that their full validity is only applicable to air-water systems, since the expressions were formulated based on interfacial shear stress measurements performed in this type of system, as shall be demonstrated later. However, unlike previous published correlations, successful predictions have been established for a large number of air-water systems, regardless of the duct properties (size, circular pipe or rectangular duct) or flow orientation (vertically upwards and downwards, or horizontal).

This was done by comparing the performance of the correlations with data not only obtained from the current study, which was reported in Chapter 5, but also from data from various works published in the open literature. A list of the different data sources used for this comparison, together with the details of their experimental campaigns is provided in Table 6.4.

Table 6.4: List of data sources used to test the performance of the correlations presented in the following subsections.

Author	Re_L	Re_G	Duct Type	Dimensions	Orientation	Axial Position	Code
Current Study	140 – 400	15,900 – 42,000	Pipe	$D = 11.7\text{mm}$	Vertical Upwards	0.330 – 0.430m	UP 
Current Study	140 – 400	15,900 – 42,000	Pipe	$D = 11.7\text{mm}$	Vertical Downwards	0.330 – 0.430m	DOWN 
(Wolf et al., 2001)	79.5 – 954	56,000 – 122,000	Pipe	$D = 31.8\text{mm}$	Vertical Upwards	0.45, 1.15, 2.78, 10.41m	WOLF 
(Cherdantsev et al., 2016)	155 – 520	43,000 – 95,000	Rect.	$H = 25\text{mm}$ $W = 161\text{mm}$	Horizontal gas-sheared	1.6m	HOR 
(Tatterson et al., 1977)	1200 – 5400	33,000 – 75,000	Rect.	$H = 305\text{mm}$ $W = 25\text{mm}$	Horizontal	N/A	TATTERSON 
(Kumar et al., 2002)	160 – 12,000	3,000 – 38,000	Rect.	$H = 6.35\text{mm}$ $W = 63.5\text{mm}$	Vertical Upwards	1.04m	KUMAR 

Before addressing the proposed correlations, a few points need to be taken into consideration.

The liquid Reynolds numbers, Re_L , reported in Table 6.4 are based on the liquid flowrate, as given by Equation 3.6. These are 4 times smaller than the one obtained if calculating the Reynolds number using the liquid superficial velocity. In the instances where the literature data was reported in this manner, the values were simply divided by 4 in order to achieve a direct comparison. Moreover, in the cases where rectangular ducts were employed, before being divided by 4, the Reynolds number were calculated using the hydraulic diameter, D_h , as the length scale, which for a rectangular duct is given by the following relationship:

$$D_h = 4A/Per \quad (\text{Eq. 6.17})$$

where A and Per are the duct's area and perimeter, respectively.

These values are going to be applied throughout the entire next subsections. Additionally, the work of Wolf et al. (2001) is of particular importance to the research field, as it covers an extensive range of axial locations, ranging from 6 up to 327D. Particularly at the latter location, it will be shown in Section 6.2.3 that the entrainment rate is very high, which presents a significant effect on the parameters being estimated. To take this factor into consideration, the authors measured the liquid film flowrate by sucking off the film by a means of a sinter that could be inserted at different axial positions. This was then connected to a cyclone separator, which allowed for the flowrate to be obtained by measuring the amount of water collected over a certain time interval. As a result, for the case of Wolf et al. (2001), the (effective) liquid superficial velocity was measured from the actual liquid flux, G_L , using the following equation:

$$V_{SL} = G_L / \rho_L \quad (\text{Eq. 6.18})$$

From this, the (effective) liquid Reynolds number was measured for each axial position, given a set of input liquid and gas fluxes into the system. Through this, the effect of axial location could be taken into consideration, as shall be discussed in more details in the next sections. It is also worth noting that in the work of Wolf et al. (2001), the inlet pressure was fixed at 2.38 bar and the pressure decreased with axial location. Consequently, this leads to a change in gas density, which directly affects various parameters such as gas superficial velocity or the gas Reynolds number. This was taken into consideration since pressure and temperature measurements were obtained at the multiple axial locations where other parameters were measured. From this, the gas density was then calculated assuming that air behaves as an ideal gas.

Additionally, the data from Cherdantsev et al. (2016) consists of a dataset in a gas-sheared liquid film configuration that is yet to be published and that has been conducted at the University of Nottingham under the MEMPHIS collaboration. More details regarding the experimental setup for this experiment can be found in Cherdantsev et al. (2014), although the paper focuses mostly on the characterization of ripples waves, together with mechanisms of

entrainment. The study regarding the investigation of the parameters to be predicted in this chapter will be published soon.

6.2.1 Prediction of the disturbance wave velocity

The first correlation to be proposed is to predict the disturbance wave velocity. From the correlations to be proposed, this can be regarded as the least satisfactory as developments in the understanding of the physical parameters that govern this parameter still need to be better achieved. As shown in Chapter 5, upon coalescence of the wavelets formed due to the Kelvin-Helmholtz instability that the gas phase induces into the liquid phase, the newly formed disturbance waves undergo an acceleration phase until their velocities start to become constant further downstream. Once they reach a constant velocity, which can be seen as one of the pre-requisites that researchers typically use to consider the flow to be developed, the waves are assumed to travel at this velocity for a considerable axial distance. However, one has to consider the effect that the entrainment rate and the gravitational action will have on this parameter, where changes are expected to occur. As discussed in Chapter 2, Pashniak (1969) has reported on the linear relationship that exists between the disturbance wave velocity and the wave height. This is to some extent further substantiated by the work of Karapantsios and Karabelas (1995), which report on the same trend in falling films configurations. Due to the lack of availability of a wide amount of data in terms of measurement of wave height, and since, as discussed in Chapter 3, there are some inherent issues regarding the accuracy of the height measurements in the wave region, no attempt has been made to establish a universal correlation based on these parameters. Interestingly, however, a similar dependence was found between the wave velocity and the mean film thickness, as shown by Figures 6.4 and 6.5 for the current study and the data of Wolf et al. (2001), respectively.

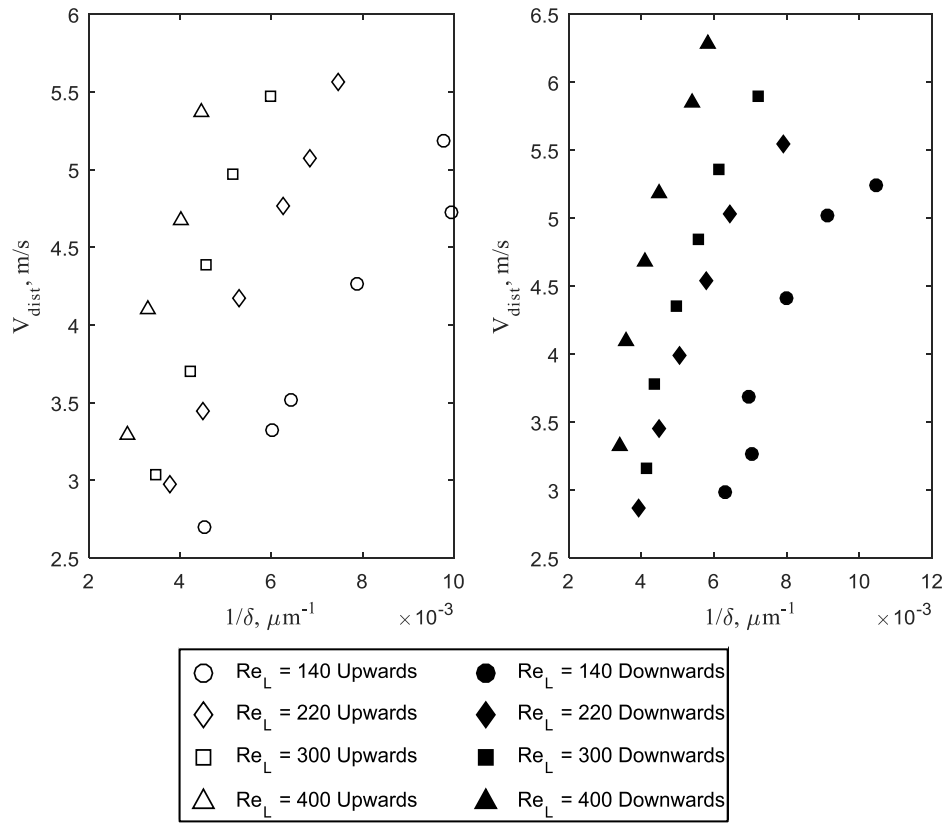


Figure 6.4: Dependence of disturbance wave velocity on film thickness.

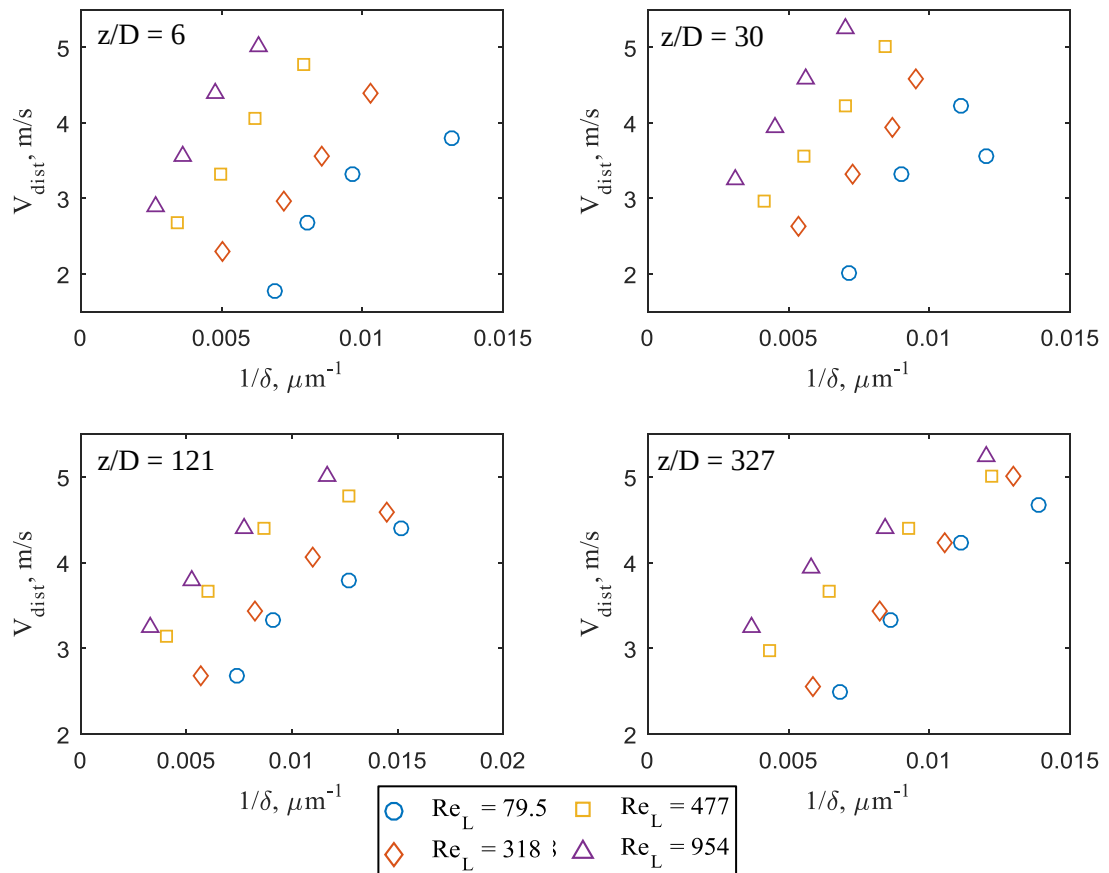


Figure 6.5: Dependence of disturbance wave velocity on film thickness at different axial locations from the work of (Wolf et al., 2001).

In the Figures 6.4 and 6.5, the measured disturbance wave velocity is seen to be inversely proportional to the mean film thickness. Increasing the gas superficial velocity leads to an increase in disturbance wave frequency, and conversely, to a reduction in film thickness. As expected, increasing the liquid Reynolds number leads to an increase in the wave speed, and since more liquid is present in the system, it also leads to an increase in film thickness. Hence, the profiles for these parameters are seen to shift towards the right hand side of the graphs when subjected to an increase in this parameter. This is observed not only in the upwards and downwards configurations in a 11.7mm pipe, which were reported in Chapter 5, but also for the experiment of Wolf et al. (2001). In the latter, results are reported for the four different axial positions where measurements were conducted. Interestingly, although both the mean film thickness and disturbance wave velocity vary with axial location, the linear relationship can be seen from Figure 6.5 to be maintained with downstream distance. Attempts to derive an universal relationship that relates both the effect that changing both the gas and liquid flowrates and the axial location have on these parameters across all the data sets present in Table 6.4 has been unsuccessful so far.

However, based on a graph of the work of Kumar et al. (2002), an interesting relationship was investigated. It consists of a logarithmic plot of the dimensionless wave velocity (non-dimensionalised by the liquid superficial velocity) against the ratio of the liquid and gas Reynolds numbers. As discussed in Section 6.1.2, plotting the same variable in both axes is not the best engineering practice. More specifically, this occurs due to the presence of the liquid superficial velocity in both axes, which is used to derive the liquid Reynolds number. As a result, in a logarithmic plot, a linear relationship is expected to be encountered for each individual dataset. Interestingly however, as shown in Figure 6.6a, not only is a linear collapse of each individual dataset observed, but also it can be seen that all the datasets collapse into a single straight line relationship, regardless of the flow orientation or duct properties.

