

Near-wall and interfacial studies of gas-liquid horizontal stratified flows

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Abstract

In multiphase systems, the pressure drop and liquid holdup are two governing parameters which heavily influence the design of downstream facilities and selection of pipeline sizes. In stratified pipe flow, the determination of both these parameters requires an accurate prediction of the wall and interfacial shear stresses.

In this report, a detailed literature review is presented in the research area of near-wall and interfacial studies of gas-liquid stratified pipe flows. Gaps in literature concerning the circumferential distribution of the wall and interfacial shear stresses are uncovered, and the novelty element of future work is delineated in the context of laser-based diagnostic techniques.

Descriptions are provided on the recommissioning of the TOWER flow facility, which now has the provision to perform gas-liquid flow experiments, from what was originally a liquid-liquid only facility. A cooling system has also been incorporated to enable low-temperature two-phase flow experiments

An adiabatic gas-liquid phase flow experiment was carried out using air and water as the test fluids, in an 8.5m long, 50 mm internal diameter ETFE pipe. The water flow rate and air flow rate used ranged from 5-65 L/min and 63- 375 L/min, respectively. Three Differential Pressure transmitter (DP1, DP2, and DP3) were used to evaluate pressure gradient, and a high-speed camera was used to observe the flow structure.

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Declaration of originality

I hereby declare that the work reported in this thesis is my own, and any which is not, has been fully and properly cited.

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Nomenclature

Abbreviations

2-D	Two-dimensional
3-D	Liquid density
CFD	Computational Fluid Dynamics
ERT	Electrical Resistance Tomography
KH	Kelvin Helmholtz waves
LDA	Laser Doppler Anemometry
LA	Large amplitude
PIV	Particle Image Velocimetry
PLIF	Planar Laser-Induced Fluorescence
PTV	Particle Tracking Velocimetry
RANS	Reynolds-Averaged Navier-Stokes equations
rms	Root-Mean-Square
SA	Small amplitude
VOF	Volume of Fluid

Roman symbols

A	Cross-sectional area	m^2
A_G	Cross-sectional area of the gas flow	m^2
A_L	Cross-sectional area of the liquid flow	m^2
D	Pipe diameter	m
D_e	Effective pipe diameter	m
D_G^*	Effective diameter for free surface flow	m
$D_{H,G}$	Mean hydraulic diameter in the gas phase	—
$D_{H,L}$	Mean hydraulic diameter in the liquid phase	—
d_p	Particle diameter	m
Fr	Froude number	—
Fr_L	Liquid Froude number	—
Fr_0	Froude number value at the onset of 2-D waves	—
f	Friction factor	—
f_G	Gas phase friction factor	—
f_i	Interfacial friction factor	—

f_L	Liquid phase friction factor	—
g	Gravitational acceleration	m/s^2
h_L	Liquid phase height	m
h_L^+	Dimensionless liquid film height	—
h_L'	Liquid height fluctuations	m
h_w	Wave height	m
I	Image/pixel intensity	—
I_p	Normal of the incidence point	—
I_w	Wave intermittency	—
k	Interfacial roughness	m
P	Pressure	Pa
R	Pipe radius	m
$R_{H,G}$	Mean hydraulic diameter in the gas phase	—
$R_{H,L}$	Mean hydraulic diameter in the liquid phase	—
Re	Reynolds number	—
Re_G	Gas Reynolds number	—
Re_L	Liquid Reynolds number	—
Re_{SG}	Superficial gas Reynolds number	—
Re_{SL}	Superficial liquid Reynolds number	—
$\mathcal{R}$	Cross-correlation function	—
S_G	Pipe circumference fraction wetted by the gas	m
S_i	Interface length	m
S_L	Pipe circumference fraction wetted by the liquid	m
U	Velocity	m/s
U^*	Friction velocity	m/s
U_G	Gas phase velocity	m/s
U_L	Liquid phase velocity	m/s
U_{Lact}	Actual liquid velocity	m/s
U_i	Interfacial velocity	m/s
U_{SG}	Superficial gas velocity	m/s
$U_{SG,t}$	Gas transitional superficial velocity	m/s
U_{SL}	Superficial liquid velocity	m/s
u'	Velocity fluctuation	m/s
$\mathcal{W}$	Interrogation window size	m
We	Weber number	—

X	Martinelli parameter	—
y	Wall-normal direction from the bottom pipe wall	m

Greek letters

β	The angle of light incidence and refraction	rad
ν_G	Kinematic gas viscosity	m^2/s
ε_G	Gas Void fraction	—
ε_L	Liquid holdup	—
θ_w	Wetted wall fraction	rad
θ_{wo}	Minimum wetted wall fraction	rad
μ_L	Liquid viscosity	$Pa \cdot s$
ρ_G	Gas density	kg/m^3
ρ_{GO}	Gas density at atmospheric pressure.	kg/m^3
ρ_L	Liquid density	kg/m^3
τ_c	Characteristic stress	Pa
τ_i	Interfacial shear stress	Pa
τ_{WG}	Gas-wall shear stress	Pa
τ_{WL}	Liquid-wall shear stress	Pa
τ_{WL0}	Liquid wall shear stress as the pipe bottom	Pa
ν_L	Kinematic liquid viscosity	m^2/s
δ	The average thickness of the liquid film	m
η	Refractive index	—
θ	Angle of inclination	rad
ρ	Density	kg/m^3
σ	Surface tension	kg/s^2
τ	Shear stress	Pa

1 Introduction

1.1 Multiphase Flow

In the field of fluid mechanics, ‘multiphase flow’ is a term used to describe multi-component gas, liquid and solid flow regimes (Johnson, 2016). Of principal focus to this thesis, a specific case of multiphase flow is considered, concerning two-phase gas-liquid flow in horizontal pipes. Over the past 50 years, gas-liquid flows have gained considerable interest and have become the most studied combination of multiphase flows in pipes, perhaps due to its widespread applications in the chemical, mechanical, oil and nuclear industries (Tzotzi and Andritsos, 2013). In contrast to liquid-liquid flows, the large difference in density between the gas and liquid phases tends to create well-defined flow regimes. Characteristically, these flow regimes can be categorized into six major forms, as illustrated in Figure 1.1.

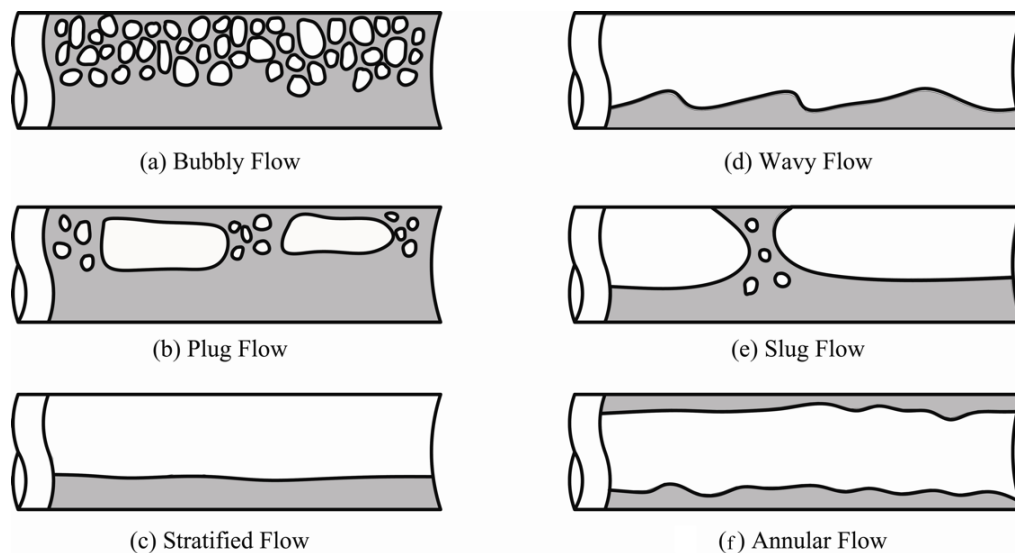


Figure 1.1: Gas-liquid horizontal stratified flow regimes (Thermal Fluids Central, 2010)

- (1) **Bubbly Flow** - In bubbly flow, small gas bubbles are dispersed in a continuous liquid phase, which accumulate at the top of the pipe due to buoyancy effects. A more uniform distribution of bubbles is observed for higher liquid flow rates.
- (2) **Plug Flow** - Relative to bubbly flow, an increase in the gas flow rate results in the formation of bullet-shaped plugs, also dispersed at the top of the flow channel due to buoyancy forces.
- (3) **Stratified Flow** - At low gas and liquid flow rates, gravity causes the stratification of the two phases, resulting on the liquid layer flowing at the bottom of the pipe, whilst

the gas layer flows at the top. This separation between the two phases is characterised by a smooth interface.

- (4) **Wavy Flow** - For a further increase in the gas flowrate, the interfacial shear forces increase, rippling the liquid surface to produce a wavy interface. This flow regime is sometimes referred to as 'stratified-wavy' to better define the distribution of the two phases.
- (5) **Slug Flow** - Eventually, as the gas and liquid flow rates increase, the development of a sufficiently large wave could block the entire cross-section of a pipe, generating a 'liquid slug'. Long bullet-shaped gas bubbles surround these slugs and move along a relatively thin film of liquid. Hence, an intermittent regime develops where elongated bubbles and liquid slugs that alternately surge along the pipe (Omgba-Essama, 2004).
- (6) **Annular Flow** - Further increases in the gas flowrate causes a central core region of gas to flow along the pipe, surrounded by liquid layers on each side. The core may contain a degree of entrained droplets. Visually, the flow regime is similar to the one that can be seen in vertical annular flows; however, in this case, the liquid film at the bottom is thicker than the top due to gravitational effects.

In many previous works, large data sets have been acquired for a wide range of flow conditions to identify each of the above flow patterns. The graphic proposed by Taitel and Dukler (1976) in Figure 1.2, based on a semi-theoretical method using generalized flow parameters, is perhaps the most widely used predictive flow mapping tool for horizontal two-phase flows.

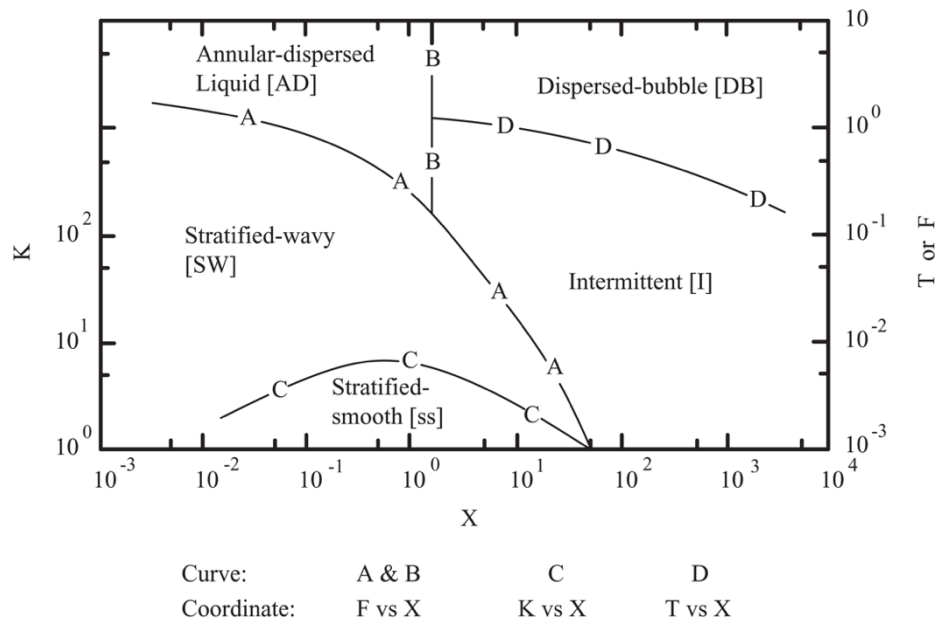


Figure 1.2: Flow regime map for two-phase horizontal flow. Adapted from Taitel and Dukler (1976).

1.2 Stratified flow

In this thesis, the studies of a specific case of multiphase flow are considered, concerning gas-liquid horizontal stratified flow. In industrial pipelines, many multiphase systems carry small quantities of liquid and large quantities of gas. As mentioned above, for horizontal pipes of low gas and liquid velocities, gravity will cause the stratification of these two phases. In which case, a smooth or wavy interface develops, separating the liquid phase flowing at the bottom of the pipe and the gas phase which flows at the top.

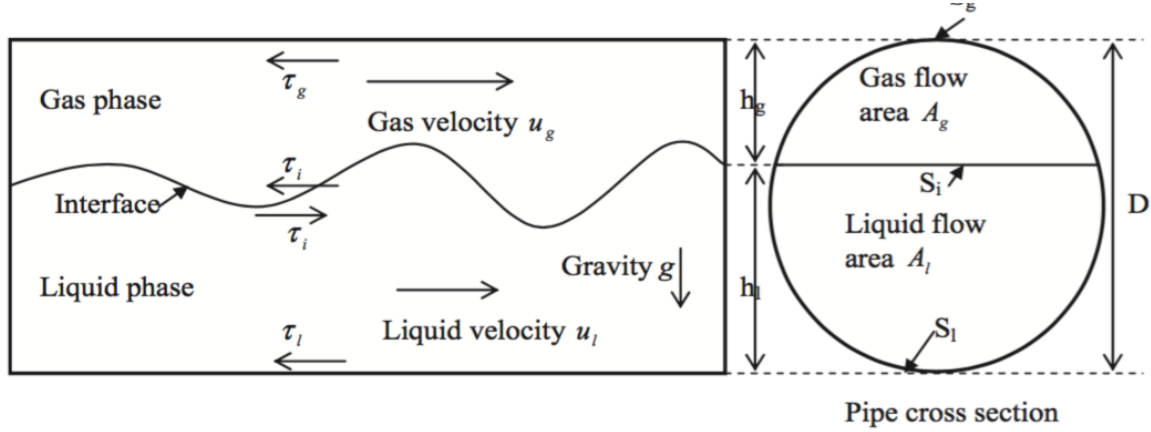


Figure 1.3: Schematic description of the stratified flow regime illustrating the main hydrodynamic features relevant to the current study (Liao et al., 2015).

The stratified flow regime is a rather simple one, especially when considering the minimal interfacial area that exists between the two phases compared to other multiphase regimes, such as slug, bubbly and annular flow (Liao et al., 2015). Despite this apparent simplicity, the flow characteristics, such as the pressure drop, liquid holdup, and interface shape are not easily predictable when the stratified structure becomes unstable at high relative velocities between the two phases, or when fluids of many different properties than air-water are utilised (Tzotzi and Andritsos, 2013).

Stratified flow is regularly encountered during the transportation of hydrocarbons in the petroleum industry, the nuclear industry, and process industries under steady or transient conditions (Ayati et al., 2016). For example, in off-shore gas fields, the raw production is commonly transported in multiphase pipelines before being processed in a dedicated unit. These pipelines are situated at the bottom of the sea and are arranged in horizontal or near-horizontal configurations.

When dealing with flow transitions, a plethora of works consider stratified flow to be starting flow regime (e.g. Taitel and Dukler, 1976a; Lin and Hanratty, 1986); therefore, a better understanding may also help describe and model adjacent flow patterns, such as slug and annular flow. According to Andritsos and Hanratty (1987b), Chen et al. (1997), Fernandino and Ytrehus (2006) and Tzotzi et al. (2011), four distinct subregimes of horizontal gas-liquid stratified flow can be classified:

- (1) A smooth region where the gas-liquid interface is smooth. This occurs at very low gas and liquid velocities.
- (2) A two-dimensional wave region where the gas-liquid interface is covered a small amplitude and short wavelength; both which increase along the length of the pipe. The 2-D waves are periodic, uniform and maintain their identity for several wave periods (Andritsos, 1992).
- (3) A wavy region with large amplitude, irregular waves characterised by a steep front and a gradually sloping back. Within literature, they are sometimes classified as ‘roll waves’ or ‘Kelvin-Helmholtz (K-H) waves’. For higher liquid velocities, these waves may temporarily come into contact with the top of the pipe, forming the appearance of slugs (Viera et al, 2014).
- (4) An atomization region where droplets are torn off from the crest of large-amplitude waves and deposited on the pipe wall. Transition to this region is defined by the first instance droplets are observed at the top of the pipe; thus, its occurrence fundamentally depends on the pipe size. It is worth noting that the behaviour of this subregime closely resembles annular flow in large pipe diameters and high viscosity liquids.

The above categorization of waves is phenomenologically based; however, substantial experimental evidence supports the above description and clearly distinguishes between each classification (e.g. Mandhane et al., 1974; Taitel and Dukler., 1976; Lin and Hanratty, 1987b; Petalas and Aziz, 2000). In the subsequent chapter of this thesis, a full review of gas-liquid horizontal flow maps is provided, showing the flow conditions necessary for the existence of stratified flows and other regimes. These maps usually differentiate between the smooth and wavy stratified subregimes described above.

1.3 Motivation

Central amongst the parameters of interest to the proper design and operation of multiphase pipelines concerns the pressure drop and liquid holdup; both which heavily influence pipeline size selection and the design of downstream facilities (Vieira et al., 2014). In stratified flow, the determination of both these parameters requires an accurate prediction of the wall and interfacial shear stresses (Rosant, 1984; Kowalski, 1987), which the experimental studies of the present project will seek to elucidate.

Considerable efforts have been made by researchers to establish sophisticated Computational Fluid Dynamics (CFD) models to accurately predict the pressure drop and liquid hold up within gas-liquid flow applications (Vestol et al., 2017). Currently, companies rely on industry-standard OLGA or LedaFlow simulation packages, or company in-house codes e.g. Shell’s ‘Shell Flow Correlations (SFC)’ package (Birvalski, 2015). These packages solve conservation equations for mass, momentum, and energy with the inclusion of various closure relations for the wall and interfacial shear stresses.

Over the years, as the understanding of the phenomena influencing the shear stresses improved, the implemented closure relations to become increasingly mechanistic i.e. based on physical principles. However, many still include an empirical aspect, which is tuned against a set of lab or field data. For example, the Shell Flow Correlations package which uses the

interfacial shear stress correlation of Churchill (1977) and the OLGA simulation package which incorporates the recently developed stratified flow model of Biberg (2007), have both been tuned with experimental data. The latter simulation package was implemented in the recently developed Ormen Lange gas field in Norway, wherein the initial absence of empirical tuning for the wall and interfacial shear stress relations, large uncertainties were caused in the predictions of the pressure drop and liquid holdup. Detailed experimental data is therefore essential to accurately assess and inform the validity of these CFD models, as well the primary objective of improving our physical understanding of the phenomena taking place.

1.4 Aims & Objectives

The current thesis aims to provide the necessary fundamentals and groundwork of the chosen research area, such that the commencement of any future work is readily and structurally defined. To facilitate this, achieving the following four objectives is essential:

- Conduct a complete literature review of the research area and clearly delineate the potential novelty of future work.
- Carry out a full recommissioning of the research facility to prepare further experimental work.
- Perform a full risk assessment outlining the special hazards, general hazards and standard operating procedure (SOP) of the experimental facility.
- Generate preliminary experimental results (e.g. flow regime maps, pressure drop measurements, high-speed images) and compare with works from literature.

2 Literature Review

The structure of the literature review presented in this chapter is divided into four of following subsections:

- I. **Flow regime maps:** regimes are central to any detailed two-phase flow analysis and accordingly, their determination using flow mapping techniques are considered first.
- II. **Mechanistic modelling of gas-liquid horizontal flows:** simple steady-models are discussed, and estimations of the wall and interfacial shear stresses are also considered in detail, where some experimental studies are reviewed in this context.
- III. **Experimental work:** Experimental methods applicable to the present work are first discussed, placing an emphasis on spatiotemporal laser-based techniques. All relevant experimental studies then considered in detail, in terms of both the setup employed in the works and the results provided.
- IV. **CFD:** as the last step, numerical studies applicable to the studied multiphase flow combination are reviewed.

Before we proceed, it is worth mentioning that this review is specific for gas-liquid horizontal pipe flows, but not for channel flows. Since the fundamental flow characteristics are dissimilar in each of the respective setups, one must distinguish between them. For example, of key contrast to channel flows, the liquid heights in stratified pipe flows are not constant, causing different wave patterns and pressure drops to be encountered. In addition, different secondary currents occur within pipe flows, generating different wall and interfacial shear stress distributions (Fernandino and Ytrehus, 2006).

2.1 Flow regime maps

Within gas-liquid horizontal studies, numerous flow regime maps have been developed to predict the flow conditions at which each flow regime occurs. Since the present study will seek to initially demarcate the boundaries of the stratified flow regime, it is important to review and provide a perspective of the necessary flow conditions that would cause a transition to other flow patterns. However, many flow maps were developed specifically with air-water data using dimensional quantities e.g. superficial velocities. The applicability of these maps is thus, limited to the original flow conditions considered by the investigator(s). As a result, there have been considerable efforts to generalise flow maps and widen their applications for different fluids and pipes of different sizes.

Table 2.1 summarises an extensive list of the most commonly cited publications that mapped gas-liquid horizontal flows, using one of the three following different generalisation methods:

- (1) Use of correction factors for the fluid properties (e.g. Baker, 1954);
- (2) Use of velocity ratios (e.g. Hoogendorn, 1959);
- (3) Use of dimensionless numbers to account for the forces present in the flow system (e.g. Eaton et al., 1967).

The use of correction factors or velocity ratios has demonstrated to be effective for only a limited range of conditions, with these being based on experimental data (Ibarra, 2017). Since dimensionless numbers describe forces in the flow e.g. inertial, viscous, gravitational and capillary, one would expect flow maps constructed on this basis to apply for a wider range of conditions. However, such generalisations are also limited in value as several transitions are typically presented in flow pattern maps, and the corresponding instabilities are governed by a set of different fluid properties (Brennen, 2005). For example, transitions to dispersed flows may occur at a critical Reynolds number, whilst instabilities at the interface may occur at a critical Weber number We . Hence, the number of dimensionless groups used are somewhat large and complex. Beyond these limitations, several other issues exist. Compared to single-phase flow, the entry length i.e. the length required to initiate fully developed turbulent pipe flow is less well established for multiphase systems. It is likely that many of the reported experimental observations are only relevant for developing flow patterns. Furthermore, an assumption is often made that a particular flow pattern arises for a given fluid with a given flow rate. According to Brennen (2005), this assumption is by no means fully reasonable, since the occurrence of certain flow patterns may depend on the initial conditions, specifically on the way one generates multiphase flow. Hence, there should remain caution on the overall ‘generality’ of flow maps, with there being no current universal flow map to accurately delineate all flow patterns.

Table 2.1: Summary of publications mapping gas-liquid horizontal flows using generalised approaches. Note that some authors (e.g. Taitel and Dukler, 1976) developed their maps analytically; these are in principle ‘universal’ and could be applied to any flow property or pipe configuration.

List of publications	Fluids	Pipe Diameter
Bergelin and Gazely (1949)	Air-water	1 in.
Kosterin (1949)	Air-water	1, 2, 3 and 4 in.
Johnson and Abou-Sabe (1952)	Air-water	0.87 in.
Krasiakova (1952)	Air-water	30 mm
Alves (1953)	Air-water	1.049 in.
Baker (1954)	Air-water	Data from others
	Natural gas-oil	
White and Huntington (1958)	Air-water	1, 1.5 and 2 in.
	Air-oil	
	Natural gas-oil	
Hoogendorm (1959)	Air-water	24-140 mm
	Air-oil	

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Hoogendorm and Beutelaar (1961)	Freon-11 vapour-water	15 mm
Scott (1963)	Air-water	Data from others
	Air-oil	
Knowles (1965)	Natural gas-liquid	2 and 4 in.
Eaton et al. (1967)	Natural gas-water	2 and 4 in.
	Natural Gas-crude oil	
	Natural gas-distillate systems	
Schicht (1969)	Air-water	94 mm
Al-Sheikh et al. (1970)	Gas-liquid	Data from others
Govier and Aziz (1972)	Air-water	Data from others
	Natural gas-oil	
Beggs & Brill (1973)	Air-water	0.0254 and 0.0381 m
Mandhane et al. (1974)	Gas-liquid	UC multiphase pipe flow data
	Data bank	bank
Taitel and Dukler (1976)	Universal	Universal
Simpson et al. (1977)	Air-water	127 mm
Weisman et al. (1979)	Air-water	1.2-5 cm
Spedding and Nguyen (1980)	Air-water	4.55 mm
Spedding and Chen (1981)	Gas-liquid	Data from others
Weisman and Kang (1981)	Air-water	1.2-5.1 cm
Kadambi (1982)	Air-water	2.5-10.1 cm
	Gas-oil	
Petalas and Aziz (2000)	Universal	Universal
Royal Dutch Shell (2007)	Gas-liquid	500 mm
Spedding et al. (2008)	Universal (for $\mu_l < 0.02 \text{ kgm}^{-1} \text{ s}^{-1}$)	Universal

It is worth noting that the studies outlined in Table 2.1 were developed either through an empirical or analytical approach. Empirical flow maps (e.g. Mandhane et al., 1974) plot observations and experimental data with some defined parameter to distinguish between different flow regime transitions. In contrast, the analytical or semi-empirical approach (e.g. Taitel and Dukler, 1976) seeks to formulate a set of equations for each transition curve by hypothesizing the mechanisms that influence the transitions (Pawloski, 2001). One advantage of

the analytical approach is that each transition can be best described using the most appropriate variables which incorporate effects such as flow direction or fluid properties (Yadigaroglu and Hewitt, 2018).

Due to the enormous number of studies related to gas-liquid flow mapping in horizontal pipes, the review herein is not intended to be an exhaustive one, but rather, a summary of the most important aspects of the most commonly cited flow maps. Where appropriate, we shall concentrate on certain maps that be extended to model air-oil flows, as this is the focus of the present study. Some of the more recently developed flow maps are also considered in the review.

Baker (1954)

Historically, one of the earliest attempts to construct a dimensionless flow map originated from Baker (1954), based on a wide range of experimental data for various air-liquid and pipe diameter combinations. Since the flow map is based on industrially relevant data, it still holds great popularity among researchers despite its age (Azzopardi, 2010). It was constructed using data from Jenkins (1947), Gazley (1949), Alves (1953) and Kosterin (1949) and partitioned into seven flow regions: stratified, wavy, slug, plug, dispersed, annular and bubble (or froth) flow. Figure 2.1 illustrates the Baker's original map, whose axis is given by generalised coordinate parameters.

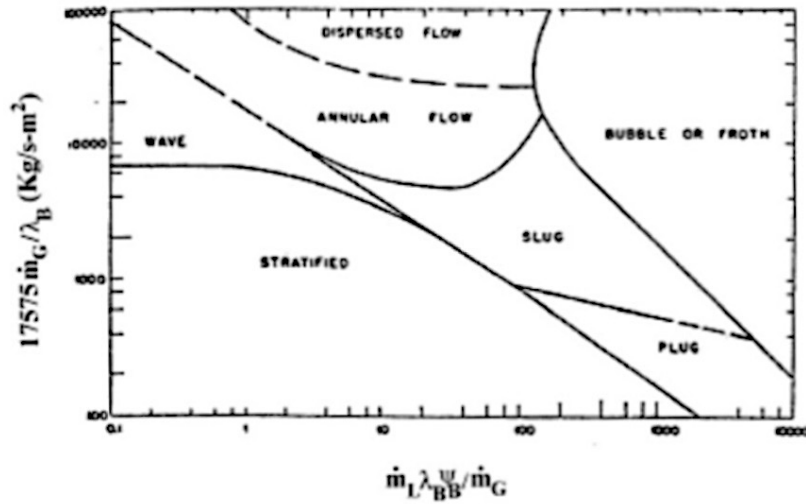


Figure 2.1: Original flow pattern map of Baker (1954) for gas-liquid horizontal flows.

Baker introduced the fluid property correction factors λ_B and φ_B , enabling the transfer of atmospheric air-water data to other systems. The parameters are given by:

$$\lambda_B = \left[\left(\frac{\rho_G}{\rho_A} \right) \left(\frac{\rho_L}{\rho_W} \right) \right]^{\frac{1}{2}} \quad (2.1)$$

and

$$\varphi_B = \frac{\sigma_W}{\sigma} \left[\left(\frac{\mu_L}{\mu_W} \right) \left(\frac{\rho_W}{\rho_L} \right)^2 \right]^{\frac{2}{3}}, \quad (2.2)$$

where σ is the surface tension, ρ is the density and μ is the viscosity. The subscripts A and W are reference values air and water at atmospheric conditions; whilst G and L indicate the chosen gas and liquid values in question.

For a ‘standard’ case of air and water, under atmospheric pressure and room temperature, both parameters are equal to unity. One should note that the horizontal coordinate is dimensionless, but the vertical coordinate has dimensions of mass flux (kg/sm^2). This indicates that the map cannot be completely general as the choice of dimensional y-axis units limits its results to conditions closely matching the original experiment carried out. Indeed, Rouhani and Sohal (1983) demonstrated that Baker’s map does not adequately predict horizontal flow regimes in numerous situations. Despite its apparent limitations, the map has been shown to generally, perform well for air-water and gas-oil mixtures in small diameter ($< 0.05 \text{ m}$) pipes (del Corral, 2014).

Scott (1964)

The original map of Baker (1954) was later modified of by Scott (1964), incorporating the effect of the pipe diameter to improve the agreement with Hoogendoorn (1959). The modified Baker’s map is shown in Figure 2.2. Other modifications of Baker’s original map can be found in Bell et al. (1970), who eliminated and redefined the numerical constants from the axes, and within Whalley (1987), who redrew the map using SI unit axes.

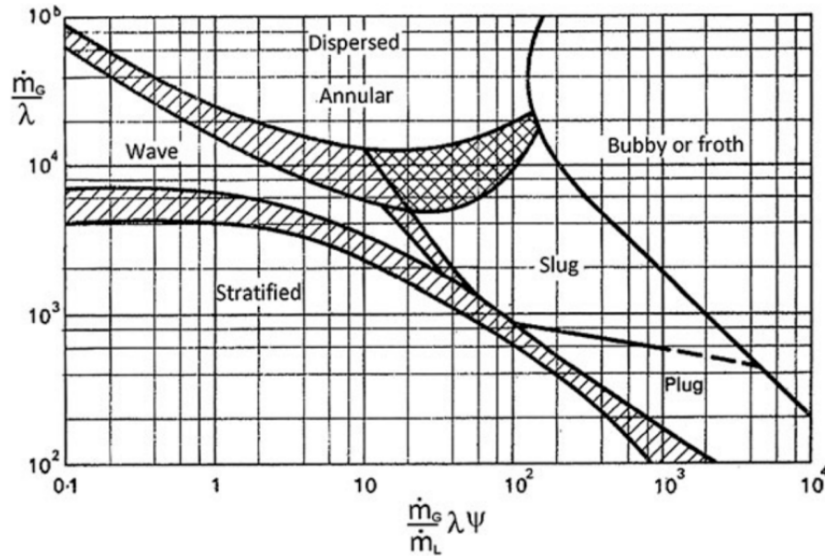


Figure 2.2: The map of Baker (1954) as modified by Scott (1964) who broadened its applications.

Beggs and Brill (1973)

Due to the aforementioned limitations, later studies had attempted to develop alternative flow transition maps. Beggs and Brill (1973) presented a simplified flow map based on only three major flow patterns: separated (stratified, wavy and annular), intermittent (plug and slug) and distributed (bubble), as depicted in Figure 2.3.

The flow regime transition was obtained using air-water data collected at pressures between 2.4 and 6.5 bar, in 0.0254 m and 0.0381 m pipelines. In this case, the map is fully dimensionless, presented in terms of the Froude number, Fr against the liquid content, λ_L , given by:

$$Fr = \frac{(U_{SL} + U_{SG})^2}{gD} \quad (2.3)$$

and

$$\lambda_L = \frac{U_{SL}}{U_{SL} + U_{SG}}, \quad (2.4)$$

where U_{SL} and U_{SG} is the superficial liquid and gas velocity, respectively, g is the acceleration due to gravity and D is the tube diameter.