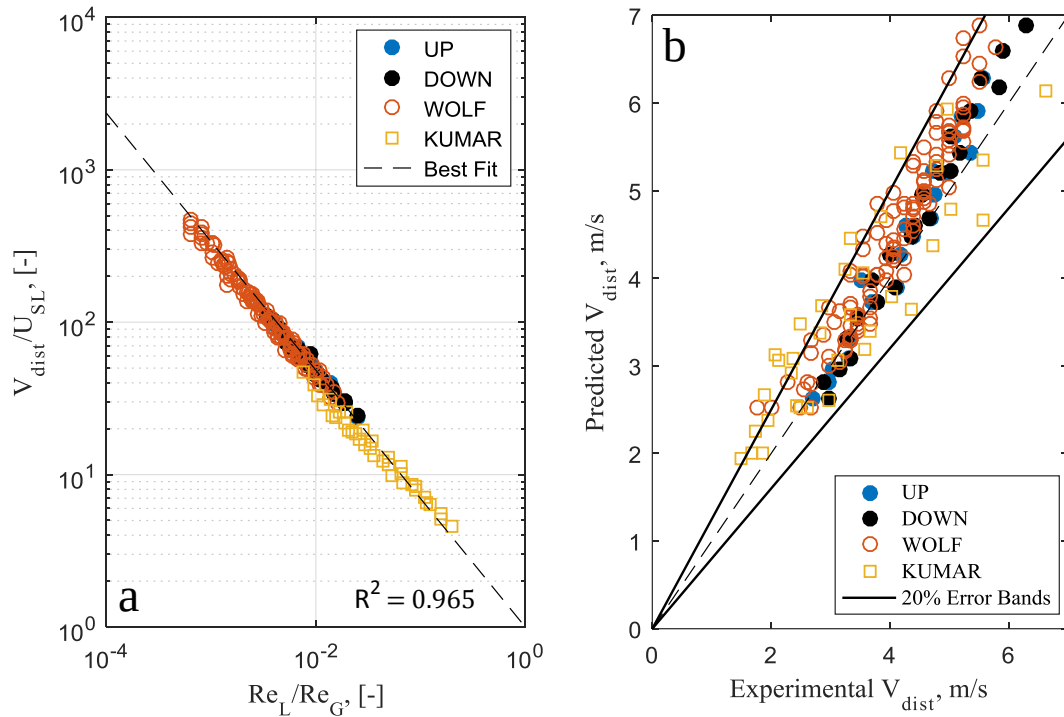


Figure 6.6: a) Proposed correlation of disturbance wave velocity to liquid superficial velocity ratio against the ratio of liquid and gas Reynolds numbers; b) direct comparison between experimental and predicted values.

With the exception of the work of Wolf et al. (2001), most of the data sets for the various authors here compared were obtained at axial locations that can be considered as relatively closed to the inlet section (they did not exceed $150 z/D$). At this stage, liquid entrainment from the disturbance waves into the gas core was already taking place. However, due to the short distances involved, and the range of liquid and gas flowrates being tested, the level of liquid entrainment can be assumed to not be particularly significant. As a result, the estimation of the disturbance wave velocity parameter can be obtained using the input experimental values of the liquid flowrate being tested to derive the liquid superficial velocity, and consequently, the liquid Reynolds number. However, as shall be seen in Section 6.2.2, through the work of Wolf et al. (2001) which performed measurements at axial locations higher than $300z/D$, the entrainment level can be quite significant, which affects the parameters being predicted. In this case, if one used the input experimental parameters to derive the velocity of the disturbance waves at different axial positions using the relationship displayed graphically in Figure 6.6a, a successful prediction would not be obtained. This is

because a prediction of a parameter whose value is changing with axial distance is being attempted using a set of input parameters that are constant. However, as discussed in Section 6.2, by measuring the amount of liquid entrained at different axial positions, it is possible to calculate the effective liquid superficial velocity and hence the effective liquid Reynolds number for each given set of liquid and gas flowrates tested at different positions along the pipe. Through this method, the effect of variability of the disturbance wave properties with axial position is taken into consideration, and as can be seen from Figure 6.6a, the data collapses onto the same straight line as the rest of the data sets. From this, an universal best fit line for all the data sets could be empirically determined, which is shown by the following relationship:

$$V_{dist}/V_{SL} = (Re_L/Re_G)^{A \cdot \exp(B)} \quad (\text{Eq. 6.19})$$

where A and B have been empirically determined to be -0.8214 and 0.0258, respectively.

The coefficient of determination, R^2 , of the prediction of the data from Equation 6.19 was calculated to be 0.965. This was obtained using the following relationship:

$$R^2 = 1 - \frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{\sum_{i=1}^n (y_i - \bar{y})^2} \quad (\text{Eq. 6.20})$$

Where $\hat{y}$ represents the predicted values of y , and $\bar{y}$ is the mean of y .

Using Equation 6.19 and the experimental values of the liquid superficial velocity tested, a direct comparison between the experimental and predicted values of the disturbance wave velocity for the datasets shown in Figure 6.6a could be performed. This is shown in Figure 6.6b, where regardless of the difference in geometry and flowrates tested, the data is in general predicted with less than 20% error. More specifically, the mean absolute error (MAE) of the disturbance wave velocity prediction was calculated to be 11.2%. As detailed in Schubring et al. (2010a), the MAE is defined by relating the number of flow combinations tested, η_{FC} , the modelled results, XX_{mod} , and the experimental results, XX_{exp} , as given by the following relationship:

$$MAE = \frac{1}{\eta_{FC}} \sum_{FC} \left| \frac{XX_{mod} - XX_{exp}}{XX_{exp}} \right| \times 100\% \quad (\text{Eq. 6.21})$$

6.2.2 Prediction of disturbance wave frequency

This subsection reports on the correlation developed in order to predict the frequency of the disturbance waves present in the various air-water experimental campaigns being considered. A successful universal relationship was found when plotting the disturbance wave frequency multiplied by the equivalent circumference, E_c , of each dataset against the corresponding loading factor inside the duct divided by the mean film thickness, as shown in Figure 6.7a.

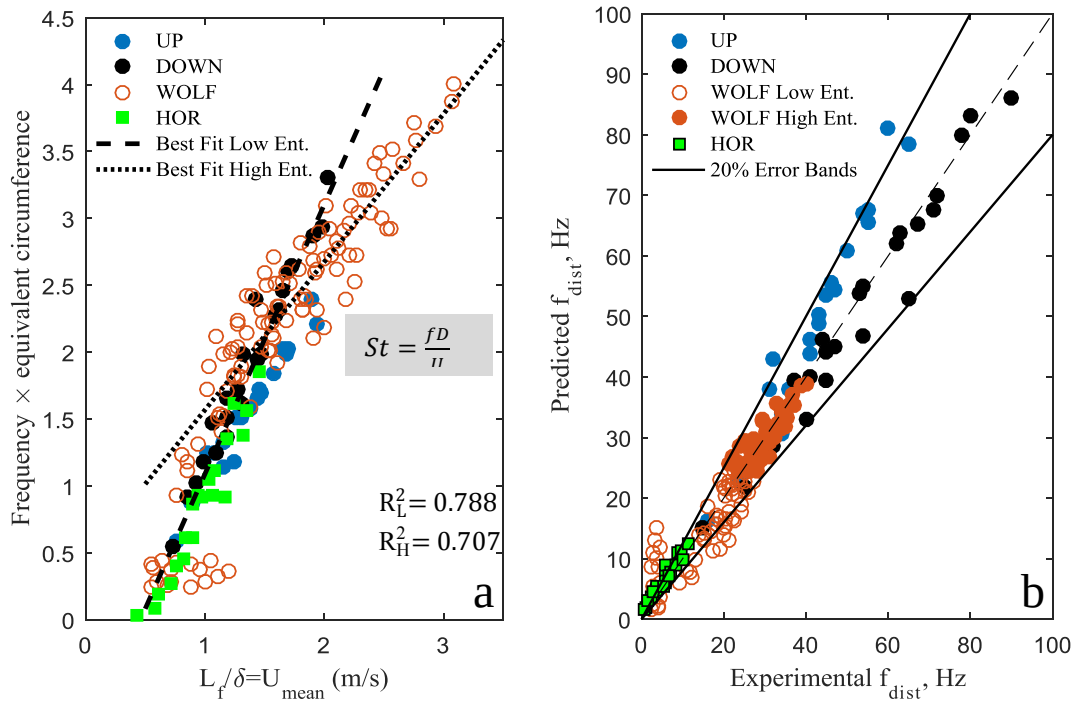


Figure 6.7: a) Proposed correlation of disturbance wave frequency multiplied by the equivalent circumference against the corresponding loading factor divided by the mean film thickness; b) direct comparison between experimental and predicted values.

The division of the loading factor by the mean film thickness corresponds therefore to the mean velocity of the liquid phase, $U_{lf,mean}$. The loading factor, L_f , was determined in a different manner, depending on the duct geometry, as shown as follows:

$$L_f = \begin{cases} \dot{Q}_L / \pi D & \text{for circular pipes} \\ \dot{Q}_L / W & \text{for horizontal ducts} \end{cases} \quad (\text{Eq. 6.22})$$

As a result, the correlation in Figure 6.7a related the frequency of the disturbance waves that are coherent around the circumference of a pipe against the mean velocity of the liquid film, in which by the definition given in Equation 2.23 in Chapter 2, the gradient of the lines plotted corresponds to a Strouhal number, which is classically employed in the description of

the frequency of a given structure being investigated. As in the case of the loading factor, the equivalent circumference, E_c , was determined differently depending on the duct geometry, as it can affect the wetted perimeter covered by disturbance waves. These are given by:

$$\text{Equivalent circumference, } E_c = \begin{cases} \pi D & \text{for circular pipes} \\ W & \text{for horizontal ducts} \end{cases} \quad (\text{Eq. 6.23})$$

For Figure 6.7a, several observations can be made. Firstly, there is a minimum film speed above which disturbance waves occur, which can be seen to be around $U_{lf,mean} = 0.5$ m/s. The mean film velocities above this value correspond to what Azzopardi (1997) describes as an excess Reynolds number, i.e. the film flowrate that is above the critical film flowrate required for the inception of disturbance waves. This therefore corresponds to the transition from a ripple wave dominated regime into a disturbance wave dominated regime, where entrainment occurs. Secondly, there is a change in behaviour in the collapsed data at around $U_{lf,mean} = 1.735$ m/s, where the rate of increase in wave frequency with increasing film velocity decreases. This feature can be observed mainly through the analysis of the data from Wolf et al. (2001). As discussed in the previous sections, they measured the entrainment fraction at different axial locations, and their results can be seen in Figure 6.8.

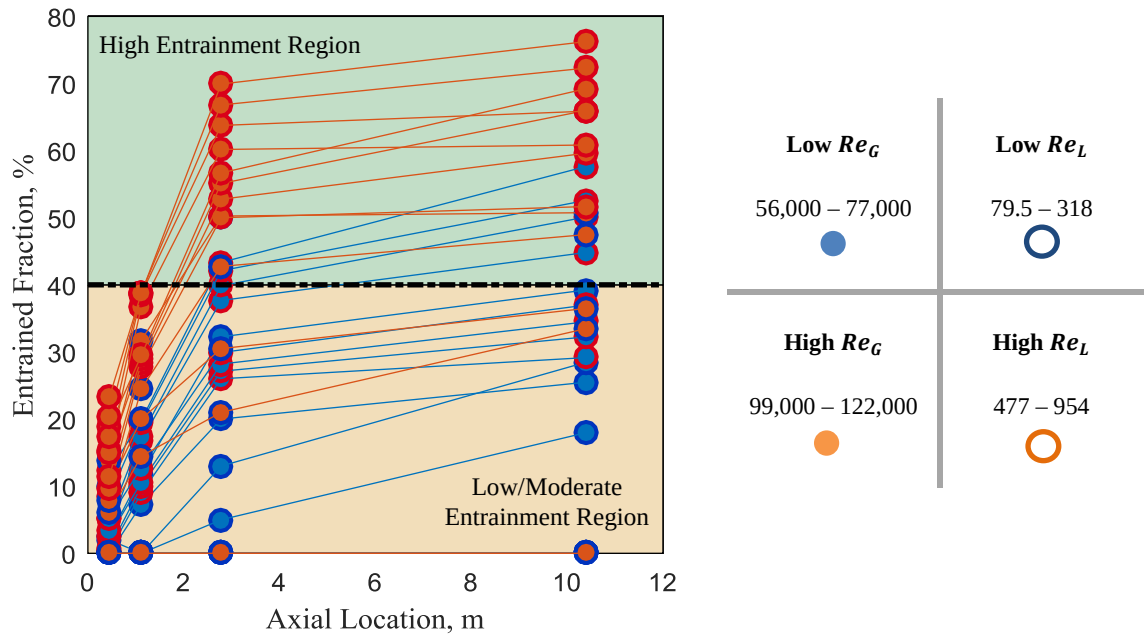


Figure 6.8: Entrainment fraction at different axial positions from the work of Wolf et al. (2001). The flow conditions at which these take place are colour coordinated according to sub-categories given to both the gas and liquid Reynolds numbers, as shown in the legend on the right hand side.

From Figure 6.8, it can be seen that for a particular gas and liquid flowrate combination, there is a substantial increase in the entrainment rate with axial location, probably due to the continuous and compounding level of secondary entrainment that takes place as a droplet impinges into the liquid film, as shown by Figure 3.12 in Chapter 3. As discussed in the previous section, this significant increase in entrainment rate with axial location has an effect on the disturbance wave parameters, as it induces variation in the momentum and energy exchange between the gas phase and the liquid phases. Additionally, increasing both the gas and liquid Reynolds number leads to an increase in the entrainment fraction. When high enough liquid Reynolds numbers and high levels of gas Reynolds numbers are being tested, it can be seen in Figure 6.8 that the entrainment rate can exceed 40% of the total liquid present in the system, below which it is herein defined as a region of low/moderate entrainment. Conversely, above 40%, it is herein defined as a high entrainment region. The threshold value of 40% has not been randomly selected. The points above this level correspond to the points in Figure 6.7a above the mean liquid speed, $U_{lf,mean}$, of 1.735 m/s, where the change in the gradient of the proposed correlation occurs. With increasing gas Reynolds number, the level of Kelvin-Helmholtz instability increases, which has been proven to be associated with the increase in disturbance wave generation. However, when in the high entrainment regime, the level of turbulence resulting from the action of gas shearing in the system and more specifically on the disturbance waves is so intensive that changes in the shape of the disturbance waves start to occur. It is therefore postulated that in this scenario, a certain number of disturbance waves can ‘disappear’ as most of the bulk of the liquid present in them is entrained into the gas core, leading to a change in the gradient observed in the relationship between the wave frequency and the mean film velocity.