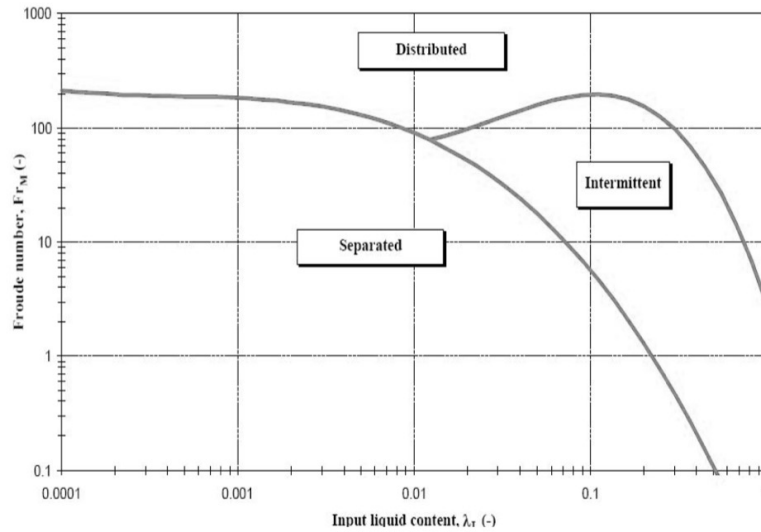


Figure 2.3: The Beggs and Brill (1973) flow pattern map for gas-liquid horizontal flows.

Although the map is dimensionless, the transition lines are ‘best fits’ and only truly applicable to systems that are similar to those originally obtained. In particular, the map fails to account for the variation of important physical properties such as the density, viscosity or interfacial tension (Emamzadeh, 2012).

Mandhane et al. (1974)

Mandhane et al. (1974) acknowledged the vast contradictions between different flow pattern maps that were present. Consequently, the researchers attempted to re-evaluate various flow pattern maps using a substantial amount of data from the University of Calgary Multiphase Pipe Flow Data Bank, using a near 14000 experimental data points that spanned from the years 1962 to 1973. Using all the research results, their own map was defined in terms of the superficial gas velocity (U_{SG}) versus superficial liquid velocity (U_{SL}) based on air-water data, and divided into six regimes: stratified, wavy, elongated bubble, slug, dispersed and annular (Figure 2.4).

In their experiments, extensive pipe diameters (12.7 – 165.1 mm), liquid phase densities (704.81 – 1009.16 kg/m³), gas phase densities (0.8 – 50.46 kg/m³), liquid phase viscosities (3×10^{-4} – 0.09 Pa.s), gas phase viscosities (10^{-5} – 2.2×10^{-5} Pa.s), surface tensions (0.024 – 0.103 N/m), superficial liquid velocities (9×10^{-4} – 7.32 m/s) and superficial gas velocities (0.043 – 170.69 m/s) were examined. To account for the effect of physical properties on the transition boundaries, two correction factors were proposed with the addition of viscosity terms, based on the earlier work by Govier and Aziz (1973).

Although the map was formulated based purely on a correlational approach, the expansive database used in their experiments should, over a wider range of conditions, provide a more reliable prediction of flow patterns compared to that of Beggs and Brill (1973). However, Lin and Hanratty (1987b) indicated that the map failed to correlate the transition from slug to annular flow in large diameter pipes. This is reinforced by del Corral (2014), who notes that the map is most suited in pipe diameters less than 5 cm and, of course, over the prescribed range of other parameters used.

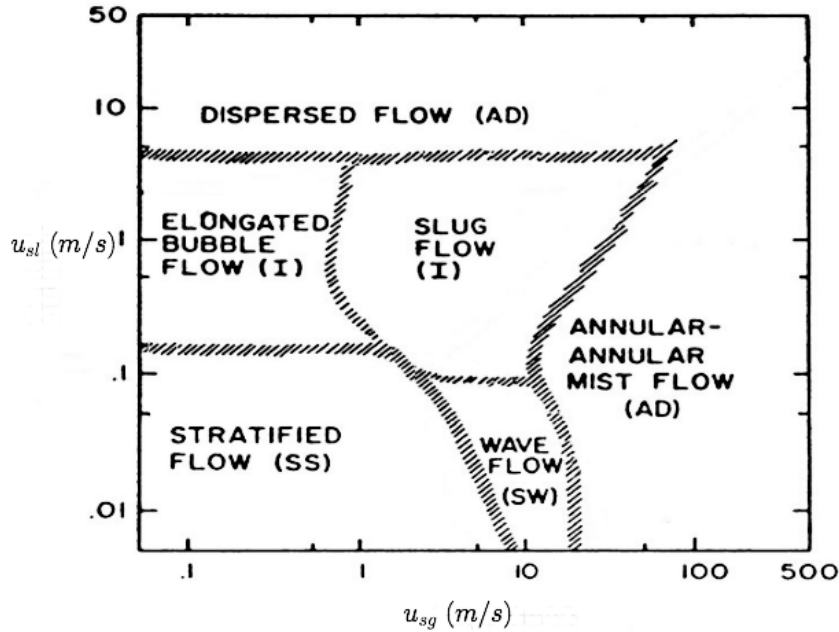


Figure 2.4: Flow pattern map of Mandhane et al. (1974).

Taitel and Dukler (1976)

To date, Taitel and Dukler (1976) developed the most widely used and recommended flow regime map for gas-liquid horizontal flows. Taitel and Dukler's map was analytically based and each transitional boundary was represented by two parameters defining the transition mechanism. Computationally, it requires more effort as it requires the calculation of four dimensionless numbers. Systematically, it was based on a one-dimensional steady-state separated flow model, where momentum balances were derived for both phases, and then combined by eliminating the pressure gradient terms from both expressions. The combined momentum balance equation was then converted to its dimensionless form by assuming a smooth gas-liquid interface of constant height and that the interfacial shear stress term is equal to the wall shear stress. The authors graphically superimposed their model to the experimental data of Mandhane et al. (1974), displaying a great level of accordance (Figure 2.5).

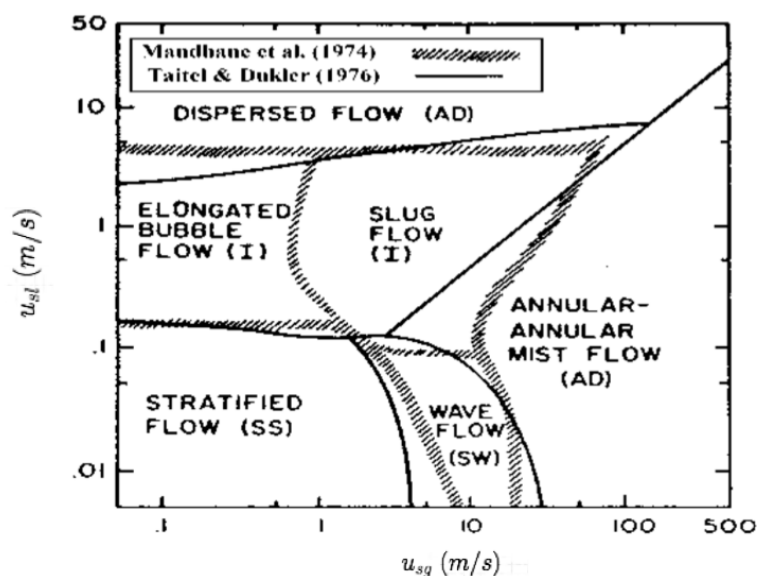


Figure 2.5: Flow map of Taitel and Dukler (1976) superimposed over the flow map of Mandhane et al. (1974). Note that transition boundaries are specific for air-water flows in a 2.5 cm ID pipe.

Since Taitel and Dukler's map is analytically based, it should not, in principle, carry the restrictions of the experimental ones. Nonetheless, caution should remain on the underlying theoretical assumptions stipulated by the authors e.g. it being developed for Newtonian gas-liquid mixtures, assuming a negligible hydraulic liquid gradient at transition conditions and using the criteria of Gazley (1949) for smooth stratified flow. These assumptions may affect the level of accordance between other experiments. In addition, the effects of pipe roughness and interfacial shear were not accounted for.

A comparison study between the flow maps of Mandhane et al. (1974) and Taitel and Dukler (1976) has also been performed by Pawloski et al. (2004), who utilised their experimental

data to evaluate the overall usefulness of both maps. The methodology used to assess the accuracy of each map was adapted from a criterion suggested by Mandhane et al. (1974): the number of correctly predicted points in an individual flow regime map divided by the total number of observed points in the flow regime considered (in percentage form). Through this approach, the total number of correctly predicted points and the average accuracy of each map was easily determined. Overall, the Taitel and Dukler map was shown to be superior with an average overall accuracy of 53.3%, compared to Mandhane et al. (1974) with 50.4%. However, this comparison was based on the transition boundaries for air-water properties. Through the application of appropriate correction factors, Pawloski et al. (2004) recognised that both flow maps may be converted for the air-oil case. With this conversion, the corrected map of Taitel and Dukler (1976) decreased in prediction accuracy (dropping to 45%), while Mandhane et al. (1974) increased significantly (to 74.6%). Hence, the authors concluded that the Taitel and Dukler (1976) map serves as the best predictive flow regime map without any correction factors applied, and the corrected Mandhane et. al. (1974) map as the best overall map.

Weisman et al. (1976)

Weisman et al. (1979) performed a systematic series of experiments to study the effects of fluid properties and pipe diameter on air-water horizontal flow pattern transitions, in 1.2, 2.5 and 5.1 cm diameter pipes. The authors identified stratified smooth, stratified wavy, intermittent annular and dispersed flow regimes; where the intermittent region includes both plug and slug flow, and the dispersed region combines both bubble and mist flow. Their results were presented in a generalised plot of U_{SL}/ϕ_2 against U_{SG}/ϕ_1 (Figure 2.6), where ϕ_1 and ϕ_2 are physical property correction factors, such that $\phi_1 = \phi_2 = 1$ for air-water systems at atmospheric pressure.

The transition line correlations of Weisman et al. (1979) were compared by Spedding and Spence (1993), using data collected for 45.5 mm and 93.5 mm diameter pipes. Apart from the stratified to wavy transition, the authors found the transition line correlations to be poorly compatible with their experimental data. However, in several cases, Spedding and Spence (1993) seemingly used the wrong coefficients and constants in the correlations proposed by Weisman et al. (1979). It is unclear if these are inadvertent errors in the typing of equations, or introduced upon how they originally based their analysis of the transition equations (Limayem Lamari, 2001).

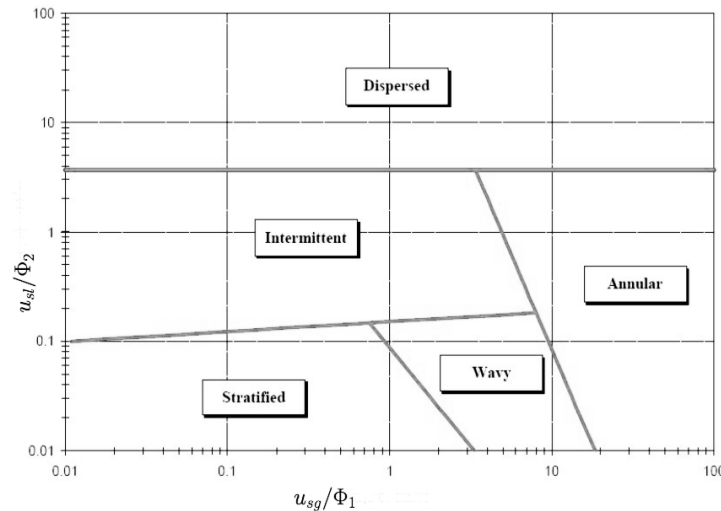


Figure 2.6: The Weisman et al. (1979) flow pattern map.

Spedding and Nguyen (1980)

The Spedding and Nguyen (1980) flow regime map was developed with dimensionless plotting parameters, using air and water two-phase flow results in a 4.55 mm diameter pipe to obtain the transition boundaries.

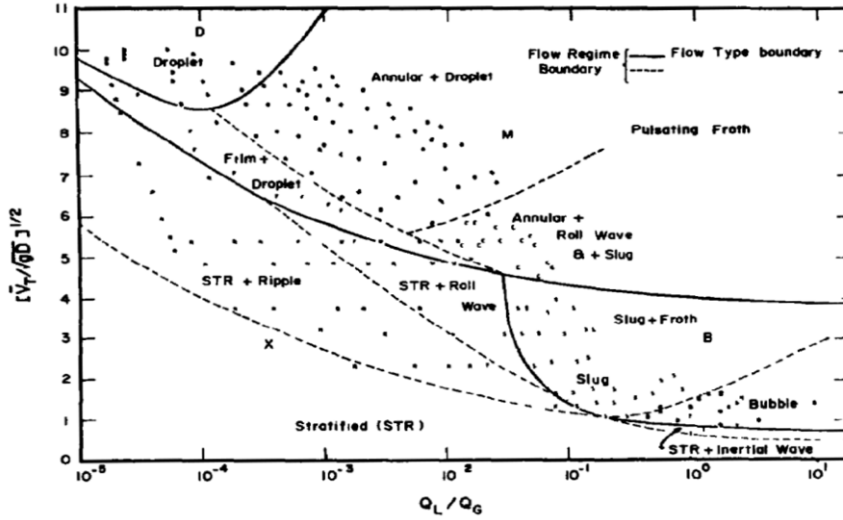


Figure 2.7: The Spedding and Nguyen (1980) flow regime map.

In this map, the square root form of the Froude number was plotted against the logarithmic form of the volumetric flow rate ratio (Figure 2.7). Unlike other flow maps, the blow through slug and wavy to slug flow transitions are, in fact, represented as flow regions. Later studies showed that the map predicts the transitions effectively for all stratified and intermittent patterns, but fails to account for diameter effects at high gas flow rates (Lin and Hanratty, 1987b; Spedding and Spence, 1993).

Royal Dutch Shell (2007)

Royal Dutch Shell (2007) developed a gas-liquid horizontal flow map (DEP 31.22.05.11) for the transport of combustibles using a 500 mm pipe with the following flow properties: gas density = 8 kg/m³; liquid density = 860 kg/m³; gas viscosity = 1.2 × 10⁻⁵ Pa.s; liquid viscosity = 1.6 × 10⁻⁴ Pa.s; surface tension = 0.03 N/m. Whilst they do not define any pressure ranges, their manual suggests pressures below 90 bar were used in the development of the map. As shown in Figure 2.8, the flow map was generalised using both the gas and liquid form of the Froude number, given by equations (2.5) and (2.6), respectively.

$$Fr_G = U_{SG} \sqrt{\frac{p_G}{(p_L - p_G)gD}} \quad (2.5)$$

$$Fr_L = U_{SL} \sqrt{\frac{p_L}{(p_L - p_G)gD}} \quad (2.6)$$

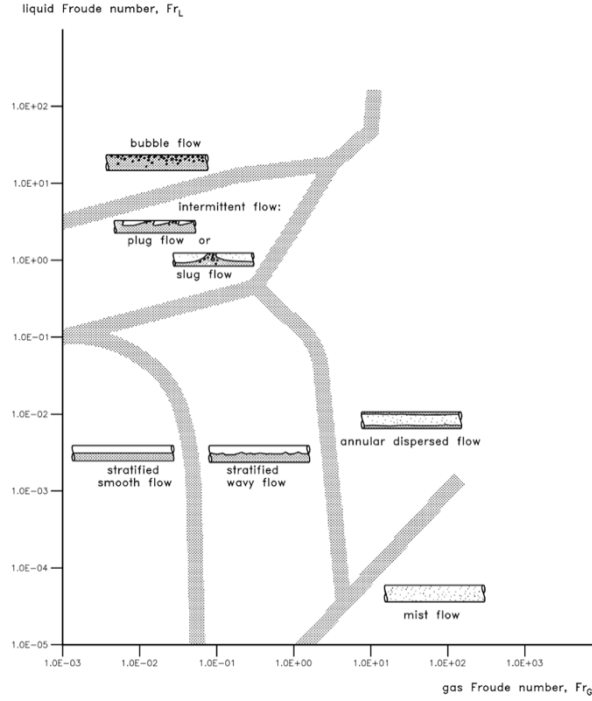


Figure 2.8: Gas-liquid horizontal flow map developed by Royal Dutch Shell (2007).