As a result, two different correlations have been derived: one for the low/moderate entrainment region, which consists of the region where most of the datasets here reviewed are inserted, together with part of the data from Wolf et al. (2001); and one for the high

entrainment region. These are respectively marked in Figure 6.7a, and their equations can be found below:

$$f_{dist} \times E_c = 2.014 \frac{L_f}{\delta} - 0.9248 \quad \text{for } \frac{L_f}{\delta} \leq 1.735 \text{ m/s} \quad (\text{Eq. 6.24})$$

for the low/moderate entrainment region. In the case of the high entrainment region, the relationship is given as:

$$f_{dist} \times E_c = 1.107 \frac{L_f}{\delta} + 0.461 \quad \text{for } \frac{L_f}{\delta} > 1.735 \text{ m/s} \quad (\text{Eq. 6.25})$$

Using Equation 6.20, the coefficient of determination, R^2 , for the proposed correlations was estimated, being 0.788 and 0.707 for the low/moderate and high entrainment correlations, respectively. Additionally, using Equations 6.24 and 6.25, together with the corresponding equivalent circumference, E_c , for each dataset, direct comparison can be established between the experimental and the predicted values, which can be seen in Figure 6.7b. It can be seen from Figure 6.7b, that for the values predicted in the low/moderate entrainment region, that the predictions for the disturbance wave frequency are generally acceptable, mostly within the 20% error bands, and with a calculated MAE of 23.7%. The main discrepancies occur at the low frequency values encountered in certain flow conditions in the work of Wolf et al. (2001) and in the work conducted in gas-sheared flows in an horizontal duct. Due to the low values of the frequency of the waves in these scenarios, a small discrepancy between the predicted and the experimental value induces a bigger percentage difference between these same values. This is somewhat reduced when considering higher frequency values. Furthermore, according to Azzopardi (1986), differences of up to 50% can be encountered in the measurement of disturbance wave frequency by different workers for the same nominal conditions. This can vary depending on both the experimental technique employed for the measurement of the film thickness and on the data processing technique. For instance, most of the authors that employed conductance probes in the measurement of the film thickness (such as Wolf et al. (2001)), typically employ a Fourier spectral analysis in the measurement of the disturbance wave frequency. However, as discussed in Section 3.4.2 of Chapter 3, as reported by Huang et

al. (1998), for a successful application of this method, the system must be linear and the data must be strictly periodic or stationary, otherwise the resultant spectrum can make little physical sense. Since there is a level of non-periodicity associated with the disturbance wave behaviour, some errors can occur in the determination of their actual frequency, which can account for the discrepancy between the proposed correlation and the experimental value. Additionally, although satisfactory, in this low/moderate region, it can be seen that using the experimental input parameters to derive properties such as the loading factor leads to reasonable predictions of the disturbance wave frequency, although this scenario could be improved if the knowledge of the actual amount of liquid was present as a liquid film was known for all cases. From this, a more accurate (effective) loading factor could be estimated (as in the work of Wolf et al. (2001)). Finally, from Figure 6.7b it can be seen that using the effective loading factor, predictions of the wave frequency in the high entrainment region (orange full points) is highly successful, with a measured MAE of 6.4%.

It can be therefore concluded that using a Strouhal number like relationship, with different pre-set conditions depending on the duct geometry and on the level of entrainment present, a successful predictive tool for the disturbance wave frequency across a multitude of flowrate combinations and orientations has been established. This has been demonstrated by the collapse of multiple datasets into monotonic relationships.

6.2.3 Prediction of mean film thickness

This section reports on a proposed correlation presented here for the estimation of the mean film thickness in the annular flow regime. This is a key parameter in the understanding and prediction of the annular flow regime, as it plays a major role in various parameters that describe this flow regime. For instance, from the previous section, it was seen to play a crucial role in the prediction of the disturbance wave frequency, as it is used in the derivation of the mean film velocity, $U_{lf,mean}$. Additionally, it has been shown in Section 6.2.1 that there is an inversely proportional relationship between the mean film thickness and the disturbance wave velocity, and therefore its prediction is required. Lastly, as shown in Chapter 2, it has been demonstrated to be a vital parameter in the estimation of the interfacial shear stress parameter, which itself ultimately plays a major role in the estimation of the pressure drop across the system in question.

In the derivation of an expression for the film thickness, the principle of the triangular relationship postulated by Hewitt and Hall-Taylor (1970) was revisited. As discussed in Chapter 2, it asserts a close relationship between the liquid film flowrate, the liquid film thickness and the gas-liquid interfacial shear. The liquid film flowrate is computed by integrating the liquid film velocity profile, which depends on the shear across the liquid film thickness, which is a function of both the gas and liquid velocities in the system.

As a result, the dependence of the shear stress as a function of the velocities in the system was initially investigated. This was performed by relying on experimental data for film thickness and pressure drop measurements provided by our collaborators at the Kutateladze Institute of Physics, in Novosibirsk, Russia. This can be seen as an updated version of the current study's downwards annular flow experiment, since pressure drop measurements were obtained in the same flow, pipe and axial configurations as this study's experiment. However, not only water was tested, but also slightly more viscous solutions (up to 2x the viscosity of water) were tested by adding small concentrations of glycerol. With the knowledge of both the mean film

thickness and pressure drop, a simplified version (without taking into consideration the entrainment factor) of Equation 2.37 was used to obtain the experimental interfacial shear, τ_i . Empirically, a monotonic relationship for all the datasets between the interfacial shear, τ_i , the gas superficial velocity, V_G , and the liquid loading factor, L_f , was found, as shown by Figure 6.9:

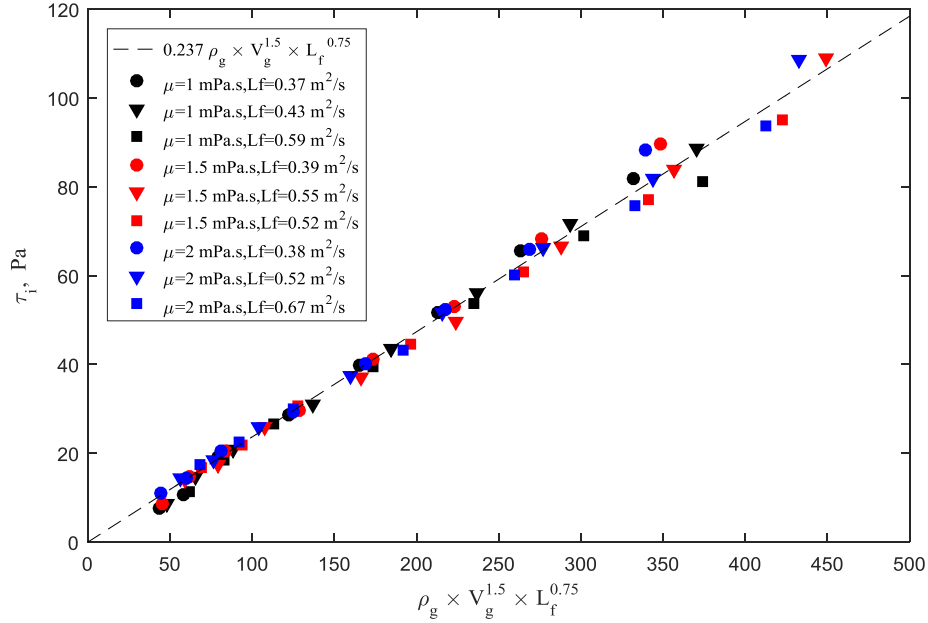


Figure 6.9: Empirical correlation derived for air-water/glycerol solutions of slightly different viscosity.

It can be seen from Figure 6.9 that a very good collapse of the data is obtained, where it is seen that the interfacial shear stress is not affected by small changes in the liquid viscosity.

It was found therefore that the interfacial shear stress for air-water/glycerol solutions can be estimated using the following relationship:

$$\tau_i = 0.237 \rho_G \times V_G^{1.5} \times L_f^{0.75} \quad (\text{Eq. 6.26})$$

From Equation 2.33, the interfacial friction factor has been demonstrated to be related to the interfacial shear stress using the following relationship:

$$\tau_i = \frac{1}{2} \times f_i \times \rho_G \times V_G^2 \quad (\text{Eq. 2.46})$$

Equating and re-arranging both Equations 2.33 and 6.26 results in:

$$f_i = AL_f^{0.75} / V_G^{0.5} \quad (\text{Eq. 6.27})$$

The proposed correlation for the mean film thickness is based on a mathematical computation between the empirical correlation here derived for the interfacial shear stress, and the film thickness correlation derived by Kosky and Staub (1971), who was one of the first authors to develop a model to predict this parameter. This has been later on adopted by Ambrosini et al. (1991), as described in Section 6.1.3. Their correlation was derived based on a force balance between the liquid film, assuming the velocity profile to be that for a single phase turbulent flow. Since the turbulent profile is dependent on the film height, the following relationship was established for the dimensionless film thickness, δ^+ :

$$\delta^+ \propto Re_L^{0.875} \quad (\text{Eq. 6.28})$$

From Section 2.6.2 of Chapter 2, the Universal Velocity Profile (UVP) assumption within the film asserts that:

$$u_L^* = \sqrt{\frac{\tau_i}{\rho_L}} \quad (\text{Eq. 2.41})$$

$$\delta^+ = \frac{\delta u_L^*}{v_L} \quad (\text{Eq. 2.42})$$

Dividing both sides of Equation 6.26 by ρ_L , and square rooting them leads to:

$$\sqrt{\frac{\tau_i}{\rho_L}} = A \times V_G^{0.75} \times L_f^{0.375} \quad (\text{Eq. 6.29})$$

Inserting 6.29 into Equation 2.41, and Equation 2.41 into 2.42 results in:

$$\delta^+ = \frac{\delta \times A \times V_G^{0.75} \times L_f^{0.375}}{v_L} \quad (\text{Eq. 6.30})$$

Equations 6.28 and 6.30 can be therefore equated with each other:

$$Re_L^{0.875} \propto \frac{\delta \times A \times V_G^{0.75} \times L_f^{0.375}}{v_L} \quad (\text{Eq. 6.31})$$

Given that $L_f = Re_L v_L$ can be inserted into 6.31, it can be re-arranged to give:

$$\delta \propto B \frac{Re_L^{0.875}}{V_G^{0.75} \times Re_L^{0.375}} \rightarrow \delta \propto B \cdot Re_L^{0.5} V_G^{-0.75} \quad (\text{Eq. 6.32})$$

Equation 6.32 was then tested against different datasets from Table 6.4 by first non-dimensionalising it by each correspondent hydraulic diameter. For circular pipes, it is equivalent to the pipe diameter and for rectangular ducts, it was found using Equation 6.17. This resulted in the monotonic relationship observed in Figure 6.10a, where all the data is seen to be collapsed into a single line, independent of the flow conditions and geometries.

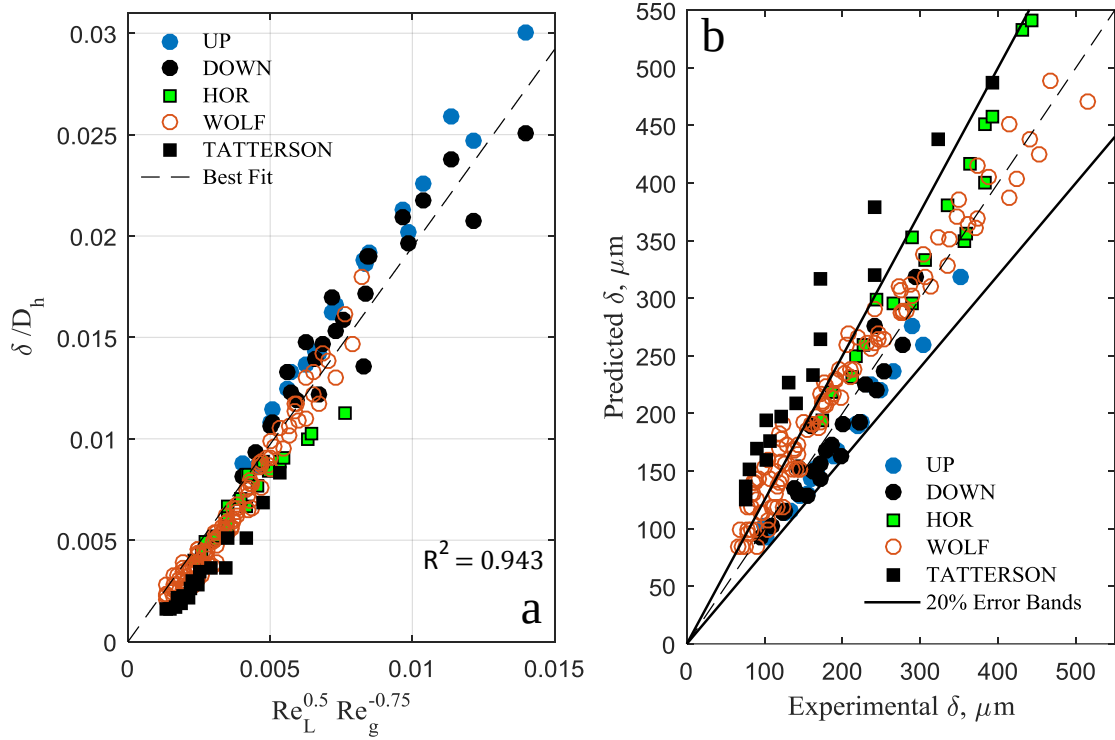


Figure 6.10: a) Proposed correlation for the dimensionless mean film thickness in the annular flow regime in different system configurations; b) direct comparison between experimental and predicted values.

It can be seen from Figure 6.10a, that a successful relationship has been derived, from which an universal best fit line could be empirically determined. As expected, it crosses the 0 point value where no liquid and gas is present in the system. The dimensionless film thickness is therefore given by the following relationship:

$$\delta/D_H = 1.947 \times Re_L^{0.5} Re_G^{-0.75} \quad (\text{Eq. 6.33})$$

The coefficient of determination, R^2 , of the prediction of the data from Equation 6.33 was calculated to be 0.943.

Using Equation 6.33 and the corresponding hydraulic diameter and flow conditions tested, a direct comparison between the experimental and predicted values of the mean film thickness could be performed. This is shown in Figure 6.10b, where regardless of the difference in geometry and flowrates tested, the data is in general predicted under 20% error. The only exception is the data of Tatterson et al. (1977), which consists of an unorthodox experimental campaign of a annular flow system in an horizontal rectangular duct whose height is several orders higher (12.2), than the duct width, where the flow dynamics can be therefore be slightly different. Nonetheless, the mean absolute error (MAE) of the absolute mean film thickness prediction was calculated to be 20.1%, thus validating the application of this universal correlation.

However, it is important to stress one more time the importance of having the knowledge of the effective liquid Reynolds number to predict the data from Wolf et al. (2001). This is a paramount factor whose prediction based on the input experimental parameters needs to be investigated by the research community in order to relate the entrainment rate with axial position. This is of vital importance if annular flow parameters are to be be successfully predicted, as it has been shown to play a major role on the variability of the parameters here predicted, especially in the high entrainment region. As shown by the ‘Up’, ‘Down’ and ‘Hor’ datasets, in the region of low/moderate entrainment, the application of the input experimental parameters results in a successful prediction of the parameters that characterize the annular flow regime.

6.3 Summary and conclusions

This Chapter reported on the prediction of three major parameters that characterize the annular flow regime in the entrained region (i.e. where disturbance waves are present). These comprise the disturbance wave velocity and frequency, together with the mean film thickness of the liquid phase.