The transition between different regimes is relatively gradual and the boundaries do not represent sharp changes in the flow pattern. Strictly, the map is only suitable for very long pipes with fully developed two-phase flow. However, a feed pipe longer than 10 pipe diameters will still provide a somewhat accurate prediction of the flow pattern for a particular set of conditions.

Spedding et al. (2008)

Spedding et al. (2003) developed a universal flow regime map for two-phase co-current pipe flow (Figure 2.9) for the condition that the liquid viscosity, $\mu_L < 0.02 \text{ kgm}^{-1}\text{s}^{-1}$. The map was constructed using two dimensionless plotting parameters (defined by ψ and Ω); both of which encapsulate several dimensionless groups that describe, namely, the ratio of the inertial to surface tension forces, inertial to viscous forces and inertial to gravitational forces.

The flow map successfully tested against a wide variety of data for various geometrical, phase properties and operating conditions. Six models were proposed for the transitions involving: (1) smooth stratified to stratified ripple and inertial wave; (2) stratified ripple to roll wave; (3) stratified roll wave to film plus droplet; (4) film plus droplet to annular flows; (5) blow through slug to slug and (6) slug to bubble flow. The proposed transitional boundaries agreed with five other reliable models from the works of Ishii and Grolmes (1975), Wesiman et al. (1979), Spedding and Nguyen (1980), Kowalski et al. (1987) and Kokal and Stanislav (1989).

The authors also claimed that the map could successfully handle the demarcation between ripple and roll wave stratified flow.

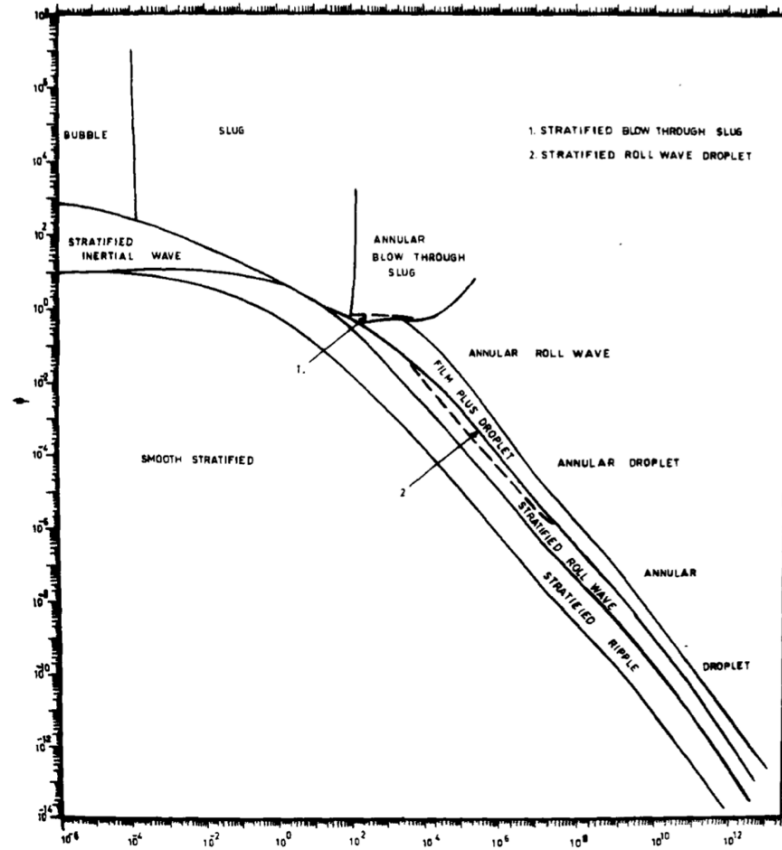


Figure 2.9: The Spedding et al. (2003) flow regime map.

2.1.1 Summary

In summary, there remain many challenges associated with the fundamental understanding of multiphase flow patterns. Despite the plethora of works, a considerable amount of discrepancies was evident when comparing different flow pattern maps. Limayem Lamari (2001) indicates that these discrepancies can be attributed to one or more of the following reasons:

- (1) Use of different two-phase systems e.g. air-water vs. air-oil;
- (2) Use of different test apparatus and instrumentation;
- (3) Use of different terminologies to classify flow regime patterns;
- (4) Incorrect drawing of flow regime boundaries;
- (5) Selection of unsuitable mapping parameters (inapplicable to all flow regime transitions).

Again, it should be noted that in general, only the most commonly cited flow regime maps were discussed and compared in the present section of the review. Many more gas-liquid horizontal flow regime maps may be found in recent pieces of literature, particularly for applications involving heat and mass transfer (e.g. Grauso et al. 2013).

2.2 Mechanistic modelling of gas-liquid horizontal flows

2.2.1 Key design parameters

The mechanical work being done in forcing fluids through a multiphase pipeline causes significant losses in pressure to occur across the length of the pipe. This pressure loss is referred to as the pressure gradient $\frac{dp}{dz}$ and is the sum of three terms:

$$\left(\frac{dp}{dz}\right)_{2-ph} = \left(\frac{dp}{dz}\right)_F + \left(\frac{dp}{dz}\right)_G + \left(\frac{dp}{dz}\right)_M, \quad (2.7)$$

where the subscripts F , G and M refer to the frictional, gravitational and momentum components, respectively.

For horizontal flows, where gravity acts in the direction normal to the flow, we neglect the gravitational component. In addition, for adiabatic flows, many researchers term (e.g. Nicholson et. al., 1978; Whalley, 1987) have shown the momentum term to be negligible in comparison to the frictional. Under these assumptions, equation (2.7) reduces simply to:

$$\left(\frac{dp}{dz}\right)_{2-ph} = \left(\frac{dp}{dz}\right)_F. \quad (2.8)$$

The determination of the pumping and power requirements in industrial subsea pipelines is heavily reliant on the accurate estimation of the pressure gradient and is thus, one of the principal aims of modelling two-phase flows. The second aim of modelling multiphase flows is to determine the liquid holdup ε_L , defined as the fraction of the pipe occupied by the liquid phase

$$\varepsilon_L = \frac{\varepsilon_L}{\varepsilon_L + \varepsilon_G}, \quad (2.9)$$

where ε_G is the gas void fraction.

The wavy surface of the liquid contributes to the interfacial friction factor, which is directly related to the frictional pressure gradient. Therefore, the amount of liquid present as a fraction of the pipe cross-section is also an important quantity to determine.

Aside from the existing empirical correlations, the pressure gradient and the liquid holdup in stratified flows can be obtained by solving one-dimensional momentum balance equations for each phase (known as the two-fluid model), which will be discussed in section 2.2.2. However, as we will highlight, these models rely crucially on having accurate closure relations for the wall shear stress and interfacial shear stress; in the absence of which, it can generate significantly worse predictions than those of empirical correlations.

2.2.2 One-dimensional steady state models

From the available literature, nearly all stratified flow models are one-dimensional, where flow property changes are considered in the axial direction only. Often considered the panacea, the

most widely used for steady state stratified flow is the two-fluid model, introduced by Agrawal et al. (1973) and later developed by Taitel and Dukler (1976) to evaluate flow regime transitions in steady state gas-liquid flows. The approach is to start with a simplified one-dimensional momentum balance for each phase, where one assumes the interface to be flat or invariant in its shape. Other mechanistic models can be found that do not impose this assumption and consider the exact (curved) shape of the interface (see Hart et al., 1989; Grolman and Fortuin, 1996; Chen et al., 1997; Vlachos et al., 1999).

In two-phase gas-liquid smooth stratified flows, with reference to Figure 2.10, the integral forms of the momentum equations for the two phases can be written as:

$$-A_L \left(\frac{dp}{dz} \right)_L - \tau_{WL} S_L + \tau_i S_i - \rho_L A_L g \sin \theta = 0; \quad (2.10)$$

$$-A_G \left(\frac{dp}{dz} \right)_G - \tau_{WG} S_G - \tau_i S_i - \rho_G A_G g \sin \theta = 0, \quad (2.11)$$

where A_G and A_L the cross-sectional areas occupied by the gas and liquid phases respectively, S_G and S_L are the circumferences of the pipe in contact with the respective phases, S_i is the length of the gas-liquid interface; θ is the angle of inclination, τ_{WG} , τ_{WL} and τ_i are the gas-wall, liquid-wall and interfacial shear stresses respectively. Note that the sign of τ_i reflects that the gas moves faster relative to the liquid.

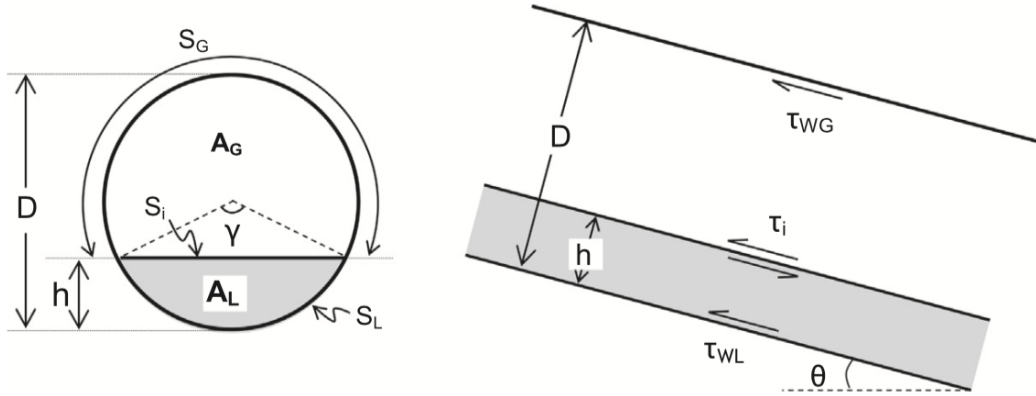


Figure 2.10: Geometrical parameters of gas-liquid smooth stratified flow in a near-horizontal pipe (Tzotzi and Andritsos, 2013).

The geometrical parameters were calculated based only on the variables of the liquid height h_L and the pipe radius R (Agrawal et al., 1973):

$$A_L = R^2 \left[\pi - \cos^{-1} \left(\frac{h_L}{R} - 1 \right) + \left(\frac{h_L}{R} - 1 \right) \sqrt{1 - \left(\frac{h_L}{R} - 1 \right)^2} \right] \quad (2.12)$$

$$A_G = R^2 \left[\cos^{-1} \left(\frac{h_L}{R} - 1 \right) + \left(\frac{h_L}{R} - 1 \right) \sqrt{1 - \left(\frac{h_L}{R} - 1 \right)^2} \right] \quad (2.13)$$

$$S_L = 2R \left[\pi - \cos^{-1} \left(\frac{h_L}{R} - 1 \right) \right] \quad (2.14)$$

$$S_G = 2R \cos^{-1} \left(\frac{h_L}{R} - 1 \right) \quad (2.15)$$

$$S_i = 2R \sqrt{1 - \left(\frac{h_L}{R} - 1 \right)^2} \quad (2.16)$$

Assuming fully developed pipe flow, the axial pressure gradients for the two phases must be equal, thus eliminating them from equations (2.10) and (2.11) now yields:

$$\frac{\tau_{WG} S_G}{A_G} - \frac{\tau_{WL} S_L}{A_L} + \tau_i S_i \left(\frac{1}{A_L} + \frac{1}{A_G} \right) - (\rho_L - \rho_G) g \sin \theta = 0. \quad (2.17)$$

Taitel and Dukler (1976b) represented the various stresses as functions of the phase velocities and densities as follows:

$$\tau_{WG} = f_G \frac{\rho_G U_G^2}{2}; \quad (2.18)$$

$$\tau_{WL} = f_L \frac{\rho_L U_L^2}{2}; \quad (2.19)$$

$$\tau_i = f_i \frac{\rho_L (U_G - U_L)^2}{2}, \quad (2.20)$$

where U_G is the gas velocity, U_L is the liquid velocity, and f_G , f_L and f_i refer to friction factors for the gas, liquid and interface, respectively.

Although, in practice, the generation of waves near the interface causes f_i to be significantly higher than f_G ; their assumption of smooth stratified flow grants that $f_G = f_i$. The authors also assume that $U_G \gg U_L$ and thus, it implies that $\tau_{WG} = \tau_i$. The gas and liquid friction factors may be evaluated from the standard Blasius relationship:

$$f_G = C_G Re_G^{-m} = f_i; \quad (2.21)$$

$$f_L = C_L Re_L^{-n}, \quad (2.22)$$

where the coefficients used depend on the phase Reynolds number:

$$C_G = C_L = 0.046 \text{ and } m = n = 0.2 \text{ for turbulent flow } (Re_L > 2000 \text{ and } Re_G > 2000); \quad (2.23)$$

$$C_G = C_L = 16 \text{ and } m = n = 1.0 \text{ for laminar flow.} \quad (2.24)$$

The Reynolds numbers are written as

$$Re_G = \frac{D_G U_G}{v_G}; \quad (2.25)$$

$$Re_L = \frac{D_L U_L}{v_L}, \quad (2.26)$$

where v_G and v_L are the kinematic viscosities of the gas and liquid phases, respectively, and the hydraulic diameters D_G and D_L were defined through suggestions of Agrawal et al. (1973):

$$D_{H,G} = \frac{4A_L}{S_L}; \quad (2.27)$$

$$D_{H,L} = \frac{4A_G}{S_G + S_i}. \quad (2.28)$$

Whilst analytical solutions are possible in cases of smooth stratified flow (where the interface is flat), these solutions are of limited practical benefit as the interfacial structures are invariably wavy. For such cases, the specified Blasius relations, particularly for the liquid-wall and interfacial interactions, become inapplicable. Indeed, several studies have served to highlight this, where considerable discrepancies have occurred between the experimental results obtained and the predictions given by Blasius relations. In response, many of these studies have aimed at improving the modelling of friction in stratified gas-liquid flows, implying that the two-fluid model retains a strong element of empiricism. These studies are reviewed in detail in the following section.

2.2.3 Wall and interfacial shear stress in stratified flow

Having discussed the two-fluid model, we will now turn our attention by reviewing the closure relations necessary for the solution of the problem, involving shear stress calculations for the fluid-wall and gas-liquid interface. These closure laws are usually formed through the prediction of dimensionless friction factor parameters, which depend only on the relative roughness of the pipe surface and the flow Reynolds number (Ng, 2002). For the sake of clarity, we will first review works concerned with the wall friction factors (both the gas-wall and liquid-wall). The bulk of the studies, concerning the interfacial friction factor, are subsequently reviewed in detail. Where appropriate, important physical results obtained regarding the shear stress distributions are also discussed.

2.2.3.1 Liquid-wall friction factor

As previously noted, the Blasius relation for the liquid-wall friction factor adopted by Taitel and Dukler (1976) is not appropriate for stratified wavy flow patterns. Kowalski (1987) performed direct measurements of the liquid wall shear stress and found that equation (2.22) underestimates the liquid wall friction factor by up to 100%. Indirect measurements performed by Andreussi and Persen (1987), Andritsos and Hanratty (1987a) and Spedding and Hand (1997) have revealed similar trends. To improve prediction accuracies, new empirical correlations for the liquid-wall friction factor have been proposed by numerous investigators, a number of which are reviewed herein.