This was first conducted by comparing the results of this study's annular flow campaign in an 11.7mm pipe with a multitude of existing correlations published in literature. It was shown that a successful prediction of any of the three parameters discussed above has not been established for this study's dataset using the correlations from the open literature, since the results obtained are generally above the 30% error band. This was attributed to the fact that all the correlations were empirically derived from measurements conducted at axial distances much higher than the current study's, where variation of the annular flow parameters occurs. As these correlations rely solely on the input experimental parameters (such as individual liquid and gas flowrates injected into the system), this variability of the values of the parameters being predicted is therefore not taken into consideration. Additionally, due to empiricism associated with these correlations, their application to other scales and flow conditions is at times severely constrained. More specifically, with regard to the performance of the published correlations in literature in the prediction of this study's data, the following conclusions were drawn:

- In the prediction of the disturbance wave velocity, it was found that the two best performing correlations from literature were from the work of Kumar et al. (2002) and Schubring and Shedd (2008). Both successfully captured the feature of increasing wave velocity with both increasing liquid Reynolds and gas superficial velocity. However, both under predict the actual disturbance wave velocity by more than 45%;
- In terms of the disturbance wave velocity, the best performing correlations are those of Sekoguchi et al. (1985) and Azzopardi (2006). The former derived their empirical correlations based on an experimental campaign whose conditions match the current

study's annular flow experiment. However, due to a discrepancy on the axial position from which the data was acquired, the prediction of the data is again under predicted by about 45%. In the case of the prediction of Azzopardi (2006), the predicted values range across the entirety of the 50% error bands and the correlation is not able capture the increase in wave frequency with an increase of the liquid Reynolds number;

- Finally, in terms of the mean film thickness, a discussion was presented on the level of high complexity of the empirical correlations being proposed, where multiple forces that are assumed to play a role in the behaviour of this parameter are attempted to be considered. This usually takes place in the form of multiple dimensionless groups being combined into a complex expression. For this study's data, the two best performing correlations were found to be of Fukano and Furukawa (1998) and Hori et al. (1978). Both captured the increase in film thickness with increasing liquid Reynolds and the decrease in its value with increasing gas superficial velocity. However, both failed to predict the experimental mean film thickness by more than 50%.

As a result, it was concluded that for a successful prediction of these parameters, that the basic underlying physical components that are believed to govern these parameters needed to be revisited. This, in general led to more simplified monotonic relationships to be established. The only drawback for these relationships is that their validity is to a large extent constrained to air-water systems. This is due to the fact that the prediction of the mean film thickness (which plays a role in the two remaining parameters being predicted) is based on interfacial shear stress measurements performed in such a system. However, in contrast to what was previously reported in literature, a successful universal application of all the proposed correlations was established for a large number of air-water systems, regardless of the duct properties (size, circular or rectangular geometry), flow orientation (vertically upwards and downwards, or horizontal), or flow conditions. It is worth mentioning that the subject of variability of the parameters being predicted with axial location was taken into consideration by taking into account the entrainment rate at various axial positions, as it was demonstrated

that they have an influence on these parameters. This was conducted through the analysis of the data obtained by Wolf et al. (2001). With the knowledge of this information, which was obtained up to axial locations much greater than the other cases considered, calculation of the effective liquid superficial velocity based on the actual amount of liquid present a particular location, given a set of flowrates being tested was achieved. From this, the effective values of parameters such as liquid Reynolds or loading factor, which are employed on the proposed correlations, were derived.

In terms of this study's proposed correlations and their performance, the following conclusions were made:

- From the correlations to be proposed, although it shows a high level of predicting accuracy, the disturbance wave velocity correlation can be regarded as the least satisfactory parameter being proposed. This is because further developments in the understanding of the physical parameters that govern this parameter need to be achieved. It was initially discussed that using data from various datasets, an inversely linear proportional relationship was observed between the mean film thickness and the disturbance wave velocity, even though both parameters varied with axial position. Despite this, attempts to establish a correlation that relates these two parameters in a straight line function across all datasets has not been achieved to date. However, a relationship was found when plotting the results of all datasets in a logarithmic graph which equates the dimensionless wave velocity (non-dimensionalized by the liquid superficial velocity) against the Reynolds number ratio. Although it is not the best engineering practice to equate parameters that are present in both axis against each other (which leads to straight line relationships), it was found that all the datasets collapsed into a single line, which was then empirically determined. When comparing the experimental results for all the various datasets being investigated from the ones derived from this expression, an MAE of 11.2% was achieved;

- In terms of the prediction of the disturbance wave frequency, a successful correlation was proposed in the form of disturbance wave frequency multiplied by the equivalent circumference (depending on the duct geometry), against the loading factor divided by the mean film thickness. The latter corresponds therefore to the mean velocity of the liquid phase. As a result, the gradient of all the collapsed data based on this relationship corresponds to a Strouhal number, which is a dimensionless group that is typically employed in the estimation of the frequency of a given parameter. Several aspects regarding this correlation were reported. It was found that there is a minimum film speed above which disturbance waves occur, which was shown to be around 0.5 m/s, where the transition from the ripple wave to a disturbance wave regimes takes place. Additionally, it has been demonstrated that above a liquid film mean velocity of 1.375 m/s, a change on the gradient of relationship was observed. With the aid of the data from Wolf et al. (2001), it was demonstrated that this corresponded to the point where more than 40% of the liquid in the system was entrained into the gas core. It was therefore postulated that in this scenario, a certain number of disturbance waves can ‘disappear’ as most of the bulk of the liquid present in them is entrained into the gas core, leading to a change in the gradient observed in the relationship between the wave frequency and the mean film velocity. As a result, two different correlations were derived: one for the low/moderate entrainment region, which consists of the region where most of the datasets here reviewed are inserted, together with part of the data from Wolf et al. (2001); and one for the high entrainment region. The MAE of the prediction of the frequency values in the low/moderate and high entrainment regions for all the datasets investigated was found to be 23.7% and 6.4%, respectively;
- Finally, a successful correlation was proposed for the mean film thickness divided by the hydraulic diameter (depending on the duct geometry) against both the liquid and gas Reynolds numbers (each with an individual exponent). The exponent of each

Reynolds number was shown to be mathematically determined by combining an empirical correlation derived from results obtained from an interfacial shear stress experiment, together with the Universal Velocity Profile (UVP) assumptions and the dimensionless film thickness relationship from the work of Kosky and Staub (1971). This resulted in a collapsed relationship from which a best fit line that goes through zero was empirically determined. The MAE for the prediction of the experimental absolute mean film thickness values was found to be 20.1%, thus showing the validity of the relationship.

A list of this study's proposed universal correlations for four key parameters that describe the annular flow regime in the entrainment region, together with their predicting performances for all the cases investigated can be found in Table 6.5

Table 6.5: This study's proposed correlations for the prediction of the disturbance wave velocity and frequency, together with the mean film thickness of the annular flow regime, in the entrainment region.

Parameter Predicted	Expression	R^2	MAE of actual value
Disturbance wave velocity	$V_{dist}/V_{SL} = (Re_L/Re_G)^{A \cdot \exp(B)}$ $A = -0.8214; B = 0.0258$	0.965	11.2%
Disturbance wave frequency (low/moderate entrainment region)	$f_{dist} \times E_c = 2.014 \frac{L_f}{\delta} - 0.9248$ $for \frac{L_f}{\delta} \leq 1.735 m/s$	0.788	23.7%
Disturbance wave frequency (high entrainment region)	$f_{dist} \times E_c = 1.107 \frac{L_f}{\delta} + 0.461$ $for \frac{L_f}{\delta} > 1.735 m/s$	0.707	6.4%
Mean film thickness	$\delta/D_H = 1.947 \times Re_L^{0.5} Re_G^{-0.75}$	0.943	20.1%

Lastly, it is important to stress that further research needs to be conducted in the understanding of how not only the parameters here predicted, but also the entrainment rate

parameter, evolve with axial location. This would result in a full prediction of the annular flow regime using this study's proposed correlations over any range of flowrate conditions. From the previous sections, it was demonstrated that when operating in the low/moderate entrainment region, using the experimental input parameters is sufficient for a acceptable prediction of the annular flow parameters. However, in the high entrainment region (when either the axial location or the gas and liquid flowrates are high), the knowledge of the actual amount of water present in the system as a liquid film is required for successful predictions to be obtained. Additionally, because all the cases here investigated employ water with similar viscosity, surface tension and density, it is not possible to generalise these relationships to all flow configurations. It is also possible that higher viscosities will affect the friction factor in different ways and all these factors need to be investigated.

Additional experimental campaigns with different liquid properties are planned, which will contribute to the determination of fully universal rules that can be used in the flow assurance design process, which can minimise environmental impacts and increase the efficiency of multiphase transportation.

Chapter 7. Conclusions and Future Work

This chapter summarises the conclusions drawn from the findings of the experimental work conducted in this study. Furthermore recommendations of future work are provided based on research gaps that were identified during the discussions of the results obtained.

7.1 Conclusions

The main aim of this thesis was to investigate the interfacial structures that are present in the slug and annular flow regimes in vertical gas-liquid flows. This was achieved using the Brightness Based Laser Induced Fluorescence (BBLIF) technique. The merits of employing such a high temporally and spatially resolved diagnostic tool in the study of film flows have been demonstrated. Due to the versatility of its application, it was employed in two different experimental arrangements, which comprised of an artificially generated Taylor bubble experimental arrangement (which simulates the dynamics of the slug flow regime), and measurements of annular flows at multiple locations in an 11.7mm pipe in different vertical flow orientations.

In **Chapter 4**, the results obtained from the Taylor bubble experimental campaign were presented. The aim of this study was to investigate the behaviour of the falling film surrounding a Taylor bubble and the wave structures present in it. This was complemented with the observation of how their behaviour affects the gas exchange between the Taylor bubble and the wake region that is located directly underneath it. It was concluded that with increasing liquid flowrates, an increase of the parameters of mean film thickness of the falling film, on the relative amplitude, velocity and frequency of the waves is observed. Due to mass conservation, during the thinning region of the Taylor bubble profile, a linear relationship was established between the wave velocity and the inverse square root of the mean film thickness of the falling film. Changing the gas flowrate shows no change in the aforementioned

parameters. With regard to the link between the falling film dynamics and the gas entrainment process, it was observed that the wave behaviour is indeed the driving force behind these events. It was shown that with increasing liquid flowrate, the level of disruption that the incoming waves have on the perturbation of the wake region increases significantly, which leads to an increase in the entrainment rate. Due to the ability to acquire highly detailed visual data over a certain area of the pipe with the BBLIF, two new modes of entrainment have been identified and characterized for the first time. They consist of (i) entrainment through crater generation and (ii) entrainment through self enhancement of entrainment by action of re-coalescing bubbles, with both occurring simultaneously in slug flow conditions ($Fr_{TB} \geq 1$). It was concluded that the action of re-coalescing bubbles has been overly disregarded in terms of its impact on the entrainment. This is due to the fact that it was observed that these bubbles, once present near the skirt of the Taylor bubble, cause a great number of instability events, which lead to further entrainment.

In **Chapter 5**, the effect that the flow orientation (in vertical flows) has on the dynamics of the annular flow regime was investigated. More specifically, its effect on the behaviour of the disturbance waves (where a full characterization was provided), the ripple waves and finally the base and mean film thickness was demonstrated. This study was conducted by obtaining measurements at two different axial locations along a 11.7mm ID pipe: namely between 0 – 100mm and 330 – 430mm from the inlet. Close to the inlet, the mechanism of disturbance wave formation from the coalescence of small, high frequency wavelets has been observed. These periodic wavelets are originally formed due to the Kelvin-Helmholtz instability, where the interface becomes wavy due to the shearing action of the gas phase on the liquid phase. Due to a momentum balance, it was seen that the velocity and frequency of the wavelets increase with both gas and liquid flowrates. This will also be the case for the disturbance waves that were studied further downstream. By performing a spectral analysis of the film thickness data close to the inlet, the initial frequency of the wavelets was measured, which was shown to be independent of the flow orientation at this stage.

At 330 – 430 mm it was shown that the disturbance waves present in the film are travelling at a constant speed, thus allowing for the assumption that the flow is in a developed condition. The full characterization of the parameters that describe the behaviour of the disturbance waves was achieved by employing a modified tracking algorithm. The algorithm obtains the spatial and temporal location of all the individual disturbance waves present in the spatiotemporal plots obtained through the BBLIF technique. It was observed that, with the exception of the lowest liquid Reynolds number tested that, at this stage, the frequency of the disturbance waves is higher for the downwards orientation, although they travel at the same velocity. This difference has an impact on the resultant time and distance separation between disturbance waves, which are shorter for the downwards configuration. In terms of the wave intermittency, due to a higher number of waves present in the film for the downwards configuration, higher values of this parameter were measured in this scenario. Despite the higher number of waves present in downwards flow, it was found that the wave width is the same for both flow orientations. It was also seen that with increasing gas superficial velocity, the width of the waves is reduced, again, in both orientations.

In order to analyse the behaviour of the ripple waves that cover the base film, an Omega-K analysis was performed on the spatiotemporal plots. The analysis showed that there is an increase in the ratio between the ripple and disturbance wave velocities with increasing gas flowrate for the upwards case, whereas for the downwards case, the ratio is constant under the same conditions. It was postulated that this is an indication of a discrepancy in terms of the base film thickness with flow orientation. This was confirmed from the measurements of both base and film thickness. It was observed that a thicker base is present in the upwards configuration. This is an indication that the gravitational action has an effect on the base film thickness. Since the base is thicker in the upwards configuration, the ripple waves present in it are therefore prone to higher shearing action from the gas phase, leading to a higher ripple to disturbance wave velocity ratios.

Finally, the prediction of three major parameters that characterize the annular flow regime in the entrained region was covered in **Chapter 6**. They consist of the disturbance wave velocity and frequency, in addition to the mean film thickness of the liquid phase. Firstly, a comparison of the results obtained in Chapter 5 for these parameters were made with most of the open set of correlations published in the literature. For all the parameters being predicted, no successful prediction has been achieved using classical correlations from literature. This was attributed to the fact that all the correlations reviewed were empirically determined from only the particular set of results from which they were derived. As these correlations rely solely on the input experimental parameters (such as individual liquid and gas flowrates injected into the system), the variability of these parameters with axial location is not taken into consideration. As a result, their prediction fails if they are tested at axial locations that differ greatly from the one from which they were derived, which is the current case.