Andritsos and Hanratty (1987) conducted stratified gas-liquid flow experiments in horizontal 2.52 and 9.53 cm internal diameter pipelines. The authors proposed a relatively complex relationship for the liquid wall shear stress, measuring the liquid-wall friction indirectly through:

$$\tau_{WL} = \frac{3(\tau_c - \tau_i)}{2 \left(1 - \frac{h_L}{D}\right)}, \quad (2.29)$$

where the characteristic stress τ_c ,

$$\tau_c = \rho_L \left(\frac{h_L^+ \mu_L}{h_L \rho_L} \right)^2, \quad (2.30)$$

is given in terms of the dimensionless liquid film height h_L^+ :

$$h_L^+ = \left\{ (1.082 Re_L^{0.5})^5 + \left[\frac{0.098 Re_L^{0.85}}{\left(1 - \frac{h_L}{D}\right)^{0.5}} \right]^5 \right\}^{0.2}. \quad (2.31)$$

Kowalski (1987) presented values for the liquid wall shear stress through a hot film anemometry experimental technique performed in a 50.8mm internal diameter horizontal pipe, using air-water and Freon 12-water as the test fluids. The experimental data for the liquid-wall friction factor was compared with the original Blasius correlation used by Agrawal et al. (1973):

$$f_L = 0.079 (Re_{SL})^{-0.25}, \quad (2.32)$$

where Re_{SL} is the Reynolds number based on the superficial velocity.

Poor correspondence was observed between the experimental results of Kowalski (1987) and equation (2.32). The discrepancy obtained was a reason to the fact that equation (2.32) was originally derived by assuming single-phase flow. To obtain a better fit to the data, Kowalski (1987) related the liquid wall friction factor to the product of Re_{SL} and the liquid holdup ε_L , which varies with the interfacial shear stress and the gas velocity. This was defined by equation (2.33):

$$f_L = 0.263(\varepsilon_L Re_{SL})^{-0.5}. \quad (2.33)$$

Hand (1991) developed a similar correlation to that of Kowalski (1987), in terms of the liquid holdup and the superficial liquid Reynolds number. However, different coefficients were used for both laminar and turbulent flows, based on experiments performed in a 93.5 mm internal diameter pipe using air-water, air-water with surfactants and air-glycerine data.

$$f_L = 24Re_{SL}^{-1} \text{ for laminar flow,} \quad (2.34)$$

$$f_L = 0.0262(\varepsilon_L Re_{SL})^{-0.139} \text{ for turbulent flow.} \quad (2.35)$$

In the experimental work of Srichai (1994), where the liquid holdup and pressure gradient was determined for stratified flow, the author proposed a correlation for the liquid wall friction factor of a similar form to the above equation (2.35),

$$f_L = 0.765(\varepsilon_L Re_{SL})^{-0.562}; \quad (2.36)$$

for a highly pressurised 78mm internal diameter pipeline system. Data was collected based on air-water and air-oil as the test fluids, using liquid Reynolds numbers in the range of laminar-turbulent (transitional) and fully turbulent regimes. Since the oil had a viscosity of approximately 50 times greater than that of water, the oil Reynolds number was much smaller, generating a much larger oil liquid-wall friction factor. Fundamentally, this suggests that higher liquid-wall shear stresses are encountered in industrial pipelines using oils.

Rosant (1994) experimentally investigated stratified gas-liquid flow in a horizontal and slightly inclined 82mm internal diameter circular pipe. An electrochemical method using single microelectrodes was used to determine the liquid-wall shear stress at different circumferential locations. A rather complex implicit relationship for the liquid-wall friction factor was proposed, designed to take into account the effect of the interfacial shear stress:

$$\sqrt{\frac{2}{f_L}} = 2.46 \log \left(\varepsilon_L \frac{\pi D}{S_L} Re_L \sqrt{\frac{f_L}{2}} \right) - \left(2.5 + 6.2 \frac{\tau_i S_i - \tau_L S_L}{\tau_L S_L} \right). \quad (2.37)$$

Paras et al. (1994) measured the liquid-wall shear stress in a 50.8 mm internal diameter horizontal pipe using a conductance probe technique. Air and water were used as the test fluids at near-atmospheric conditions, with superficial liquid and gas velocities between 2-12 cm/s and 10-30 m/s, respectively. Average values of the liquid-wall shear stress were obtained from their reported data and the corresponding friction factor was computed. The liquid-friction factor was then plotted against the Reynolds number and the following correlation was fitted:

$$f_L = 2.86 Re_L^{-2/3}, \quad (2.38)$$

where Re_L was based on the real mean liquid velocity and the mean liquid thickness at the pipe bottom. Noteworthy is the similarity between equation (2.38) and that proposed by Kowalski (1987), given by equation (2.33). The authors concluded that the time-averaged liquid-wall shear stress tends to decrease in the lateral direction i.e. away from the pipe bottom, which was associated with a decreasing liquid film thickness. Although interfacial waves had a clear influence on the stress at the wall, the authors noted that a certain class of dominant interfacial waves may not influence the stress if the liquid layer was thick enough in that location.

Spedding and Hand (1997) developed an iterative procedure for the prediction of the pressure drop and liquid holdup. To evaluate the predictions of various models, an extensive bank of data was compiled from pipelines with internal diameters between 0.025-0.0935 m, using viscosities between 0.001-0.1 Nsm⁻². Under conditions of laminar flow ($Re_L < 2100$), equation (2.34) was found to be a better fit to the experimental data compared to the Blasius equation, for both smooth and wavy interfacial conditions. For turbulent conditions, the accuracy of equation (2.33) proposed by Kowalski (1987) did not compare as well as equation (2.35), against the air-water data of Andritsos (1986) and Hand and Spedding (1991). As a result, the authors, incorporated the relationships for liquid wall friction factors proposed by Hand (1991), which when substituted into the one-dimensional momentum balance or stratified flow, gave accurate predictions for the pressure drop and liquid holdup.

Vlachos et al. (1997) used an electrochemical method to determine the liquid-wall shear stress at various circumferential locations around a 50.8mm internal diameter pipe.

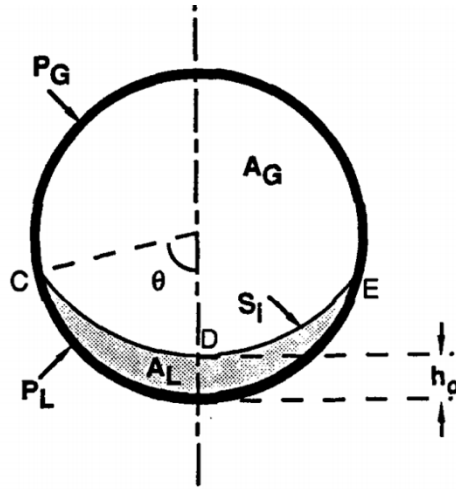


Figure 2.11: Circumferential variation of gas-liquid stratified horizontal pipe flow (Vlachos et al., 1997). The reference angle is specified at the pipe bottom, where $\Theta=0^\circ$.

The following exponential expression was proposed to represent the circumferential distribution of the axial liquid-wall shear stress:

$$\frac{\tau_{WL}(\Theta)}{\tau_{WG}} = 1 + \left(\frac{\tau_{WL0}}{\tau_{WG}} - 1 \right) \left[1 - e^{-m \frac{\theta - \Theta}{\Theta}} \right], \quad (2.39)$$

where θ is the wetted wall fraction and m is a fitting parameter defined as:

$$m = 70u_{SG}^{-2}u_{SL}^{-0.4}. \quad (2.40)$$

The liquid wall shear stress as the pipe bottom τ_{WL0} ($\Theta = 0^\circ$) and the actual liquid velocity U_{Lact} was used to define a friction factor such that:

$$\tau_{WL0} = f_{L0} \frac{\rho_L U_{Lact}^2}{2}, \quad (2.41)$$

where $U_{Lact} = \frac{U_L}{\varepsilon_L}$. Values of f_{L0} were obtained using equation (2.41) and were fitted satisfactorily with the following Blasius type relationship:

$$f_{L0} = 0.2Re_L^{-0.25}. \quad (2.42)$$

An important result was the lateral variation that existed for the liquid wall shear stress, which agreed with previous observations obtained by Paras et al. (1994). Away from the pipe bottom, the time-averaged liquid-wall shear stress decreased. This was again, attributed to the decreasing liquid film thickness that occurs in the lateral direction. At relatively low gas superficial velocities ($U_{SG} < 15$ m/s), a roughly constant mean shear stress value was observed up until $\Theta = 45^\circ$. Beyond that position, the mean shear stress value decreased with decreasing liquid film thicknesses. These results are corroborated in Figure 2.12.

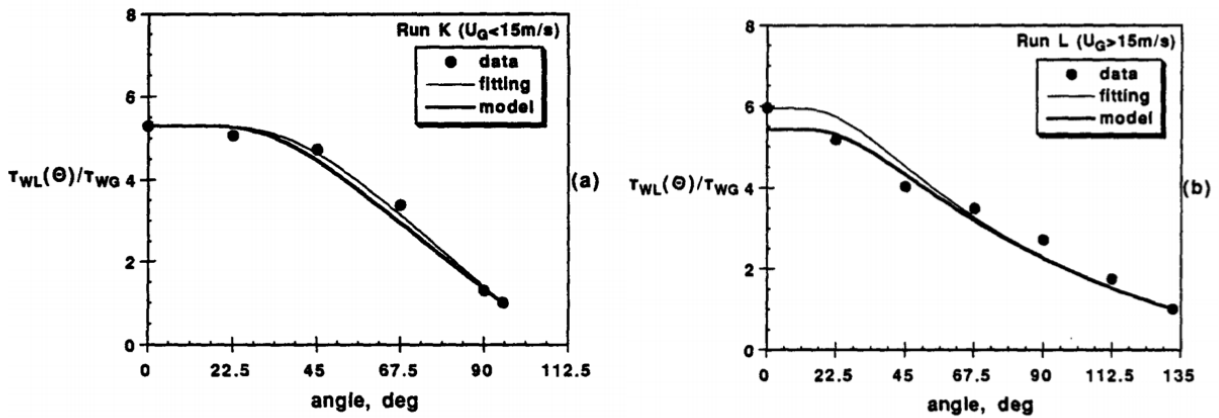


Figure 2.12: Circumferential distribution of $\tau_{WL}(\Theta)$ normalized with respect to τ_{WG} at (a) relatively low superficial gas velocities i.e. $U_{SG} < 15$ m/s and (b) relatively high superficial gas velocities i.e. $U_{SG} > 15$ m/s.

Espedal (1998) performed gas and liquid stratified wall shear stress measurements around the periphery of the pipe, using an acrylic test section with an internal diameter of 60mm. Of the available literature, the liquid-wall friction factor expressions suggested in the thesis Hand (1991), and later published by Spedding and Hand (1997), gave the best overall predictions for the liquid-wall shear stress. Espedal (1998) also developed his own correlation, which was fitted to his pressure gradient and liquid holdup measurements for stratified wavy flows:

$$f_L = \left(1.07 - 7.14\sqrt{0.0225 - 0.0886Re_L^{-0.25}}\right)^2. \quad (2.43)$$

Espedal (1998) noted that the liquid-wall shear stress in the circumferential direction was dependent on the state of the gas-liquid interface. For stratified smooth flows with small amplitude waves, the liquid wall shear stress was relatively constant near the bottom of the pipe before it decreased towards the gas-liquid interface; coherent with the observations of Paras et al. (1994) and Vlachos et al. (1997). However, for high gas flow rates, where large amplitude 3D waves were present, the liquid-wall shear stress was somewhat constant, as far as half the liquid-wetted perimeter, but increased towards the contact point. In the transitional zone between smooth and wavy flows, the shear stress distribution was found to be dependent on the liquid flow rate.

Shaha (1999) measured the liquid wall shear stress at various circumferential locations, as part of two-phase steady-state experiments on conducted on a low-pressure rig, using a stainless-steel test section with an internal diameter of 77.92 mm. The liquid wall friction factor was derived from experimental the data and the results were compared with four different models previously described: Taitel and Dukler (1976), Andritsos and Hanratty (1987), Srichai (1994) and Spedding and Hand (1997); given by equations (2.22), (2.29)-(2.31), (2.36) and (2.34)-(2.35), respectively. As illustrated in Figure 2.13, the Taitel and Dukler (1976) model under-predicted the experimental data for f_L , whilst the model of Srichai (1994) provided an over-prediction. The model predictions by Andritsos and Hanratty (1987) and Srichai (1994) were in between the two extremes yielding similarly good predictions.

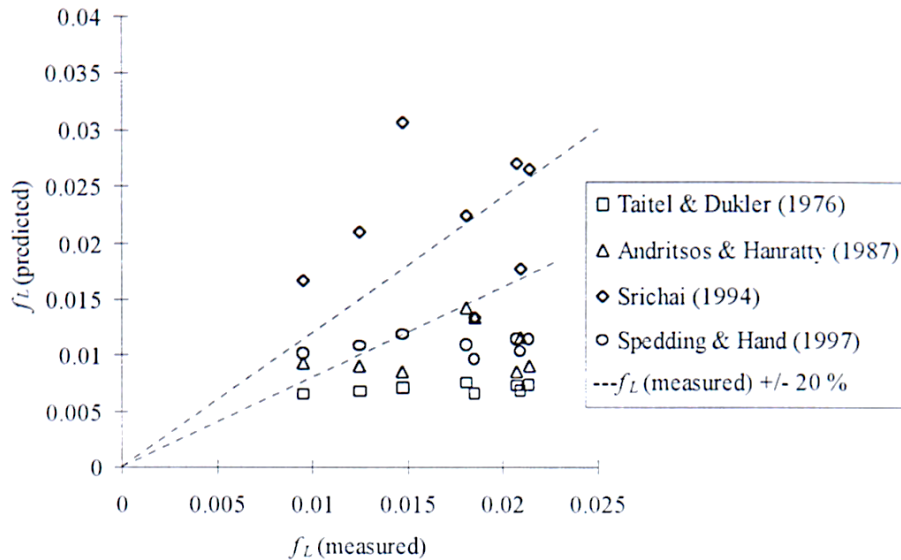


Figure 2.13: Comparison of the liquid wall friction factor f_L between the experimental data of Shaha (1999) and the models of Taitel and Dukler (1976), Andritsos and Hanratty (1987), Srichai (1994) and Spedding and Hand (1997).

The physical results verified that over the whole range of gas flow rates, the shear stresses at $\Theta=45^\circ$ were approximately 20% higher than at the bottom of the tube ($\Theta=0^\circ$). This could

be explained from the aforementioned reasons, linked to the decreased film thickness in the lateral direction (Figure 2.14).

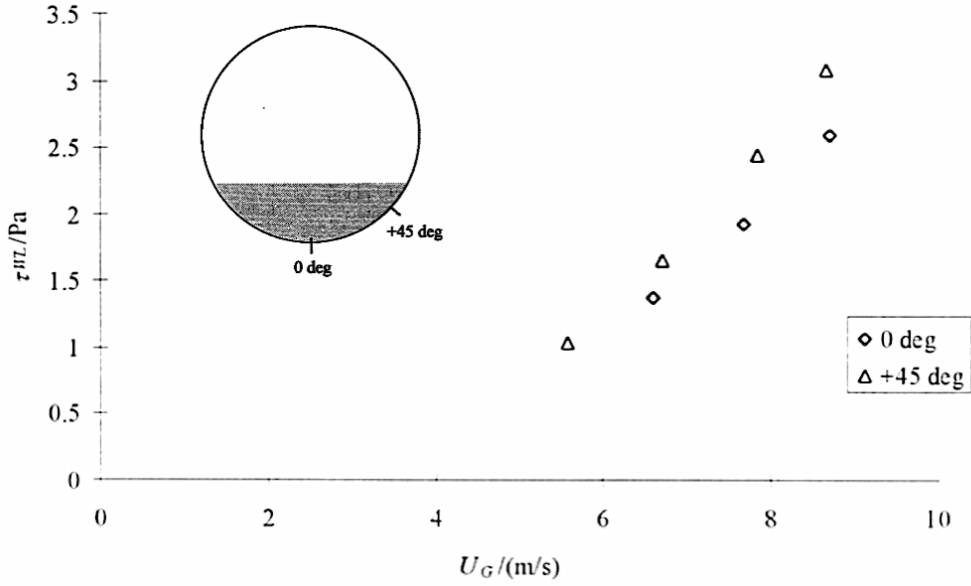


Figure 2.14: Circumferential variation of the liquid wall shear stress over a range of gas flow rates

Liu et al. (2007) presented an interfacial shear stress calculation model for the air-water stratified pipe flows, relevant for a stainless steel 50 mm internal diameter pipeline. The model relied on the accurate estimation of the liquid-wall shear stress. However, since there was an absence of direct measurements of these stresses, it was necessary to employ an empirical correlation for the liquid-wall friction factor. The correlation of Kowalski (1987) given by equation (2.32) was opted for, perhaps due to the very similar pipeline diameter specified in their work.

2.2.3.2 Gas-wall friction factor

Previous discussions revealed that the original Blasius correlation introduced Agrawal et al. (1973), and later modified by Taitel and Dukler (1976), was inappropriate for the calculation of the liquid-wall friction factor. However, as parts of the following discussion will highlight, the Blasius equations are seemingly adequate for the predictions of the gas-wall case, with many researchers obtaining satisfactory predictions through their use.

Colebrook (1939) proposed an implicit friction factor correlation for pipe flows with a rough-wall:

$$\frac{1}{\sqrt{f_G}} = -2 \log_{10} \left(\frac{2.51}{Re \sqrt{f_G}} + \frac{\left(\frac{k}{D}\right)_e}{3.7D} \right), \quad (2.44)$$

where $\left(\frac{k}{D}\right)_e$ is the relative roughness given by:

$$\left(\frac{k}{D}\right)_e = \frac{\bar{k}}{D_e}, \quad (2.45)$$

where D_e is the effective pipe diameter and $\bar{k}$ is the average roughness which depends on construction method, material and age of the pipe.

Eck (1973) developed an explicit form of equation (2.44) and generated very similar values to the original expression, without the need to apply an iterative method:

$$f_G = \frac{0.0625}{\left(\log_{10} \left(\frac{15}{Re_G} + \frac{\left(\frac{k}{D}\right)_e}{3.715} \right)\right)^2}. \quad (2.46)$$

Kowalski (1987) measured the gas-wall shear stress at various circumferential locations using a hot film anemometry technique. The experimental measurements for the gas-wall friction factor f_G agreed reasonably well with the gas phase versions of the Blasius equations proposed by Agrawal et al. (1973) and Taitel and Dukler (1976), which is consistent with the conclusions of many other researchers (Cheremisinoff and Davis, 1979; Chen and Spedding, 1981; Shoham and Taitel, 1984; Andritos and Hanratty, 1987a). Importantly, Kowalski (1987) reported that the major variations in the gas wall shear stress occurred near the gas-liquid interface, where a decrease was observed near the contact point (Figure 2.15).

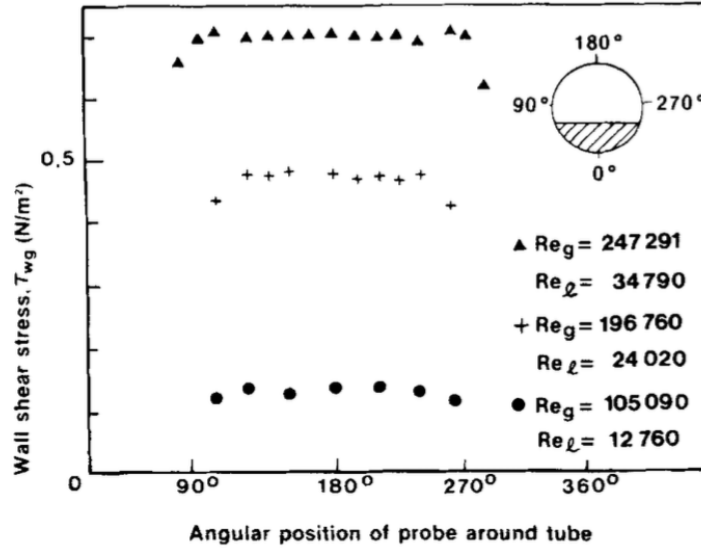


Figure 2.15: Variation of the gas wall shear stress τ_{WG} around the circumference of the pipe in Freon gas-water flow (Kowalski, 1987).

Hart et al. (1989) carried out experiments for gas-liquid horizontal pipe flows using internal diameters ranging from 25-95.3 mm and small liquid hold-ups of less than 0.06. The following correlation was proposed for the gas-wall friction factor:

$$f_G = 0.07725 \left[\log_{10} \left(\frac{Re_G}{7} \right) \right]^{-2}, \quad (2.47)$$

valid for $2100 < Re_G < 10^8$.

Newton and Behnia (1996) measured the gas-wall shear stress in two horizontal acrylic pipes of 50 and 80 mm internal diameters, using air and water as the test fluids. Different subcategories of the stratified flow regime were studied, with the interface being either smooth, rippled or wavy. Based on the wall shear stress data, the following correlation was developed for the gas-wall friction factor:

$$f_G = 0.015 Re_G^{-0.094}, \quad (2.48)$$

valid in the range of: $6 \times 10^3 < Re_G < 3 \times 10^4$.

The measured gas-wall shear stress distributions were found to be strongly influenced by the state of the gas-liquid interface, which from previous discussions, was also true for the liquid-wall case. Referring to Figure 2.16, for stratified flows with small ripples, the wall shear stress relaxes near the interface, as was reported by Kowalski (1987). However, Kowalski (1987) did not mention the subsequent rise adjacent to the interface, which serves to increase the average value of the gas-wall shear stress. As the gas flow rate increased and interface became wavy, a reversal in the wall shear stress profile was observed, causing higher overall average values than the rippled case. Noteworthy is the qualitative distribution these wall stress measurements, which were identical for both pipe diameters, over the same range of interfacial conditions.

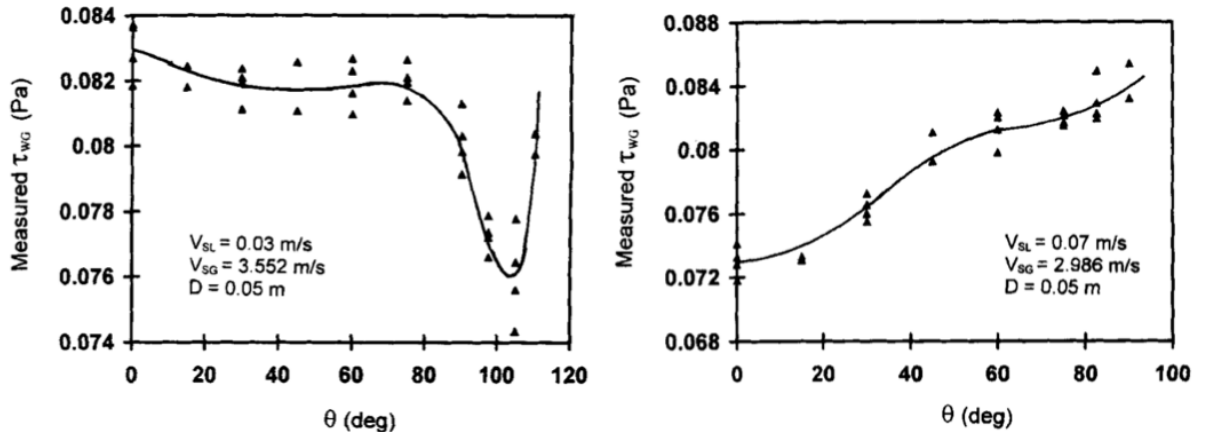


Figure 2.16: Gas-wall shear stress profile around the circumference of the pipe for stratified-ripple flow (left) and stratified-wavy flow (right). The top of the pipe is located at $\Theta = 0^\circ$ and the average interfacial location at $\Theta = 111^\circ$. Adapted from Newton and Behnia (1996).

Biberg (1998) presented an analytical approach for the derivation of the gas-wall friction factor, given by equation (2.49). Although the expression was obtained using classic single phase pipe friction laws, the two-phase flow situation was considered by taking account the effect of flow rate variation in both phases. In addition, the interface was modelled as a solid moving wall with a distinct surface roughness and interfacial velocity.

$$\frac{1}{\sqrt{f_G}} = \frac{-1.8 \log \left(\frac{6.9}{Re_{SG}} + \left(\frac{k_s}{3.7 D_G^*} \right)^{1.11} \right)}{1 + 2 \log \left(1 + \frac{S_i}{S_G} \right) \frac{U_s}{U_G} \sqrt{f_i}}, \quad (2.49)$$

where D_G^* is the effective diameter for free surface flow and U_s is the characteristic slip velocity. Once the corresponding interfacial friction factor term f_i is known, equation (2.49) may be evaluated for a given holdup and flow rate combination. The expression was found to predict the gas-wall shear stress data of Espedal (1998) reasonably well, producing a maximum error of $\pm 5\%$.

Newton et al. (1999) performed experiments in a 0.05m internal diameter pipeline, with several air-liquid stratified flow systems using Propan-22, kerosene or water as the liquid phase. Experimental data for the gas-wall shear stress was compared with equation (2.21) of Taitel and Dukler (1976) and equation (2.48) of Newton and Behnia (1996). The authors concluded that the interfacial conditions or liquid properties did not depend on the gas-wall shear stress.

Shaha (1999) compared his experimental data for the gas-wall friction factor with the expressions proposed by Eck (1973), Taitel and Dukler (1976), and Espedal (1998), given by equations (2.46), (2.21) and (2.49). Espedal (1998) adopted the expression Biberg (1998), where interfacial friction factor term f_i was predicted using a correlation from Spedding and Hand (1997). The comparisons are illustrated in Figure 2.17.

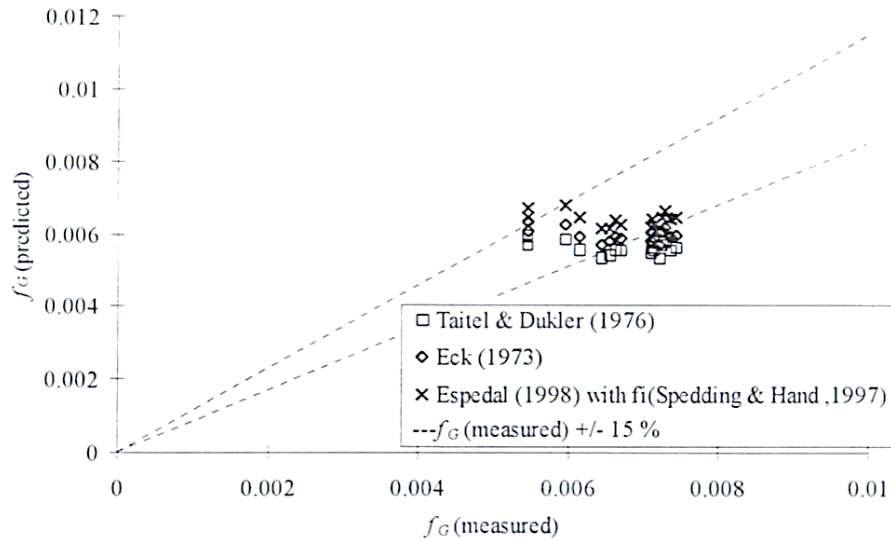


Figure 2.17: Comparison of the gas-wall experimental data of Shaha (1999) and the expressions of Eck (1973), Taitel and Dukler (1976), and Espedal (1998).

Although the quantitative difference is minimal, the highest prediction accuracy was demonstrated by Espedal (1998), followed by Eck (1973) and Taitel and Dukler (1976). The superiority of the expression adopted by Espedal (1998) was reasoned to the fact that it not only includes a term to account for the pipe wall roughness but also one that considers the interfacial structure.

2.2.3.3 Interfacial friction factor

The calculation of the interfacial shear stress is the most significant problem encountered in gas-liquid stratified pipe flows, due to the difficulty of modelling the interfacial friction factor f_i . The interfacial friction factor is a function of the fluid properties, phase velocities, the interfacial roughness and the cross-sectional area of the gas flow; all of which are influenced by the nature of the interfacial wave patterns (Ng, 2002). Thus, the determination of f_i relies heavily on one's understanding of the characteristic interfacial structures. Generally, the available correlations for the interfacial friction factor can be subdivided into five categories (Espedal, 1998):

- I. Simple correlations.
- II. Roughness based models
- III. Dimensional analysis and other methods.
- IV. Correlations developed for channel flows.
- V. Correlations developed for annular flows.

The final two categories are not directly relevant to this thesis and are thus, excluded from the following discussion. A number of the studies for the remainder of the approaches are reviewed herein.

Simple correlations

As section 2.2.2 highlighted, the application of very simple one-dimensional models for the prediction of the pressure gradient and liquid holdup in a two-phase flow system often relies on the assumption that the interfacial friction factor f_i is identical to the gas-wall friction factor f_g . This approach has been applied by Russel et al. (1974), who equated the interfacial friction factor with the Blasius gas-wall friction factor equation proposed by Agrawal et al. (1973), such that:

$$f_i = f_G = 0.079(Re_{SG})^{-0.25}. \quad (2.50)$$

The authors assumed that the liquid surface acts as a solid boundary in stratified gas-liquid flow. We recall a further assumption that was made by Taitel and Dukler (1976), in which the gas-liquid interface was considered to be smooth and planar, with a similar Blasius equation given by expression (2.21) being proposed for the interfacial friction factor.

Shoham and Taitel (1984) incorporated the eddy viscosity model in their numerical solutions for turbulent gas-liquid stratified pipe flows in horizontal and slightly inclined pipes. Throughout the wavy-stratified flow regime, a constant value of 0.0142 for the interfacial friction factor was used by the authors.

Kawaji et al. (1987) carried out measurements for the liquid holdup, phase and velocity distributions in high-pressure steam-water stratified flow. A 180 mm internal diameter, 10m long horizontal pipe was used, with the maximum steam and water flow rates being 0.194m³/s and 0.047m³/s, respectively. At high flow rates, the authors reported a highly disturbed gas-liquid interface. From their data fittings, the following correlation was proposed for the interfacial friction factor:

$$f_i = 3f_G, \quad (2.51)$$

where f_G was obtained using the Blasius equation used by Russel et al. (1974).

Spedding and Hand (1990) adopted a similar approach to Kawaji et al. (1987) and proposed the two expressions for the interfacial friction factor, depending on the flow regime.

$$f_i = 0.6f_G \text{ for transitional flows;} \quad (2.52)$$

and

$$f_i = 4f_G \text{ for fully turbulent flows.} \quad (2.53)$$

The inclusion of equations (2.52) and (2.53) into the model Spedding and Hand (1990) allowed for a seemingly accurate prediction of the liquid holdup for stratified-wavy flows and stratified flows with entrainment.

Newton et al. (1999) performed experiments in a 50 mm internal diameter horizontal pipeline using, using several gas-liquid combinations. For smooth and rippled interfaces of the stratified flow regime, the following correlation was proposed based on the gas Reynolds number:

$$f_i = 6.5 \times 10^{-4} Re_G^{0.3} \text{ valid for } 3500 < Re_G < 20000. \quad (2.54)$$

Another correlation was also proposed to account for the effect of large interfacial disturbances:

$$f_i = 0.003 Re_G^{0.2}, \quad (2.55)$$

however, the number of recorded observations were too small to assess the accuracy this relation.

Roughness based models

Many interfacial friction factor correlations have been developed in terms of the interfacial roughness for gas-liquid stratified pipe flows. A commonly used correlation is that of Colebrook (1939),

$$\frac{1}{\sqrt{f_i}} = -2 \log_{10} \left(\frac{2.51}{Re \sqrt{f_i}} + \frac{\left(\frac{k}{D}\right)_e}{3.7D} \right), \quad (2.56)$$

where the interfacial roughness k has been determined differently by different researchers.