It was then concluded that for a successful prediction of these parameters, the basic underlying physical components that are believed to govern these parameters needed to be revisited. This, in turn, led to more simplified monotonic relationships being established based on universal rules applicable to the annular flow regime. The only drawback for these relationships is that their validity has been only proven in air-water systems. Additionally, in highly entrained conditions (when more than 40% of the liquid is present in the gas core), it has been demonstrated that the knowledge of the actual amount of liquid present as a film is necessary for successful predictions to be achieved. Through the knowledge of this parameter, the factor of axial location can be taken into consideration. In systems of low/moderate entrainment, which can be achieved in moderate gas and liquid flow conditions, or axial positions shorter than $100D$, it has been demonstrated that reasonable predictions can be achieved using experimental input values in the determination of the factors that compose the correlations suggested.

The major contribution of this work to the multiphase flow field is that a set of successful universal correlations for all the aforementioned parameters has been established for a large

number of air-water systems. The correlations have been benchmarked against a multitude of systems that vary in terms of their duct properties (size, circular or rectangular geometry), flow orientation (vertically upwards and downwards, or horizontal), and flow conditions. These set of rules are of significant importance, since they allow for increased predictive capabilities during the flow assurance design processes in multiphase flow systems.

7.2 Recommendations for further work

Based on the observations and analysis of the data presented in this thesis, the following recommendations can be made for further investigation.

1. With regard to investigative work on the dynamics of the falling film, and its impact on the gas exchange process in the slug flow regime, improvements can be made in the quantification of the gas entrained through the mechanisms identified in this study. The application of the Planar Laser Induced Fluorescence (PLIF) technique could be beneficial in the artificial configuration employed by this study. It would still allow for the observation (although in a single plane) of incoming waves, but since it provides a transverse view of what is occurring, it would also allow for insights on how the surface of the liquid pool in the skirt region behaves. Studying the relation between both features could potentially help in the modelling of the entrainment mechanisms here identified. A simultaneous application of this technique with a tomography measurement technique aimed at the wake region, which allows for void fraction measurements to be obtained, could lead to advances in the validation of the entrainment rate predictions.
2. Another potential application is an experimental campaign that aims at tracking a particular Taylor bubble in conventional slug flow conditions. This could be achieved by placing both the high speed camera and the laser output source (using optical fibres) on a motorised rail that moves alongside the Taylor bubble. From this, it could be investigated if the likelihood of occurrence of each of the entrainment mechanisms here identified changes from an artificial to a conventional slug flow scenario.

3. Due to the high level of turbulence present in the annular flow regime, with a large amount of phenomenological events taking place simultaneously, multiple recommendations can be made for further investigative work, in an attempt to help the community to better understand these complex flows. The employment of the BBLIF technique in conjunction with pressure drop and entrainment rate measurements at multiple axial positions could lead to major advances in the prediction and understanding of the variation of the various parameters that characterize the annular flow regime. Ideally, conducting such experimental work across multiple pipe diameters would contribute to the knowledge of how these factors differ as the scales involved vary.
4. As discussed in Chapter 6, it is of vital importance to perform experimental work with liquids with viscosities and/or surface tensions that differ significantly from water. This will contribute massively to the improvement of the set of universal correlations proposed in this study, where these factors would then be taken into consideration, thereby making its application even broader.
5. Finally, three parameters that are part of the characterization of the annular flow regime were covered in this thesis. However, further work needs to be employed in the understanding of the physical forces that govern other parameters such as disturbance wave amplitude and intermittency, or the base film thickness. From this, predictive tools for these parameters can be potentially derived. This would result in a much more complete understanding and prediction of the annular flow regime.

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Appendix A – Pre-process of BBLIF images

Codes for calculation of absorption matrix, a

%%5mm

```
dname='E:\20mm Rig\alpha calculation\Third attempt\5mm\';
aa5=zeros(32,212);
for n=1:499
    if n<10
        fn='00000';
    end
    if n>=10 && n<100
        fn='0000';
    end
    if n>=100 && n<1000
        fn='000';
    end
    if n>=1000 && n<10000
        fn='0';
    end
    if n>=10000
        fn='';
    end
    a5=double(imread([dname 'calibration.4zb5gxmm.' fn num2str(n)
'.tif'])));
    a5=a5(155:186,567:778);
    aa5=aa5+a5;
    aaa5=aa5/499;
    a5final=median(aaa5(:));
end
```

%%2mm

```
dname='E:\20mm Rig\alpha calculation\Third attempt\2mm\';
aa2=zeros(32,212);
for n=1:499
    if n<10
        fn='00000';
    end
    if n>=10 && n<100
        fn='0000';
    end
    if n>=100 && n<1000
        fn='000';
    end
    if n>=1000 && n<10000
        fn='0';
    end
    if n>=10000
        fn='';
    end
    a2=double(imread([dname 'calibration.4zb5gxmm.' fn num2str(n)
'.tif'])));
    a2=a2(155:186,567:778);
    aa2=aa2+a2;
    aaa2=aa2/499;
    a2final=median(aaa2(:));
end
```

```

a2=double(imread([dname 'calibration.4zb5keg4.' fn num2str(n)
'.tif']));
a2=a2(155:186,567:778);
aa2=aa2+a2;
aaa2=aa2/499;
a2final=median(aaa2(:));
end

```

%%1mm

```

dname='E:\20mm Rig\alpha calculation\Third attempt\1mm\';
aa1=zeros(32,212);
for n=1:499
    if n<10
        fn='00000';
    end
    if n>=10 && n<100
        fn='0000';
    end
    if n>=100 && n<1000
        fn='000';
    end
    if n>=1000 && n<10000
        fn='0';
    end
    if n>=10000
        fn='';
    end
    a1=double(imread([dname 'calibration.4zb5dop5.' fn num2str(n)
'.tif']));
    a1=a1(155:186,567:778);
    aa1=aa1+a1;
    aaa1=aa1/499;
    a1final=median(aaa1(:));
end
x=[0 1 2 5]';
rx=[0 1 1.6834 2.7854]';
myratiotype=fitttype('a*(1-exp(-alpha*x))*(1+0.04*exp(-
alpha*x))','dependent',['rx'],'independent',['x'],'coefficients',['a','alpha']);
myfitratio=fit(x,rx,myratiotype);
figure()
plot(myfitratio,x,rx)

```

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Edge detection for $C(x,y)$ matrix in the stationary Taylor bubble experimental campaign

```

%%To detect the film thickness from the images
dn='E:\Stationary Taylor Bubble\l_30_g_10\light\down\';
dnn='E:\Stationary Taylor Bubble\l_30_g_10\light\down coordinates manual\';
tic
%list = dir('*.mat');
for t = 1:999 %260
    try
        load([dn num2str(t) 'down.mat'])
        a=double(down);
        b=edge(a,'canny');
        se0 = strel('line', 5, 0);
        bb = imdilate(b, [se0]);
        c=bwlabel(bb);
        nm=max(max(c));
        %
        figure(1)
        surf(c);
        view(0,90);
        q=80;nw=0;
        %
        for n=1:nm %for all the n lines existent in the image
            %
            [y x]=find(c==n);%find all the coordinates for the n lines
            %
            z=0;
            %
            for i=1:length(x) %for the entire length of x
                %
                z=z+abs(y(i)-45); %calculate the absolute difference between y and
the wall coordinate (in this case 45)
            %
            end
            %
            z=z/i;
            %
            if z<q %if the difference is smaller than the total y
                %
                q=z; %the coordinate of the small difference is the one chosen
                %
                nw=n; %nw is the n line for that coordinate, in this case, the n
line of the wall
            %
            end
            %
            end
            %
            nw;
            %
            [yw xw]=find(c==nw); %find the coordinates of the wall
            %
            yw=mean(yw); %average them- try to use a fit function instead
            yw=52;
            yww=55;
            e=[];
            for n=1:nm %for all the n lines existent in the image
                %
                [y x]=find(c==n); %find all the coordinates for the n lines
                %
                d=[];h=[];
                for i=1:length(x) %for the entire length of x
                    %
                    d=[d
                        a(y(i)+1,x(i))-a(y(i)-1,x(i))]; %calculate the difference in
intensity between the y coordinate just above and below the n lines
                    %
                    h=[h
                        yw-y(i)]; %calculate the height between all the n lines above and
the wall
                end
            end
        end
    catch
        continue
    end
end
tic

```

```

end
e=[e
    n mean(d) max(x)-min(x) mean(h)]; %calculate the mean differences in
intensities; calculate the maximum x minus the minimum x for every line; calculate the
mean heights
end
%figure(2)
%plot(e(:,1),e(:,2),'o')
%hold on
%plot(e(:,1),e(:,3),'ro')
%plot(e(:,1),e(:,4),'ko')

f=[];
for i=1:size(e,1)
    if (e(i,2)>60)&&(e(i,3)>200)
% if (e(i,3)>400)
%         if (e(i,2)>0)&&(e(i,3)>400) && (e(i,4)>15) && (e(i,4)<30)
f=[f
    e(i,:)];
    end
end
f;
g=find(f(:,4)>0); %for all the positive mean heights calculated;less than zero
for up;more than zero for down
gg=f(g,:);
[g1,g2]=min(gg(:,4)); %select the minimum
nf=gg(g2,1);
[yf xf]=find(c==nf);
%figure(3)
for d=1:max(max(xf))
    hh=yf-yww;
    hh=-hh;
end
%plot(xf,-hh);
ht=hh;

catch me
end
hsize=size(hh,1);
hdiff=diff(hh(:,1));
try
    for r=1:(hsize-1)
if hdiff(r)==0 && hdiff(r+1)~=0 hdiff(r+2)==(-(hdiff(r+1))) && hdiff(r+3)==(-
(hdiff(r+2))) && hdiff(r+4)==(-(hdiff(r+3)));
hh(r+2)=[];
xf(r+2)=[];
hh(r+3)=[];
xf(r+3)=[];
hh(r+4)=[];
xf(r+4)=[];
hh(r+5)=[];
xf(r+5)=[];
%ht(r+6)=[];
end
        end
catch

```

```

        coo=[xf hh];
        subplot(2,2, [1 2])
        surf(c); view(0,90);
        subplot(2,2, [3 4])
        plot(coo(:,1),coo(:,2),'bo')
        num=int2str(t);
        title(['#',num])
        reply = input('Correct line identified? 3/6 [3]:','s');
        if strcmp(reply,'3')||strcmp(reply,'33')
        %save([dnn strcat(num2str(t),'coo.mat')], 'coo');
        else continue
        end
    end
end
toc

```

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Conversion of BBLIF images into film thickness information

```

close all
clear all
K=0.04; alpha=0.6293; h0=0.098;
A=K; B=1-K;
dname='F:\!experiments\12mm_3d_p3_highdef\2016_01_22\';
dname1='F:\!experiments\12mm_3d_p3_highdef\2016_01_22\hxy\';
% mkdir(dname1)
vg=[22 29 36 43 50 57];
Re=[140 220 300 400];

% for r=1:length(Re)
for r=4

    Iop=zeros(140,1024); %change here
    for n=1:10000
        if n<10
            fn='0000';
        end
        if n>=10 && n<100
            fn='000';
        end
        if n>=100 && n<1000
            fn='00';
        end
        if n>=1000 && n<10000
            fn='0';
        end
        if n>=10000
            fn='';
        end
        i0=double(imread([dname 're40g36\s000' num2str(r) '\c001h001s00010' fn
num2str(n) '.png']));
        Iop=Iop+i0;
    end
end

```

```

end
Cx=Iop/10000/(1-exp(-alpha*h0))/(1+k*exp(-alpha*h0));
% for v=1:length(vg)
    for v=6
        tic
%
%         if r>=2 && v==length(vg)
%             continue
%         end
%         if r==3 && v>=(length(vg)-1)
%             continue
%         end
%         if r==4 && v>=(length(vg)-2)
%             continue
%         end
        [Re(r) Vg(v)]
        dname2=[dname1 num2str(Re(r)) '_' num2str(Vg(v)) '\'];
        mkdir(dname2)
        for nn=1:10000
            if nn<10
                fn='0000';
            end
            if nn>=10 && nn<100
                fn='000';
            end
            if nn>=100 && nn<1000
                fn='00';
            end
            if nn>=1000 && nn<10000
                fn='0';
            end
            if nn==10000
                fn='';
            end
            ixy=double(imread([dname 're' num2str(Re(r)) 'g' num2str(Vg(v))
'\s0001\c001h001s00010' fn num2str(nn) '.png']));
            ymax=length(ixy(:,1)); xmax=length(ixy(1,:));
            C=ixy./Cx-1;D=B*B-4*A*C;
            hxy=zeros(ymax,xmax);
            for yy=1:ymax
                for xx=1:xmax
                    if (D(yy,xx)<0) || (-B+sqrt(D(yy,xx))<=0)
                        hxy(yy,xx)=2;
                        continue
                    end
                    Ex=1/(2*A)*(-B+sqrt(D(yy,xx)));
                    if Ex<0
                        Ex=0;
                    end
                    hxy(yy,xx)=(-log(Ex)/alpha);
                end
            end
            hxy=uint16(round(hxy*1000));
%             save([dname2 num2str(nn) '.mat'],'hxy')
%             imwrite(hxy*32,[dname2 fn num2str(nn) '.png'],'png')
        end
    end
toc

```

```
end  
end
```

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Conversion of film thickness information into spatiotemporal plots

```
close all  
clear all  
  
dname='F:\!experiments\12mm_inlet\2016_01_18\hxy1\';  
vg=[22 29 36 43 50 57];  
Re=[140 220 300 400];  
% for yi=20:20:220  
for yi=80  
    dname1=[dname 'hxt\' num2str(yi) '\'];  
    mkdir(dname1)  
    for r=1:length(Re)  
        for v=1:length(vg)  
            clear hxt hxtt  
            tic  
            hxt=zeros(10000,1020);  
            for i=10000:-1:1  
                load([dname num2str(Re(r)) '_' num2str(Vg(v)) '\' num2str(i) '.mat'])  
                hxt(10001-i,:)=hxy(yi,:);  
            end  
            save([dname1 're' num2str(Re(r)) 'g' num2str(Vg(v)) '.mat'],'hxt')  
            hxtt=uint16(round(hxt));  
            imwrite(hxtt*32, [dname1 're' num2str(Re(r)) 'g' num2str(Vg(v))  
            '.png'],'png')  
        end  
    end  
    toc  
end  
% aa=flipud(hxt);
```

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Appendix B – Post processing of film thickness data