Hamersma and Hart (1987) performed experiments in the stratified-wavy and annular flow regimes for low liquid holdups of less than 0.04, using air-water and air-glycol mixtures. The authors used the explicit version of the Colebrook-White formula, given by:

$$f_i = \frac{0.0625}{\left(\log_{10} \left(\frac{15}{Re_G} + \frac{\left(\frac{k}{D}\right)^e}{3.715} \right) \right)^2}, \quad (2.57)$$

with the interfacial roughness k being:

$$k = 2.3\delta, \quad (2.58)$$

where δ is the average thickness of the liquid film on the wetted angle of the tube wall θ_w , given by:

$$\delta = \frac{\varepsilon_L D}{4\theta_w} \quad \text{if } \frac{\delta}{D} \leq 1. \quad (2.59)$$

For the wetted angle θ of the tube wall, the following equation was derived:

$$\theta = \frac{1}{\pi} \arccos(1 - C_1 Fr_L) \quad \text{valid for } Fr_L \leq \frac{2}{C_1}, \quad (2.60)$$

where the value of C_1 was determined empirically as $C_1 = 0.66$, and the liquid Froude number was defined as:

$$Fr_L = \left(\frac{\rho_L}{\rho_L - \rho_G} \right) \left(\frac{U_L^2}{gD} \right). \quad (2.61)$$

Andreussi and Persen (1987) developed an empirical correlation of the interfacial friction factor for stratified-smooth and stratified-wavy flows and reported measurements for the liquid holdup, pressure drops and velocity profiles in the gas phase. Experiments were performed with air and water in a slightly downwardly inclined pipe of 50 mm internal diameter at atmospheric conditions. The authors revealed a large dependence of the interfacial shear stress on the structure of the interface. For example, when transitioning from the stratified-smooth to stratified-wavy regime, a large increase in the interfacial shear stress was observed; however, no significant change occurred between the stratified-wavy regime to the large disturbance wave regime. An assumption was also made that the instantaneous roughness depended on the actual Froude number Fr and the Froude number value at the onset of 2-D waves Fr_0 , hence:

$$\begin{aligned} \frac{f_i}{f_G} &= 1; \quad \text{for } Fr \leq Fr_0, \\ \frac{f_i}{f_G} &= 1 + 29.7(Fr - Fr_0)^{0.67} \left(\frac{h_L}{D} \right)^{0.2}; \quad \text{for } Fr > Fr_0, \\ Fr_0 &= 0.36, \end{aligned} \quad (2.62)$$

where the Froude number Fr is defined as:

$$Fr = U_G \left[\frac{\rho_G}{\rho_L - \rho_G} \frac{\frac{dA_L}{dh_L}}{A_G} \frac{1}{g \cos \theta} \right]^{0.5}. \quad (2.63)$$

Due to the limited data upon which the correlations were based, caution should remain on their applicability for different pairs of fluids or flow geometries.

Oliemans (1987) studied the stratified-wavy regime in gas condensate lines using internal diameter pipelines that ranged from 20-36 inches. The interfacial friction factor was determined using the implicit relation of Colebrook (1939), given by equation (2.56). Since the presence of interfacial waves was observed to increase the interfacial roughness, Colebrook (1939) proposed a relationship between the interfacial roughness k and the wave height, such that:

$$k = 3\sqrt{2} \cdot h_L^{rms}; \text{ for } h_L^{rms} < h_L, \quad (2.64)$$

$$k = 3\sqrt{2} \cdot h_L; \text{ for } h_L^{rms} \geq h_L, \quad (2.65)$$

where h_L^{rms} is the root mean square wave height.

Hart et al. (1989) proposed an Apparent Roughness Surface (ARS) model, in which the presence of a rough gas-liquid interface was assumed to be a result of the interfacial drag exerted by the gas phase. Their experiments were performed in a 51 mm internal diameter horizontal pipe, with the results being presented for air-water and air-water + ethylene glycol systems, using low liquid holdups of less than 0.06. To predict the interfacial friction factor, the authors applied the same approach of Hamersma and Hart (1987), using the explicit version of the Colebrook-White formula. However, a more accurate description of the wetted wall fraction θ_w was proposed, designed to consider the minimum value of the wetted wall fraction θ_{wo} , when Fr_L tends to zero:

$$\theta_w = \theta_{wo} + 0.26Fr_L^{0.58}, \quad (2.66)$$

where θ_{wo} can be approximated by:

$$\theta_{wo} \approx 0.52\varepsilon_L^{0.374}. \quad (2.67)$$

Hart et al. (1989) also proposed a relationship between f_L and f_i , given by:

$$\frac{f_L}{f_i} = 108Re_{SL}^{-0.726}. \quad (2.68)$$

Sinai (1983) developed a theoretical relationship for the interfacial roughness k for gas-liquid stratified pipe flows, based on a modification of a relation used in oceanographic literature. The theoretical prediction was not tested against experimental data. For stratified-wavy flows, the author acknowledged that no uniform distribution of the interfacial roughness existed.

The analysis began by introducing the classical relation between the mean and friction velocity, for fully rough conditions (Goldstein, 1965):

$$\frac{U_G}{U^*} = 5.75 \log_{10} \left(\frac{R_{H,G}}{2k} \right) + 4.73, \quad (2.69)$$

where U^* is the friction velocity and $R_{H,G}$ is the mean hydraulic radius in the gas given by:

$$R_{H,G} = \frac{2S_G}{P_L + P_G}. \quad (2.70)$$

For the interfacial roughness, the following relationship was proposed:

$$k = 0.33 \frac{\xi(U^*)^2}{g}, \quad (2.71)$$

with

$$\xi = \frac{545\rho_G}{\rho_L - \rho_G} \left(\frac{S_i}{P_G + S_i} \right). \quad (2.72)$$

Substitution of equation (2.72) into (2.69) yields the following:

$$\frac{U_G}{U^*} = 5.75 \log_{10} \left(\frac{20.1V^2}{\xi(U^*)^2} \right). \quad (2.73)$$

where $V^2 = gR$. Sinai (1983) then proposed that the interfacial friction factor could be given by:

$$f_i = 2 \left(\frac{U^*}{U_G} \right)^2 \quad (2.74)$$

However, the given solution of equation (2.73) is only relevant when the mean gas velocity lies below a certain value. Through simple calculus, we find that:

$$\left(\frac{U_G}{U^*} \right)_{max} = 5. \quad (2.75)$$

Jayanti (1991) developed a closure relation for the interfacial stress for horizontal stratified flows. The author adopted the analytical expressions of Sinai (1983). However, a different term was used for the interfacial roughness, given by:

$$k = 180 \frac{S_i}{S_G + S_i} \frac{(U^*)^2}{g} \frac{\rho_G}{\rho_L - \rho_G}. \quad (2.76)$$

In addition, equation (2.74) was used only when $f_i < 5f_G$, otherwise f_i was taken to be $5f_G$. Jayanti (1991) also compared the interfacial friction factor correlation of Sinai (1983), with two other interfacial friction factor correlations from Andritsos and Hanratty (1987) and Kowalski

(1987). The comparison was made against two experimental data sets, comprising air-water flows in a pipe of 0.305m internal diameter and a rectangular channel of 0.13m hydraulic diameter. Overall, the approach of Sinai (1983) yielded the most accurate predictions of the experimental data.

Srichai (1994) experimentally investigated steady state air-water and air-oil stratified flows at the Imperial College WASP facility at pressures of 5, 10 and 15 bar(g). A method was developed to calculate the interfacial friction factor, but was still partly based on the approach suggested by Sinai (1983), using the following previously specified equations:

$$f_i = 2 \left(\frac{U^*}{U_G} \right)^2 \quad (2.77)$$

$$\frac{U_G}{U^*} = 5.75 \log_{10} \left(\frac{R_{H,G}}{2k} \right) + 4.73, \quad (2.78)$$

However, the interfacial roughness k was now related to the root mean square fluctuations of the liquid height h'_L , in which:

$$h'_L = \sqrt{(h - \bar{h})^2}, \quad (2.79)$$

where h was the instantaneous liquid height and $\bar{h}$ was average liquid height. In their dimensionless forms, k and h'_L was correlated through the following expression:

$$\frac{k}{D} = 0.1985 \left(\frac{h'_L}{D} \right)^{0.0825}, \quad (2.80)$$

where the dimensionless fluctuation $\frac{h'_L}{D}$ incorporated effects of the system pressure:

$$\frac{h'_L}{D} = a + b(\varepsilon_L Re_{SG}) + c(\varepsilon_L Re_{SG})^2, \quad (2.81)$$

with the constants being defined by:

$$a = 2.65 \times 10^4 \left(\frac{\rho_G}{\rho_L - \rho_G} \right)^{4.517}; \quad (2.82)$$

$$b = 8.995 \times 10^{-10} \left(\frac{\rho_G}{\rho_L - \rho_G} \right)^{-1.22}; \quad (2.83)$$

$$c = 1.897 \times 10^{-13} \left(\frac{\rho_G}{\rho_L - \rho_G} \right)^{-0.925}. \quad (2.84)$$

Despite Srichai (1994) not considering the exact shape of the interface (which was crescent-shaped at high gas velocities), most of the data lied within 30% of the true measured values, indicating a reasonable level of accuracy for the developed correlation.

Paras et al. (1994) explored the possibility of using statistical film characteristics to model the interfacial friction, using the well-known resistance formula for the completely rough regime (Schlichting, 1960):

$$f_i = \frac{0.25}{\left(2 \log_{10} \frac{R}{k} + 1.74\right)^2}, \quad (2.85)$$

where R is the pipe radius and k is the apparent roughness, related to wave characteristics through:

$$\frac{k}{D} = 1.5 \left(\frac{h_w}{D}\right) I_w^{0.17}, \quad (2.86)$$

in which h_w is the wave height and I_w is the wave intermittency. It was noted that the ratio of the wave height over the mean thickness at the bottom $\left(\frac{h_w}{h_0}\right)$ was roughly equal to 2, and that the intermittency values for I_w varied in the range of 0.05-0.35. To obtain approximate solutions to equation (2.89), an intermediate value of $I_w^{0.17} = 0.2^{0.17} \approx 0.75$ could be selected, leading to:

$$k \approx 2.3h_0. \quad (2.87)$$

Noteworthy is the similarity of equation (2.88) with that developed by Hamersma and Hart (1987), given by equation (2.58). Despite the resemblance, δ in the notation of the average thickness of the liquid film is not necessarily equal to h_0 .

Emulating the rationale of Srichai (1994), Shaha (1999) also developed a relationship between the interfacial roughness k and the and the root mean square fluctuations of the liquid height h'_L . The following expression was found to best fit the experimental data obtained at pressures of 6 bar(a) and 11 bar(a):

$$\frac{k}{D} = 0.9929 \left(\frac{h'_L}{D}\right)^{0.6273}, \quad (2.88)$$

with

$$\frac{h'_L}{D} = C_s (\varepsilon_L Re_{SG}), \quad (2.89)$$

where the parameter C_s depends on the system pressure and is defined by:

$$C_s = 9.9917 \times 10^{-4} \left(\frac{\rho_G}{\rho_L - \rho_G}\right)^2 - 4.558 \times 10^{-5} \left(\frac{\rho_G}{\rho_L - \rho_G}\right) + 7 \times 10^{-7}. \quad (2.90)$$

Vlachos et al. (1997) used average liquid-wall shear stress data in the circumferential direction, along with the data obtained on the liquid film thickness, wave properties, and pressure drop measurements, to propose the following correlation for the interfacial friction factor:

$$f_i = 0.024 \varepsilon_L^{0.35} Re_L^{0.18}. \quad (2.91)$$

For their calculations, the equivalent interfacial roughness was correlated using the wave intermittency I_w and the wave amplitude dH , rather than the wave height h_w :

$$\frac{k}{D} = 2.85 \left(\frac{dH}{D} \right) I_w^{0.17}. \quad (2.92)$$

Other models

Many other interfacial friction factor models have been developed by means of both mechanistic and empirical approaches.

Andritsos and Hanratty (1987a) carried out experiments in horizontal pipes with internal diameters ranging from 25.2 mm to 93.5 mm and varying liquid viscosities from 1 mPa.s to 80 mPa.s, using co-current air-water/glycerine flows at atmospheric conditions. The authors pointed out that beyond a certain critical value of the superficial gas velocity the interfacial friction factor f_i increases linearly. This critical value was defined as the superficial gas velocity at which large irregular waves appear at atmospheric conditions, and was estimated using:

$$U_{SG,t} = 5 \left(\frac{\rho_{GO}}{\rho_G} \right)^{0.5}, \quad (2.93)$$

where ρ_{GO} is the gas density at atmospheric pressure. Using the above relation, Andritsos and Hanratty (1987a) proposed the following:

$$\frac{f_i}{f_G} = 1 \quad \text{if } U_{SG} \leq U_{SG,t}, \quad (2.94)$$

where the Taitel and Dukler (1976) gas-wall interfacial friction factor f_g (for the smooth region) was used to compute the interfacial friction. Beyond the point of criticality i.e. $U_{SG} > U_{SG,t}$ the interfacial friction factor then becomes a function of the dimensionless liquid height $\frac{h_L}{D}$:

$$\frac{f_i}{f_G} = 1 + 15 \left(\frac{h_L}{D} \right)^{0.5} \left(\frac{U_{SG}}{U_{SG,t}} - 1 \right) \quad \text{if } U_{SG} > U_{SG,t}. \quad (2.95)$$

Equations (2.93)-(2.95) were shown to under predict f_i for water at low and high gas rates, and over predict f_i from $U_{SG} = 5$ m/s to $U_{SG,t}$. Nevertheless, the correlations generated accurate predictions for very viscous liquids, where the relation given by equation (2.94) applied.

Kowalski (1987) determined the interfacial shear stress τ_i in two ways, and both methods generated roughly similar results. The first used a combination of momentum balance equations from Taitel and Dukler (1976), given by (2.10) and (2.11), with experimental values for τ_{wg} , τ_{wl} and ε_G :

$$\tau_i = \tau_{WL} \frac{S_L}{S_i} \varepsilon_G - \tau_{WG} \frac{S_G}{S_i} (1 - \varepsilon_G) \quad (2.96)$$

The second method involved the extrapolation of the Reynolds shear profile at the gas-liquid interface. Based on the data, empirical correlations were developed for the interfacial friction factor. For smooth stratified flow, equation (2.50) given by Agrawal et al. (1973) did not yield accurate predictions. Instead, the following equation was proposed and better fit the experimental data:

$$f_i = 0.96 Re_{SG}^{-0.52}. \quad (2.97)$$

For the stratified-wavy case, the data was fitted by the following equation for the interfacial friction factor:

$$f_i = 7.5 \times 10^{-5} \varepsilon^{-0.25} Re_{SG}^{-0.3} Re_{SL}^{0.83}, \quad (2.98)$$

valid for $22600 \leq Re_{SG} \leq 430600$ and $8800 \leq Re_{SL} \leq 47800$.

Xiao et al. (1990) used a dimensionless analysis approach based on empirical data to predict the interfacial friction factor, where the various groups were used to describe the interfacial shear phenomena:

$$f_i = 0.053 N_{GV}^{0.23} N_{LV}^{0.202} N_D^{-0.46} N_L^{0.23} \quad (2.99)$$

where the four dimensionless groups were developed by Duns and Ros (1962) are defined by:

$$N_{GV} = U_G \left(\frac{\rho_L}{g\sigma} \right)^{0.25}; \quad (2.100)$$

$$N_{LV} = U_L \left(\frac{\rho_L}{g\sigma} \right)^{0.25}; \quad (2.101)$$

$$N_D = D \sqrt{\frac{\rho_L g}{\sigma}}; \quad (2.102)$$

$$N_L = \mu_L \left(\frac{g}{\rho_L \sigma^3} \right)^{0.25}. \quad (2.103)$$

Hand (1991) performed experiments with air and various fluids in a horizontal pipe. The following linear relationship was proposed stratified air-water flows, providing accurate predictions for air-water data:

$$\frac{f_i}{f_G} = 1.76 \left(\frac{U_{SG}}{(U_{SG})_r} \right) + k \quad (2.104)$$

where $(U_{SG})_r$ is the reference superficial gas velocity = 6 m/s, and k was determined using a curve fitting technique:

$$k = 2.7847 \log_{10}(\beta_L)_r + 7.8035, \quad (2.105)$$

where

$$(\beta_L)_r = \frac{U_{SL}}{U_{SL} + (U_{SG})_r}. \quad (2.106)$$

For the viscous-liquid case, Hand (1991) introduced the model of Andritsos and Hanratty (1987a), given by equation (2.95).