Cross-correlation for estimation of wave velocity

```
tic
clear all
dname='F:\!!experiments\12mm_inlet\2016_01_18\hxy1\hxt\';
xres=0.1;tres=0.1;dxdt=xres/tres;
Vg=[22 29 36 43 50 57];
Re=[140 220 300 400];
Vc=[];
xsep=30;
for yi=80
    for r=1
        % for r=1:length(Re)
        for v=1
            % for v=1:length(Vg)
            load([dname num2str(yi) '\ ' 're' num2str(Re(r)) 'g' num2str(Vg(v)) '.mat'])
            hxt=medfilt2(hxt,[5 3]);
            s=size(hxt);
            XC=[];
            Vdw=[];
            xtF=medfilt2(hxt,[5 3]);
            for i=1:s(2)-xsep
                [xcor0,tlag]=xcorr(detrend(xtF(:,i+xsep)),detrend(xtF(:,i)),'coef');
                [I,In]=max(xcor0);
                XC(:,i)=xcor0;
                [t_max y_max]=crit_interp_p(xcor0(In+[-1:1]),tlag(In+[-1:1]));
                v_t=-((xsep./t_max))*dxdt;
                Vdw=[Vdw
                    v_t];
            %
            % plot(tlag,xcor0);
            % hold on;
            % plot([1 1].*t_max,[-0.5,1],'--k');
            % axis([-0.01*10^4 0.01*10^4 -0.5 1])
            % hold off
            % pause(0.1)
            end
            Vdw=[Re(r)
                Vg(v)
                Vdw];
            Vc=[Vc Vdw];
        end
    end
end
for t=1:s(2)-xsep
    xt(t)=((t+(t+xsep))/2)*xres;
end
xt=[0 0 xt];
vc=[xt' Vc];
```

```
% save([dname num2str(yi) '\\velocity\\' 'vcor_' num2str(yi) '.mat'],'vc')
% xlswrite([dname num2str(yi) '\\velocity\\' 'vcor_' num2str(yi) '.xls'],vc)
toc
```

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FFT to perform spectral analysis

```
tic
clear all
dn='F:\\!!experiments\\12mm_3d\\2015_12_23\\f10exp1bit8\\hxy\\hxt\\';
fw=7; %size of averaging window
xres=0.098;tres=0.1;dxdt=xres/tres;
vg=[22 29 36 43 50 57];
Re=[140 220 300 400];
x0=11;xi=5;xend=990;
xx=((x0:xi:xend))*xres;
xx=[0 xx];
xx=0.01*round(xx*100);
dx=10; % how many pixels will the signal be averaged for a particular point
yi=55;
for r=1:2
    for v=6
        load([dn num2str(yi) '\\ ' 're' num2str(Re(r)) 'g' num2str(Vg(v)) '.mat'])
        [Re(r) Vg(v)]
        psp=[];
        for i=1:length(hxt(1,:))
            hxtt(:,i)=detrend(hxt(:,i));
        end
        for x=x0:xi:xend
            nm=5; %number of divisions of time series
            ddt=(length(hxt(:,1)))/nm;
            for n=1:nm
                for xn=x-dx:x+dx %how many pixels it will be averaged
                    [pxx,f]=pwe1ch(hxtt(ddt*(n-1)+1:ddt*(n-1)+ddt,xn),hann(ddt),[],ddt,10000);
                    Pxx=0+pxx;
                end
                PPxx(:,n)=Pxx/21;
            end
            psp(:,x)=(PPxx(:,1)+PPxx(:,2)+PPxx(:,3)+PPxx(:,4)+PPxx(:,5))/nm;
        end
        psp(:, ~any(psp,1) ) = [];
        psp=psp.^2;
        h=fspecial('average',fw);
        psp=filter2(h,psp)*fw;
        % psp=psp(fw+1:end)/sum(psp(fw+1:end));
        for w=1:length(psp(1,:))
            psp(:,w)=psp(:,w)/sum(psp(:,w)); %to normalise the power
        end
        psp=[f psp];
        psp=[xx
            psp];
        save([dn num2str(yi) '\\fft\\' 'fft_re' num2str(Re(r)) 'g' num2str(Vg(v))
            '.mat'],'psp')
    end
end
```

```

end
% a=psp(2:202,2:154);
% b=rot90(a);
% imtool(b);
toc

```

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Disturbance wave tracking algorithm

```

close all
% clear all
clearvars -except titf vel coeff_out
dn='E:\!!experiments\12mm_3d\2015_12_23\f10exp1bit8\hxy\hxt\55\';
load([dn 're140g22f.mat']);
xres=0.098;tres=0.1;dxdt=xres/tres;
hh=medfilt2(hxtf,[15 13]);
hhh=hh(:,1);
mm=2*mean(hhh(:,1));
[pks,locs] = findpeaks(hhh(:,1));
figure()
plot(hhh(:,1),'r')
hold on
plot(locs,pks,'ob')
plot([0 10000],[mm mm],'--k')
for i=1:length(pks)
    if(pks(i,1))<=mm
        pks(i,1)=NaN;
        locs(i,1)=NaN;
    end
end
pks(isnan(pks)) = [];
locs(isnan(locs)) = [];
for i=2:length(pks)
    if locs(i,1)-locs(i-1,1)<=50 % possibly need to change accordingly
        locs(i,1)=NaN;
        pks(i,1)=NaN;
    end
end
pks(isnan(pks)) = [];
locs(isnan(locs)) = [];
figure()
plot(hhh(:,1),'r')
hold on
plot(locs,pks,'ob')
plot([0 10000],[mm mm],'--k')

xx=[1 100]; %assuming that 50 dx steps were taken
xt=1:50:1000;
vc=2.7; % specify average cross correlation velocity for particular case
dtt=round(50/vc);
mar=20; %change between 20 and 10
dt=dtt-mar:1:dtt+mar;
d=zeros(2,length(dt));
tt=zeros(length(xt),length(locs));

```

```

tt(1,:)=locs(:,1);
ti=zeros(1,length(locs));
tf=zeros(1,length(locs));
for u=2:length(xt)
for i=4:length(locs)
%     tt(u,i)=locs(1,i);
for w=1:length(d)
d(1,w)=tt(u-1,i)-(dt(w)*2);
d=abs(d);
d(2,w)=hh(d(1,w),xt(u));
end
dd(1,i)=max(d(2,:));
dm=find(d(2,:)==max(d(2,:)));
if length(dm)>=1
    dm=dm(1,1);
end
if dm==dd(1,i-1)
d(2,dm)=NaN;
dmm=find(d(2,:)==max(d(2,:)));
tt(u,i)=d(1,dmm);
else
tt(u,i)=d(1,dm);
end
end
end
t=[ti; tf];
xxx=[1 1024];
figure()
    imagesc(hxtf)
hold on
ttt=zeros(2,length(t));
for i=2:length(t)
    ff=fit(xt',tt(:,i),'poly1');
    f(i,:)=coeffvalues(ff);
    vs(1,i)=(abs(1/f(i,1)))*dxdt;
    tff=f(i,1)*1024+f(i,2);
    ttt(1,i)=tt(1,i);
    ttt(2,i)=tff;
    plot(xxx,ttt(:,i),'r--')
end
vss=mean(vs(1,2:end))

for r=1:i
tm(1,r)=(ttt(1,r)+ttt(2,r))/2;
end
B=diff(tm);
B=B(1,2:end);
xlag=[0:50:500];
histtime=hist(B,xlag);
histtimen=histtime/sum(histtime);
figure()
plot(xlag,histtimen*100,'-o')
vlag=[0:0.5:7];
histvel=hist(vs(2:end),vlag);
figure()
plot(vlag,histvel,'o-')

```

Time separation between disturbance waves

```
load(['E:\\!experiments\\12mm_3d\\2015_12_23\\f10exp1bit8\\coefficients_new.mat']);
clear p c d tsepp
x=1:1:1024;
for t=1:2:41
    for e=3:67
        for i=1:1024
            p(e,i)=(coeff_out(e,t)*x(i))+coeff_out(e,t+1);
        end
    end
    p(p==0)=NaN;
    for i=1:1024
        c(:,i)=diff(p(:,i))/10000;
    end
    for u=1:66
        d(u,1)=nanmean(c(u,:));
    end
    tsepp(:,t)=d;
    clear p c
end
% tsepp(tsepp==0)=[];
tsepp(:, ~any(tsepp,1)) = [];
```

%%mean separation times

```
for i=1:21
    tsep_mean(3,i)=nanmean(tsepp(3:end,i));
end

dn='E:\\!experiments\\12mm_3d\\2015_12_23\\f10exp1bit8\\hxy\\hxt\\55\\fft';
load([dn 'disturbance wave frequency from alg_new_new.mat'])
for i=1:21
    ta(3,i)=1./freq_alg(3,i);
end
```

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Distance separation between disturbance waves

```
clear all
load(['G:\\!experiments\\12mm_3d\\2015_12_23\\f10exp1bit8\\times_new.mat'])
load(['G:\\!experiments\\12mm_3d\\2015_12_23\\f10exp1bit8\\velocitiesNAN_new.mat'])
dn='G:\\!experiments\\12mm_3d\\2015_12_23\\f10exp1bit8\\hxy\\hxt\\55\\fft';
load([dn 'disturbance wave frequency from alg_new_new.mat'])
jj=1:2:41;
for j=1:20
    for i=3:66
        d(i,j)=((vel(i,j)+vel(i+1,j))-(titf(jj(j+1),i-1)-titf(jj(j+1),i)))/2;
        if d(i,j)>500 | d(i,j)<0
            d(i,j)=NaN;
        end
    end
end
```

```

        end
    end
end
for i=3:66
    d(i,21)=((vel(i,21)+vel(i+1,21))-(titf(42,i-1)-titf(42,i)))/2;
    if d(i,21)>500 | d(i,j)<0
        d(i,21)=NaN;
    end
end
end
% d(26:28,2)=NaN;
dist_sep=zeros(3,21);
stdisup=zeros(3,21);
errdisup=zeros(3,21);
for t=1:21
    dist_sep(3,t)=nanmean(d(3:end,t));
    stdisup(3,t)=nanstd(d(:,t));
    errdisup(3,t)=(2.*stdisup(3,t))./sqrt(freq_alg(3,t));
end
vg=[22 29 36 43 50 57];
% nanmean(d)
figure()
hold on
box on
grid on
plot(vg,dist_sep(3,1:6),'ko')
hold on
plot(vg,dist_sep(3,7:12),'kd')
plot(vg(1:5),dist_sep(3,13:17),'ks')
plot(vg(1:4),dist_sep(3,18:21),'k^')
%
save(['G:\!!experiments\12mm_3d\2015_12_23\f10exp1bit8\distance_separation_proper.mat'
], 'dist_sep')

```

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Intermittency of disturbance waves

```

% clearvars -except intermittency_comp
tic
% dn='F:\!!experiments\12mm_3d\2015_12_23\f10exp1bit8\hxy\hxt\55\';
Re=[140 140 140 140 140 140 220 220 220 220 220 220 300 300 300 300 300 300 400 400
400 400 400 400];
vg=[22 29 36 43 50 57 22 29 36 43 50 57 22 29 36 43 50 57 22 29 36 43 50 57];
for t=1:24
    clearvars -except intermittency_comp_final t Re Vg intermittency_comp
    load(['F:\!!experiments\Downwards Misha\re' num2str(Re(1,t)) 'g' num2str(Vg(1,t))
'f.mat']);
    hh=medfilt2(hxtf,[15 13]);

for w=721:997
    clearvars -except intermittency_comp hxtf hh w intermittency_comp_final t Re Vg

```

```

        hhh=hh(:,w);
        mm=2*mean(hhh(:,1));
        [pks,locs] = findpeaks(hhh(:,1));
        for i=1:length(pks)
            if(pks(i,1))<=mm
                pks(i,1)=NaN;
                locs(i,1)=NaN;
            end
        end
        pks(isnan(pks)) = [];
        locs(isnan(locs)) = [];
        for i=2:length(pks)
            if locs(i,1)-locs(i-1,1)<=50 % possibly need to change accordingly
                locs(i,1)=NaN;
                pks(i,1)=NaN;
            end
        end
        pks(isnan(pks)) = [];
        locs(isnan(locs)) = [];
        a=size(locs);
        mdn=median(hxtf(:,w));
        hxtf(1,w)=mdn;
        hxtf(20000,w)=mdn;
        for i=1:a(1)
            if locs(i,1)<19500
                [loa(i,1) ix(i,1)] = find(hxtf(locs(i,1):locs(i,1)+500,w) <= mdn,1, 'first');
            end
            if locs(i,1)>=19500
                [loa(i,1) ix(i,1)] = find(hxtf(locs(i,1):20000,w) <= mdn,1, 'first');
            end
            if locs(i,1)<=500
                [lob(i,1) ix(i,1)] = find(hxtf(locs(i,1):-1:1,w) <= mdn,1, 'first');
            end
            if locs(i,1)>500
                [lob(i,1) ix(i,1)] = find(hxtf(locs(i,1):-1:locs(i,1)-500,w) <= mdn,1, 'first');
            end
            if locs(i,1)==lob(i,1) | locs(i,1)==loa(i,1)
                dist(i,1)=NaN;
            else
                dist(i,1)=(locs(i,1)+loa(i,1)-1)-(locs(i,1)-lob(i,1)+1);
            end
        end
        distt=nansum(dist(:,1));
        intermittency_comp(w,1)=distt/20000;
    end
    intermittency_comp_final_down(3,t)=mean(intermittency_comp(721:997,1));
end
toc

```

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Omega-K for ripple wave analysis

```
function [omegak,F,lambda]=create_omegak(xtF,Nt,Nx,tcal,xcal)
% takes xt diagram oriented as time, distance and splits it into sections
% Nt * Nx in size. It then detrends each section and puts it into a stack.
% It uses a 50% overlap between stack. It then take the square of the FFT
% and averages these for the entire stack.
% Output is the omega-k array, the frequency and 1./wavelength.

[Nt_max,Nx_max]=size(xtF);
if Nt<Nt_max % check don;t put in too big a value
    tspan=1:Nt;
else
    tspan=Nt_max;
end;

if Nx<Nx_max
    xspan=1:Nx;
else
    xspan=Nx_max;
end;

i_max=floor(2*(Nt_max/Nt)-1); % number of sections in time
j_max=floor(2*(Nx_max/Nx)-1); % number of section in space
X=zeros(Nt,Nx,i_max+(j_max-1).*i_max);
for j=1:j_max, % stack sections
    for i=1:i_max,
        X(:, :, i+(j-1)*i_max)=detrend(xtF(tspan+(i-1).*Nt./2,xspan+(j-1).*Nx./2));
    end;
end;
F=(-Nt/2:Nt/2-1)./Nt./tcal;
lambda=(-Nx/2:Nx/2-1)./Nx./xcal;

Y=fftshift((abs(fft2(X))).^2);%take spectrum of each slice
omegak=mean(Y,3);% average all slices

end
```

```
clear all
dn='F:\\!!experiments\\12mm_3d\\2015_12_23\\f10exp1bit8\\hxy\\hxt\\55\\';
% A=load([dn 're140g22.mat']);
re=140; %change to value wanted
g=22; %change to value wanted
vg=[22 29 36 43 50 57];
f=find(Vg==g);
ve1=[2.698531838      3.320522838      3.51614739      4.261848003      4.727889774
      5.190885699      2.979654181      3.444584248      4.171971709      4.764100195
      5.073965058      5.563221785      3.041290052      3.703807664      4.390353036
      4.970298663      5.476022777      3.294261109      4.104083701      4.679088834
      5.367976845];
load([dn 're' num2str(re) 'g' num2str(g) 'f.mat']);
if re==140
    r=1;
end
if re==220
    r=7;
```

```

end
    if re==300
        r=13;
    end
    if re==400
        r=18;
    end
tcal=1./10000;
xcal=0.098E-3;
% A=load(filename);
% A.hxtF=medfilt2(A.hxt,[5 3]);
% imagesc(A.hxtF);
% segments to chop area into. Increase to get better frequency resolution
% but fewer averages
Nt=2000;
Nx=750;
% [omegak,F,lambda]=create_omegak(A.hxt,Nt,Nx,tcal,xcal);
[omegak,F,lambda]=create_omegak(hxtf,Nt,Nx,tcal,xcal);
figure();
subplot(2,2,1);
imagesc(F,lambda,log(omegak),[20 34]);% change clim to get better pictures [20 34]
colorbar
axis xy;
hold on;
v=vel(r+f-1); %2.75 for re140g22
div=[0.17 0.22 0.27 0.29 0.31 0.33];
plot(lambda,v.*lambda,'--k','Linewidth',3);%using 2.75 m/s wave velocity
plot(lambda,v.*lambda.*div(f),'k','Linewidth',3);
% multiply by 0.17 factor and not 0.36? Check for other conditions.
hold off
xlim([-500 500]);
ylim([-500 500]);
subplot(2,2,2);
plot(F,mean(omegak,2));
xlim([0 500]);
subplot(2,2,3);
plot(lambda,mean(omegak,1));
xlim([0 500]);

figure();
imagesc(F,lambda,log(omegak),[20 34]);% change clim to get better pictures [20 34]
colorbar
axis xy;
hold on;
v=vel(r+f-1); %2.75 for re140g22
div=[0.17 0.22 0.27 0.29 0.31 0.33];
plot(lambda,v.*lambda,'--k','Linewidth',3);%using 2.75 m/s wave velocity
plot(lambda,v.*lambda.*div(f),'k','Linewidth',3);
hold off
xlim([-500 500]);
ylim([-500 500]);

```

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Appendix C – Error Analysis

There are two sources of uncertainty that need to be taken into consideration in the error analysis of the results obtained. The sources are: uncertainty associated with the measurement equipment, from which the data is acquired and monitored; and uncertainty associated with the processing techniques employed in the analysis of the data acquired. These have a compound effect on the accuracy of the results reported. The estimation of the uncertainty associated with each experimental component is covered below.

Direct uncertainty associated with measurement equipment

Uncertainty of liquid flowrate measurement in the stationary Taylor bubble experimental campaign

The liquid flow measurement was achieved via a turbine flowmeter, model MG025 manufactured by Trimec Industries and calibrated in-house, which has a reading accuracy of $\pm 0.5\%$ and a repeatability of 0.033%.

Uncertainty of gas flowrate measurement in the stationary Taylor bubble experimental campaign

The gas flow measurement was achieved using a variable area flowmeter, model FR2A15SVVT, manufactured and calibrated by Key Instruments, which has an accuracy of $\pm 0.5\%$.

Uncertainty of liquid flowrate measurement in the annular flow experimental campaign

The liquid flowrate for the annular flow experimental campaign was measured using a rotameter, which was calibrated by filling a measuring cylinder with water for 100 seconds. As a result, the error associated with the calibration procedure of the liquid flowmeter was measured with the following equation:

$$\text{Error in calibration} = \sqrt{(\text{Error in measuring water level})^2 + (\text{Error on timer})^2}$$

$$\text{Error in measuring water level} = \frac{\text{minimum scale interval}}{\text{actual reading}} = \frac{10 \text{ ml}}{1000 \text{ ml}} = 1\%$$

$$\text{Error on timer} = \frac{\text{error on pressing button}}{\text{actual reading}} = \frac{1 \text{ second}}{100 \text{ seconds}} = 1\%$$

$$\text{Error in calibration} = \sqrt{(1\%)^2 + (1\%)^2} = \mathbf{1.4\%}$$

By combining the error associated with taking readings from the rotameter, the total uncertainty associated with the liquid flowrate measurement was calculated to be 2%.

Uncertainty of gas flowrate measurement in the annular flow experimental campaign

The gas flowrate for the annular flow experimental campaign was measured using a U-manometer, which compared the pressure difference between sensors before and after an orifice plate. The calibration of the U-manometer was achieved with a rotational air flowmeter RVG (Elster GmbH). The calibration curve was obtained over the flow range of $Q_{\min} = 3 \text{ m}^3/\text{h}$ up to $Q_{\max} = 100 \text{ m}^3/\text{h}$. Consequently, the relative error on the flowrate measured ranged from 1% to 2% over the following intervals:

$$\pm 2\% \text{ at } Q = Q_{\min} - 0.1Q_{\max}$$

$$\pm 1\% \text{ at } Q = 0.1Q_{\max} - Q_{\max}$$

By combining with the error associated with reading the manometer, the total uncertainty associated with the gas flowrate measurement ranged from 1.5 – 2.5% depending on the gas flowrate interval being measured.

Uncertainty associated with the processing techniques used to analyse the data

Uncertainty of mean and base film thickness measurements

In both experimental campaigns, calculation of the mean film thickness was performed based on the film thickness time series present in the spatiotemporal plots under investigation. This was achieved using the following equation:

$$\mu = \text{Mean} = \frac{\sum_{i=1}^N h_i}{N} \text{ where } N \text{ is the total number of measurements}$$

The standard deviation of the measurement of the mean is calculated as follows:

$$\sigma = \text{Standard Deviation} = \sqrt{\frac{\sum_{i=1}^N (h_i - \mu)^2}{N}}$$

The uncertainty associated with the estimation of the mean value of parameters such as film and base thickness was measured by taking into consideration the standard deviation, σ , on the individual values and also on N , the number of readings taken. This can be quantified using a quantity called standard error of the mean, s_m , which is estimated using the following relationship:

$$s_m = \frac{\sigma}{\sqrt{N - 1}}$$

It is such that the mean value of a given sample has a 95% chance of lying within $\pm 2s_m$ of the true value. Therefore, s_m , is a measure of how close to the mean value of a given parameter is to its unknown true value.

In each experimental campaign, the $2s_m$ of the mean values calculated varied, not only because different results were obtained, but also because the total number of measurements, N , used for each campaign varied. Since values of mean and base film thickness were different depending on the feature under investigation, the following examples are given to show the reliability of the BBLIF technique.

Uncertainty of mean film thickness measurement in the stationary Taylor bubble experimental campaign

In the stationary Taylor bubble experimental campaign, the mean film thickness at each axial location was computed from the entire time series recorded for that particular axial position, more specifically, from 4000 points ($\text{sampling frequency} \times \text{total time of sample} = 2000\text{Hz} \times 2 \text{ seconds}$). As an example, from Figure 4.7, one can extract a value of mean wave amplitude, which was obtained using Equation 4.2: $\sqrt{2} \times \sigma$. Taking for instance a value of 0.6mm for the absolute mean wave amplitude for the case of $Fr_{TB} = 0.654$ and $Q_G = 0 \text{ l/m}$ at $x = 30 \text{ mm}$, this equates to $\sigma = 0.424\text{mm}$. Consequently, this results in a $2s_m$ of $\pm 0.013\text{mm}$. From Figure 4.4, it can be seen that the mean film thickness at this point is 3.5mm for the same conditions, and therefore the relative error on the mean film thickness is 0.4%.

Uncertainty of mean film thickness measurement in the annular flow experimental campaign close to the inlet

In the case of the annular flow experimental campaign, the number of total points used in the computation of mean film thickness varied between flow orientation and the axial locations under investigation. The former ranged, since although both upwards and annular results were acquired with a sampling frequency of 10kHz, the total sample time ranged from 1 to 2 seconds for the upwards and downwards cases, respectively. With regard to the axial locations under investigation, close to the inlet (0-100mm), mean thickness values were recorded for each individual axial location in the measurement (1 mean film thickness value obtained for each pixel). For example, at $x = 30\text{mm}$ for the case of $Re_L = 140$, $V_G = 22\text{m/s}$ in upwards flow, the σ of the mean film thickness was measured using MATLAB to be 0.12mm. With $N = 10,000$, the $2s_m$ equates to $2.4 \times 10^{-3}\text{mm}$. At that position, the mean film thickness was measured to be 0.18mm, which results in a relative error on the mean film thickness of 1.3%.

Uncertainty of mean film thickness measurement in the annular flow experimental campaign further downstream

Further downstream (330-430 mm from the inlet), in the developed region, the mean film thickness was based on the mean of the entire axial location (1024 pixels), which increases the total number of measurements significantly (1024×10,000 for the upwards case). At this stage, for the same conditions reported above in upwards flow, the σ of the mean film thickness was measured using MATLAB to be 0.19mm. With $N = 10,000 \times 1024$, the $2s_m$ equates to 5.94×10^{-5} mm. At that position, the mean film thickness was measured to be 0.22mm, which results on a relative error on the mean film thickness of 0.1%.

The examples above provide a flavour of the high level of reliability associated with the calculation of the mean film thickness performed in this study.

Uncertainty on the velocity of waves measured with cross-correlation

The velocity of the waves present in all campaigns was measured with the following equation:

$$V = \frac{D}{T}$$

where D , is the distance between the two pixels whose time series were cross-correlated, and T , is the maximum time-lag obtained from the cross-correlation function. Consequently, the error associated with the velocity measurement is a factor of both these parameters, and is given as follows:

$$\frac{\Delta V}{V} = \sqrt{\left(\frac{\Delta T}{T}\right)^2 + \left(\frac{\Delta D}{D}\right)^2}$$

where

$$\Delta T = \frac{1}{\text{sampling frequency}}$$

$$T = \text{Time delay from cross - correlation function}$$

$$T = \frac{\text{Distance between two time series used in cross - correlation}}{\text{Wave velocity}}$$

$$T = \frac{\text{Pixel Distance} \times \text{spatial resolution}}{\text{Wave velocity}}$$

The uncertainty associated with the distance measurement, is related to the error in selecting the pixels to be cross-correlated, together with the uncertainty of the calibration associated with the estimation of the spatial resolution for a given experimental campaign:

$$\left(\frac{\Delta D}{D}\right)^2 = \left(\frac{\Delta P}{P}\right)^2 + \left(\frac{\Delta C}{C}\right)^2$$

$$\Delta P = \text{error on selecting both pixels} = 0$$

$$P = \text{Pixel Distance} = 25$$

In order to find the spatial resolution of each experimental campaign, a picture was taken with the camera where a ruler was placed in the visualization area. As a result, there is an uncertainty related with the pixel location on the screen and the equivalent length in the ruler:

$$\left(\frac{\Delta C}{C}\right)^2 = \left(\frac{\Delta P2}{P2}\right)^2 + \left(\frac{\Delta R}{R}\right)^2$$

Certain cases from the upwards annular flow experimental campaign will be used as examples, where a 0.1mm/pixel was the spatial resolution was calculated:

Assuming that $\Delta P2 = 2$ pixels, $P2 = 1000$ pixels, $\Delta R = 2 \times 10^{-3}$ m and $R = 100 \times 10^{-3}$ m

$$\left(\frac{\Delta D}{D}\right)^2 = 0 + \left(\frac{\Delta C}{C}\right)^2 = 4.04 \times 10^{-4}$$

- Assuming that a wave with a velocity of 6m/s was measured, this led to:

$$T = \frac{25 \times 0.1 \times 10^{-3}}{6} = \frac{1}{2400} \text{ seconds}$$

$$\frac{\Delta V}{6} = \sqrt{\left(\frac{\frac{1}{10,000}}{\frac{1}{2400}}\right)^2 + 4.04 \times 10^{-4}}$$

$\Delta V = 1.45$ m/s , which corresponds to an error of 24.1%, which is quite significant.

- Assuming that a wave with a velocity of 1m/s was measured, this leads to:

$\Delta V = 0.045$ m/s , which corresponds to an error of 4.5%.

Despite the considerable uncertainty that is associated when measuring wave velocities in the order of 6m/s, the uncertainty of this measurement was reduced given that as shown in Section 3.4.1 of Chapter 3, 44 values of average structure velocity for essentially one particular position were obtained. Assuming that $\Delta V = \sigma$, for this particular measurement, the $2s_m$ equates to $\frac{2.9}{\sqrt{43}} = 0.44\text{m/s}$, which reduced the error down to 7.4%.

This approach was applied to all flow combinations investigated in this thesis. The next section reports on the uncertainty associated with the measurement of disturbance wave velocity with the tracking algorithm, where comparison between the performance of both the algorithm and the cross-correlation function will be shown in form of error bars in Figure C.1, for the case of upwards annular flow.

Uncertainty on the velocity of disturbance waves measured with tracking algorithm

To measure the disturbance wave velocity using the tracking algorithm, the gradient between the points where each disturbance wave was first and last observed in the spatiotemporal plots for each regime point was calculated.

The uncertainty associated with this method of measuring the average disturbance velocity is dependent on the success of the applicability of the tracking algorithm, which can be affected by a false positive (i.e. an identified wave that is not actually a disturbance wave) or false negative detections. The performance of the tracking algorithm was attested by visually checking the identified trajectory of each disturbance wave for all the regime points studied and no false positive was identified. As a result, the uncertainty associated with the direct measurement of the average disturbance wave velocity was measured by taking into consideration the standard deviation, σ , on the individual velocities of the identified waves and also on N , the number of readings taken (i.e., the number of waves identified, i.e. wave frequency). From this, $2s_m$ was measured for all cases and is shown in the form of error bars in Figure C.1. Although it can be seen that there is higher uncertainty in the velocity measurements obtained with the cross-correlation (higher error bars in Figure C.1a), the direct

comparison between both methods shows that its performance is successful, as there is a close agreement on the measured disturbance wave velocity (Figure C.1b).

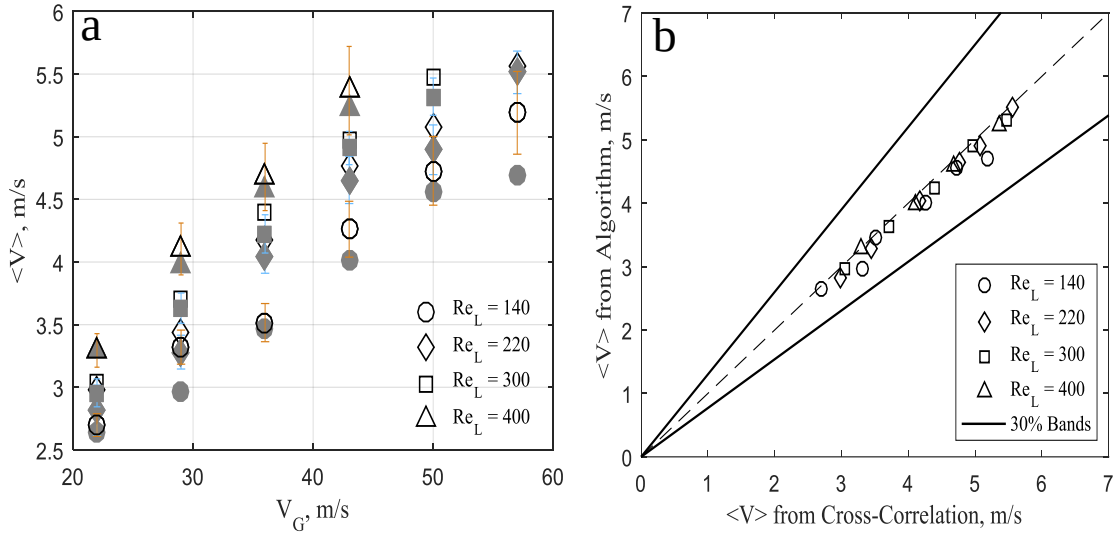


Figure C.1: a) Variation of disturbance wave velocity with gas superficial velocity measured with both the tracking algorithm (hollow symbols) and the cross-correlation function (grey symbols); b) Direct comparison between both methods to measure disturbance wave velocity. In a), for easiness of observation, the error bars associated with the implementation of the tracking algorithm are shown for the cases of $Re_L = 140$ and 400 (orange), whereas the error bars associated with the cross-correlation are shown for the cases of $Re_L = 220$ and 300 (blue).

Uncertainty on the frequency of waves measured with FFT

The uncertainty on the PSD result (profile) due to the application of FFT is reduced from 100% to $1/\sqrt{N} \times 100\%$ due to the averaging achieved from the application of the *pwelch* function on MATLAB (Welch, 1967), where N is the number of samples used in the frequency measurement (number of segments that a time series was broken into).

Although leading to a higher certainty on the PSD profile obtained from the FFT, increasing the number of segments that a time series is broken into (thus reducing the sample size), leads to a higher error on the time step in the frequency measurement. This is given by the following relationship:

$$\text{Error on time step in frequency measurement} = \Delta F = \frac{\text{Sampling frequency}}{\text{Sample size}}$$

As a result, the uncertainty on the PSD profile and the error on the time step of the frequency associated with the stationary Taylor bubble (i.e. waves on falling film) and the annular flow experimental (i.e. inlet wavelet frequency) campaigns are tabulated below:

Table C.1: Error analysis associated with the implementation of Fast Fourier Transformation to measure wave frequency.

Campaign	Number of Samples, N	Sampling Frequency, Hz	Sample Size	PSD Uncertainty, %	Error on Frequency Timestep, Hz
STB	0	2,000	4,000	100	± 0.5
Annular Up	5	10,000	2,000	44.7	± 5
Annular Down	5	10,000	4,000	47.5	± 2.5

Although having a PSD uncertainty of 100%, in the STB campaign, it was chosen to not to divide the time series into samples given the nature of low number of waves present in the film thickness time series. As a result, the focus was to achieve a detailed time step. Additionally, given that the falling film behaviour is much less turbulent (less events) than what is encountered in annular flows, there was confidence that the FFT would easily distinguish the frequency of the waves present in the film from any other periodicity present. The validity of this procedure was achieved by counting the number of waves present in the falling film manually, and given the fact that there was a close match between the instantaneous film thickness time series, and the sinusoidal wave assumption seen in Figure 4.17 in Chapter 4.

Uncertainty on the frequency of disturbance waves measured with the tracking algorithm

As discussed in Section 3.4.2 of Chapter 3, due to the inefficiency associated with the FFT to deal with non-periodic data, such as encountered when disturbance waves are present in the annular flow regime, the tracking algorithm was used to estimate their frequency. This was achieved by dividing the number of waves detected by the algorithm by the time of capture.

The uncertainty of the tracking algorithm relates to the number of disturbance waves that were missed by the algorithm, whose as discussed previously, its performance was manually inspected. Although unlikely, the chance of missing waves was higher in the high gas superficial velocity cases, where the frequency of the disturbance waves was high, and the

flow was much more irregular. More specifically, in some instances, disturbance waves were missed because their local amplitude was below the film thickness threshold set at the first pixel in the x coordinate. Consequently, it was estimated that on average, there was a 5% underestimation on the total waves detected, and this uncertainty is shown in the form of error bars in Figure C.2.

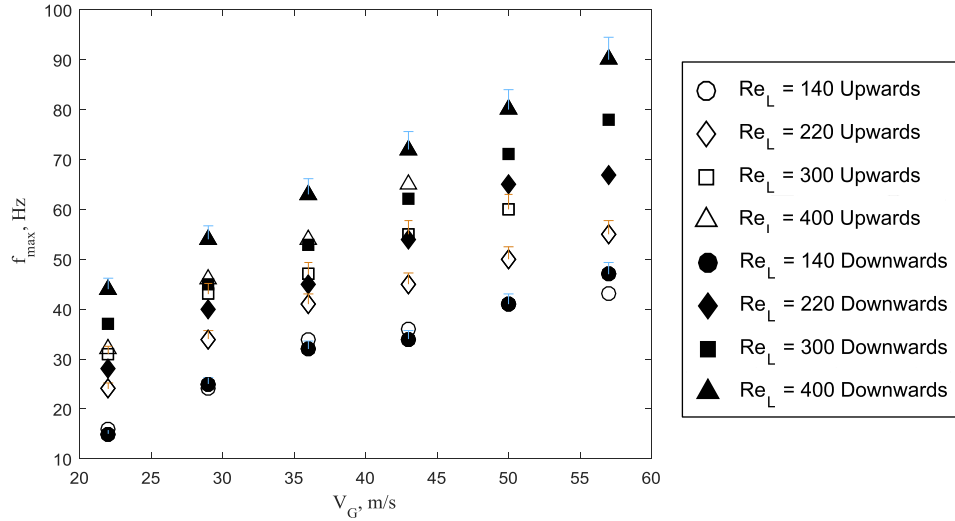


Figure C.2: Frequency of disturbance waves measured with tracking algorithm. For easiness of observation, error bars for the upwards configuration are shown for the cases of $Re_L = 220$ and 300 (orange), whereas for the downwards configuration, they are shown for the cases of $Re_L = 140$ and 400 (blue).

Uncertainty on the time and distance separation of disturbance waves measured with the tracking algorithm

The uncertainty associated with the estimation of average time separation and distance separation of disturbance waves was measured using the standard error of the mean within 95% confidence, $2s_m$. Here, σ , is the standard deviation of the individual separations obtained for each consecutive disturbance wave pair, and $N = f_{max} - 1$. The result of the application of this methodology is shown in Figures C.3a and c) for the upwards annular flow case. Additionally, a comparison between the measured average time and distance separation results and their theoretical values is shown in Figures C.3b and d). More specifically, the latter consists on the time separation estimation using $1/f_{max}$ and on the distance separation estimation using the ratio of $\langle V \rangle / f_{max}$.

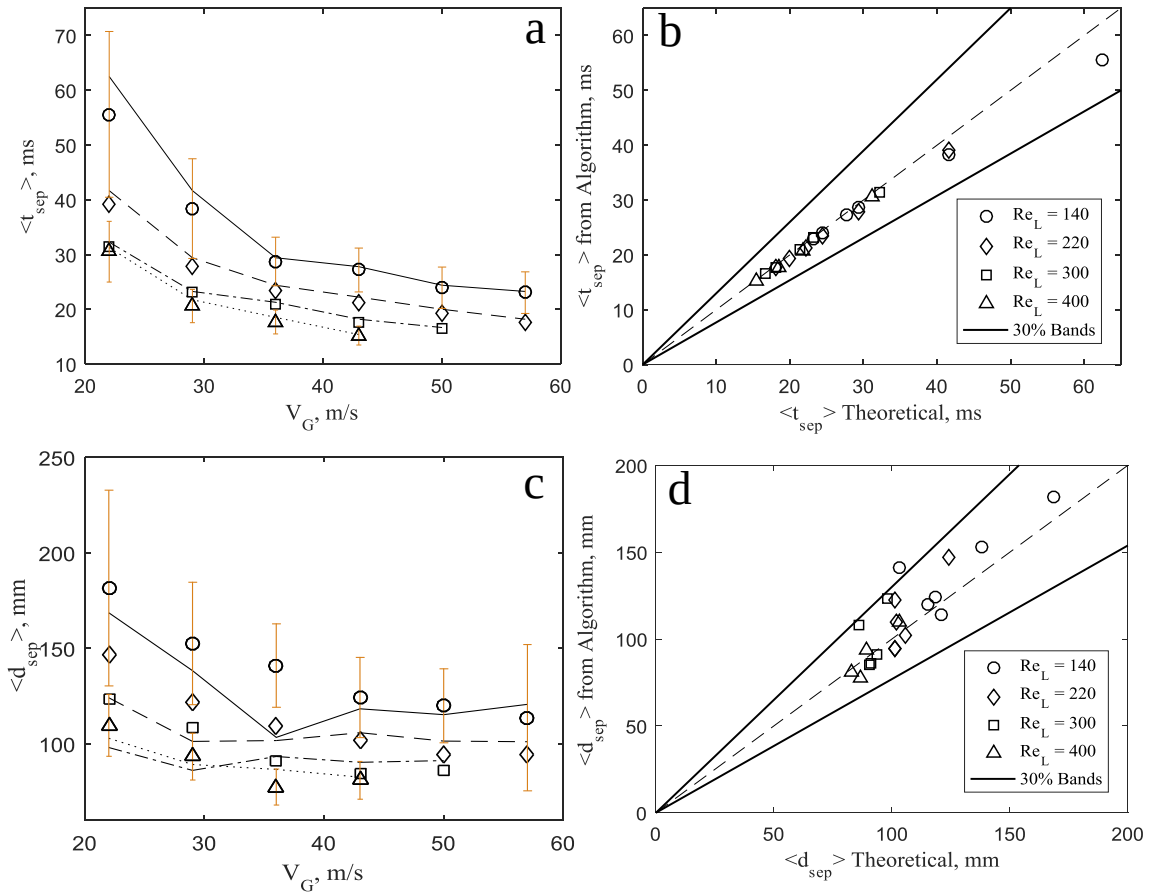


Figure C.3: Time separation (a and b) and distance separation (c and d) measured using the tracking algorithm and theoretical values for upwards flow. Similar trends were observed for the downwards case. For easiness of observation, error bars were only plotted for the cases of $Re_L = 140$ and 400 .

It can be seen that the magnitude of the error bars decreases in general with gas superficial velocity. This can be attributed to the fact that the frequency of disturbance waves is also increasing with this parameter, and consequently the variation of both the time separation and distance separation is reduced. Despite the relatively high uncertainty of the measurement, there is generally a close agreement between both the direct and theoretical methods used to measure these parameters. There are however, 5 instances in the wave spacing parameter where there is a deviation from the agreement. This disagreement can be attributed to the high sensitivity of the theoretical method, which is dependent on two variables (velocity and frequency). As was seen in Section 5.2.3 of Chapter 5, in some instances, the values of both velocity and frequency are slightly deviated from the increasing linear trend expected to be

seen with increasing gas flowrate, which affects the theoretical results. Nonetheless, the general close agreement substantiates the validity of the application of the tracking algorithm.

Uncertainty on the intermittency of disturbance waves measurement

Finally, the uncertainty associated with the method described in Section 3.4.4 of Chapter 3 was quantified by calculating the standard mean error within 95% confidence level, $2s_m$, where, σ , is the mean standard deviation of the intermittency results from all the points in the longitudinal coordinate ($N=1024$ and 303 pixels for the upwards and downward cases, respectively). This is shown in form of error bars in Figure C.4. It can be seen, the uncertainty associated with this method is very small.

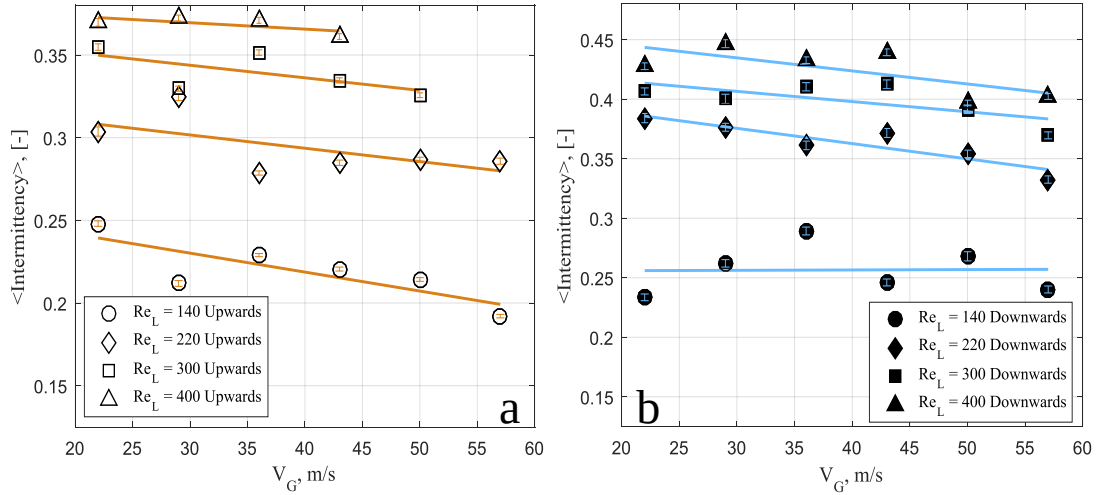


Figure C.4: Disturbance wave intermittency for a) upwards and b) downwards flow.