Brauner and Maron (1993) proposed a new form of the interfacial shear, which incorporated an explicit functional dependence on the interface slope owing to the interfacial waviness. The implementation of the model revealed the crucial role of having an unsteady term for the determination of stability characteristics. Through the inclusion of this term, the stratified-smooth/stratified-wavy transitional boundary was satisfactorily predicted for a wide range of two-fluid systems.

Kang and Kim (1993) developed a model to describe the relationship between the interfacial shear stress and the wave motion for air-water concurrent stratified flows. By assuming a simple relation between the gas velocity near the interface and the film thickness, the turbulent shear stress due to wave motion was expressed using the normal interfacial velocity and the effective gas velocity.

Spedding and Hand (1997) developed an iterative procedure for the prediction of the pressure drop and liquid holdup that incorporated relationships for the interfacial friction factor. After fitting results to their experimental data bank, the authors concluded that the correlations of Hand (1991) are the most accurate to predict the interfacial friction factor.

The interfacial friction factor correlation proposed by Kowalski (1987) for stratified-wavy flows, given by equation (2.98), agreed well with the experimental data of Paras et al. (1994). However, its validity only held at relatively low superficial gas velocities i.e. below the atomization regime. At higher superficial gas velocities, Paras et al. (1994) observed a satisfactory linearity and the best fit was obtained from the following expression:

$$f_i = 0.022 + 3.7 \times 10^{-6} Re_L, \quad (2.107)$$

where Re_L was based on the liquid height at the centre of the pipe h_0 :

$$Re_L = \frac{U_L h_0}{\varepsilon_L \nu_L}. \quad (2.108)$$

Zhou and Li (1999) proposed an interfacial friction factor correlation based on Laser Doppler Velocimetry (LDV) measurements of the Reynolds shear stresses. Experiments were performed for air-water flows in horizontal pipelines of 24 mm and 40 mm internal diameters. For smooth stratified flows, the following relation was proposed:

$$f_i = 0.96 Re_{SG}^{-0.52}, \quad (2.109)$$

and for stratified-wavy flows, the interfacial friction factor was again shown to be a function of the dimensionless liquid height $\frac{h_L}{D}$:

$$f_i = 1.35 \times 10^4 \left(\frac{h_L}{D} \right)^{0.5} Re_{SG}^{1.15}. \quad (2.110)$$

Ottens et al. (2001) tested 22 different correlations for the interfacial friction factor in one-dimensional momentum balance equations for the two phases. The calculated results were compared with an experimental database consisting of 3981 measurements for gas-liquid pipe flows in the regimes of stratified-smooth, stratified-wavy and annular flows. Among the tested interfacial friction factor correlations, the authors concluded that the best accuracy for the simultaneous liquid holdup and pressure gradient prediction was obtained through their own relation, given by:

$$\frac{f_i}{f_G} = \frac{C}{U_i} + 7.21 \sqrt{\frac{h_L}{D} \left(\frac{U_{SG}}{4.5} - 1 \right)}, \quad (2.111)$$

where $f_i = f_G$ if $U_{SG} < 4.5$ m/s, C is the interfacial wave velocity and U_i is the interfacial velocity. Of the compared relations, the model of Ottens et al. (2001) was seemingly the most sophisticated, accounting for terms like the liquid height, interface curvature, gas and liquid velocities and the physical properties of the test fluids.

Ulmann et al. (2004) proposed new wall and interfacial shear stress closure relations for the two-fluid model, applicable to stratified laminar pipe flows i.e. with a flat interface. A simple two-plate model was used to derive the expressions, which account for the interaction between the two phases. The closure relations were developed from single-phase-based expressions but were augmented with two-phase interaction factors. When testing the newly presented modified two-fluid model against the exact solution for fully developed laminar pipe flows, satisfactory results were obtained for the pressure drop and liquid holdup for a wide range of dimensionless parameters in concurrent and counter current laminar flows. The authors also claimed that the closure relations can handle a change in the wall shear stress direction, induced through gravity-driven backflow.

Liu et al. (2007) evaluated the interfacial friction factor indirectly using experimental liquid height and pressure loss measurements, which were obtained in a 50 mm internal diameter pipeline for air and water in concurrent stratified flow. The following correlation was proposed for the interfacial friction factor as the best fit for their experimental data:

$$f_i = 2.56 \times 10^{-3} + 23.19 \left(\frac{h_L}{D} \right)^{-0.27} Re_G^{-0.84} Re_L^{0.36}. \quad (2.112)$$

However, the agreement was found to be poor for larger pressure drops, where the interface is characterised by the presence of large amplitude waves.

Biberg (2007) developed an algebraic-logarithmic model for two-phase stratified pipe flow, which was characterised by its ability to reproduce the effect of interfacial waves and momentum transfer. The work was motivated by the multiphase flow challenges encountered in the Ormen Lange gas field in Norway. When defining the interfacial mixing lengths with certain empirical correlations, the pipe flow friction models were demonstrated to agree individually with pipe flow friction measurements for both smooth and wavy interfaces.

Sidi-Ali and Gatignol (2010) determined the interfacial friction factor using CFD simulations in horizontal gas-liquid stratified flows. In their numerical work, results for the vertical and horizontal gas velocity profiles were first validated using the experimental data of Strand (1993), showing a good level of agreement. An expression of the interfacial friction factor was then derived and given by:

$$f_i = 2.82 Re_G^{-0.522}, \quad (2.113)$$

valid for $9000 < Re_G < 49000$ and $21000 < Re_L < 30000$, which corresponds to the numerical simulation conditions of their study.

Tzotzi and Andritsos (2013) performed experiments in a horizontal pipe with an internal diameter of 24 mm and a total length of 12.35 m, in a smooth transparent Plexiglas pipe. The working liquid phases comprised water and a n-butanol-water solution, whilst air, helium, and carbon dioxide were used as working gas phases. Different interfacial friction factor relations were proposed for the stratified 2-D wave region and the stratified large-amplitude wave region. For the former:

$$\frac{f_i}{f_G} = 1 + 0.35 \left(\frac{h_L}{D} \right)^{0.5} (U_{SG} - U_{SG,2-D}). \quad (2.114)$$

where $U_{SG,2-D}$ is the superficial gas velocity of small amplitude 2D waves. For the transition to large-amplitude waves:

$$\frac{f_i}{f_G} = 2 \left(\frac{h_L}{D} \right)^{0.1} \left(\frac{\mu_L}{\mu_w} \right)^{0.1} + 4 \left(\frac{h_L}{D} \right)^{0.5} (U_{SG} - U_{SG,KH}). \quad (2.115)$$

where $U_{SG,KH}$ is the superficial gas velocity of large amplitude Kelvin Helmholtz waves. Noteworthy is the $\frac{\mu_L}{\mu_w}$ term that appears in equation (2.115) that serves to consider the effect of increasing values of $\frac{f_i}{f_G}$, for increasing liquid viscosities.

2.2.4 Summary

Almost all predictive methods for modelling gas-liquid stratified flows in the literature are one-dimensional, based on the momentum balances of the two phases. The two-fluid modelling approach is the most commonly applied, but as previous discussions highlighted, it is critically reliant on having accurate closure laws for the wall and interfacial shear stresses.

There is a large degree of empiricism retained within most mechanistic models. Notable examples involve the use of experimental results to determine the liquid-wall and interfacial friction factors. For the latter, many of the correlations are not elaborate enough to explain the interfacial structure and the transport phenomena between the phases. Over the last 20 years, several models have been proposed to deal with curved interfaces (e.g. Hart et al 1989; Vlachos et al., 1999). Despite these attempts, the quest to attain a universal correlation remains. New experimental results, combined with previous experimental data, may permit the development of such a tool.

Although mechanistic models are adequate to use in the basic design stage of industrial multiphase pipelines, a more accurate and comprehensive method is desirable for the final stages. For the near future, this need will increase with the development of more complex gas fields, in farther offshore and deep-water environments (Birvalski, 2015). For such conditions, any errors in determining the key design parameters i.e. the pressure gradient and liquid holdup will amplify due to the pipeline length.

2.3 Experimental work

2.3.1 Techniques

Several experimental techniques can be used to measure the wall shear stress in multiphase flows. Among the most widely used for gas-liquid stratified pipe flows are heat transfer methods, where wall shear stress information can be derived from the transfer of heat from a heated film onto a fluid (e.g. Kowalski, 1987; Hagiwara et al., 1989; Vlachos et al., 1993; Espedal, 1998; Shaha, 1999). Such techniques are suitable when a localised and continuous measurement of the stress is necessary. Mass transfer techniques i.e. electrochemical methods have also been applied in gas-liquid stratified pipe flows (e.g. Rosant, 1994; Langsholt et al., 1997; Vlachos et al., 1997). Here, the mass transfer coefficient, determined for the transport of ions in a redox reaction, can be related to the liquid-wall shear stress.

Using the above techniques, several studies have considered the distribution of the wall shear stresses in the circumferential direction (see Chapter 2.2.3). Acquiring such data in quantitative high-resolution form constitutes a major objective of the present work. However, in contrast to heat or mass transfer calculations, this information will be derived from the measurement route of the phase velocities.

Within stratified pipe flows, traditional measurement techniques for the local velocity include the use of pitot tubes (e.g. Newton and Behnia, 1996) or film removal devices (e.g. Olive et al., 2003). These techniques have the inherent disadvantage of being intrusive which may cause an adverse effect on the flow field (Kumara et al., 2010). In addition, they usually only provide time-averaged values of the velocity (Graebel, 2001); hence, important information on the instantaneous velocities and turbulence properties of the flows cannot be obtained.

Non-intrusive measurements became more practical with the development of laser-based technologies in the mid-1960s. One of the first significant advancements in fluid diagnostics originated from Yeh and Cummins (1964), through their development of Laser Doppler Anemometry (LDA). LDA is a non-intrusive optical technique which has been widely applied to perform in-situ measurements of the local flow properties of gas-liquid two-phase flows. It offers a fast dynamic response, high spatial resolution (important for the extraction of near-wall and interfacial information), wide measuring range and the possibility to detect reversal flows (Chaouki, 1997). The first to employ LDA for velocity measurements of gas-liquid flows through a pipe were Paras and Karabelas (1992) and Strand (1993). For a limited range of flow conditions, they performed velocity measurements in the liquid layer of gas-liquid flows. Their results for the mean axial velocity and the fluctuations in the liquid layer revealed similarities with previous works conducted for channel flows, which compared to pipe flows, have studied in substantially more cases (e.g. see Fabre et al., 1987; Lorencez et al., 1997; Fernandino and Ytrehus, 2008). Despite the apparent advantages of LDA, it is limited by its cumbersome point-by-point measurement method of the velocity components, which requires a considerable amount of time to accurately characterise the whole flow field. In addition, the flow must also be stationary for the acquisition of velocity data, limiting the measurements to steady-state or periodic flows.

PIV offers a means to counter the limitations of LDA. To confidently extract reliable information on the wall and interfacial shear stresses, the provision of spatiotemporally resolved information of the in-situ hydrodynamics of the entire flow field is ideal. As such, the present project will seek to simultaneously implement two spatiotemporal laser-based techniques: Planar-Laser Induced Fluorescence (PLIF) and Particle Image Velocimetry (PIV).

2.3.1.1 PLIF

PLIF is an optical diagnostic technique consisting of a laser light source that passes through an arrangement of lenses to form a light sheet (Sietzman and Hanson, 1993). In horizontal pipes, this light sheet usually passes through the vertical plane at the pipe centre, which is used to illuminate the flow. To distinguish between the two phases, a fluorescent dye is normally added to the aqueous phase, where the fluorescent emission can subsequently be captured by a high-speed camera. This facilitates the portrayal of the instantaneous phase distributions (in the vertical plane of illumination), which allows one to determine important flow information on the interface level, phase fraction, wave phenomena and droplet size/distribution. Identifying the interface level is particularly important before PIV processing, in order to mask the unwanted phase (Andre and Bardet, 2014). Noteworthy is the superiority of pulse-lasers which are commonly used as the main light source. Compared to continuous wave systems, these offer an enhanced temporal resolution and peak power.

Early PLIF studies in gas-liquid systems were performed in hollow-cone sprays (Melton and Verdieck, 1985), burning fuel sprays (Allen and Hanson, 1986) and for the combustion of gases (Hanson et al. 1990). More recent studies have applied PLIF in gas-liquid vertical flows (Schubring et al., 2010; Zadrazil et al., 2014), liquid-liquid vertical flows (Liu, 2005) and horizontal liquid-liquid flows (Morgan et al., 2012). Part of the aims of the present project will seek to extend the application of PLIF to horizontal gas-liquid flows, in order to provide the required quantitative high-resolution data concerning the spatiotemporal distribution of the two phases.

2.3.1.2 PIV

PIV can provide the instantaneous local velocity fields necessary for the determination of the velocity profiles, near wall/interfacial shear stresses, the Reynolds stresses and the turbulent intensities (Ibarra, 2017). Detailed reviews on different PIV techniques can be found in Adrian (1991), Hassan et al. (1992), Westerweel (1997) and Jensen (2004).

Among the first to apply PIV in multiphase flows was Hassan et al. (1992), who obtained simultaneous 2D velocity measurements of both the gas and liquid phases for channel flows. Through these measurements, they were able to delineate the liquid streamlines and vorticity fields. Chen and Fan (1992) applied PIV for the case of a gas-liquid-solid fluidization system, where the instantaneous full field properties of the velocity components were determined. More recent work was carried out by Zadrazil et al. (2014) who obtained the velocity information of liquid films in downwards co-current gas-liquid annular flows; and by André and Bardet (2014), who simultaneously resolved 2D velocity fields on both sides of a disturbed gas-liquid stratified flow interface. The latter was performed to measure the interfacial shear stress within a rectangular channel.

For the specific case of gas-liquid stratified pipe flows, the relevant studies employing PIV are somewhat limited from the available literature. Nevertheless, they are more common than for stratified liquid-liquid flow case and are summarised in Table 2.3. A detailed discussion of these studies is presented in the following subsection. Beforehand, it is convenient to provide a perspective of the underlying principles of PIV, its advantages, limitations and practical considerations of the setup.

Working principle

In PIV, a laser light source is used to illuminate a flow traced with ‘seeding particles’, which are assumed to accurately follow the motion of the fluid. These seeding particles must be present to ensure light is re-emitted by either one of the phases. Since the scattered light can be captured using a high-speed camera, velocity measurements can be obtained using successive instantaneous images of particles, within a defined window and known time interval. To track the mean displacement of the particles between two images, a cross-correlation function can be used and is the most common statistical approach (Voulgaropoulos, 2017). The two-dimensional cross-correlation calculation between the first image I_1 and the second image I_2 is expressible in the following form:

$$\mathcal{R}_{I_1, I_2}(\Delta \mathbf{X}) = \int_{\mathcal{W}} I_1(\mathbf{X}) I_2(\mathbf{X} + \Delta \mathbf{X}) d\mathbf{X}, \quad (2.116)$$

where $\mathcal{R}$ is the cross-correlation function; $\Delta \mathbf{X}$ is the displacement vector in the two-dimensional plane of measurement (r, z) ; and $\mathcal{W}$ is the size of the interrogation window.

Referring to equation (2.116), the most probable particle displacement is given by the maximum peak of $\mathcal{R}$ in the two-dimensional plane of measurement $\mathbf{X} = (r, z)$. An important point to consider is the size of the interrogation window $\mathcal{W}$, which the spatial resolution of the velocity vector field depends so strongly on. High spatial resolution is facilitated through a relatively small interrogation window; however, a sufficient number of seeding particles must exist within each window to attain accurate velocity vectors. For larger interrogation windows, the velocity gradients are non-extractible since the magnitude and direction of the final vector is averaged over all particles within each window (Ibarra, 2017).

Advantages

PIV shares an advantage with LDA in being, to a large degree, a non-intrusive measurement technique, where the appropriate selection of tracers generally causes negligible interference to the fluid flow (Melling, 1997). However, in contrast to single point LDA measurements, PIV represents an instantaneous, whole field measurement technique, allowing the detection of the spatial flow structure and a direct indication of the interface coupling (Kumara et al., 2010). This not only helps improve the fundamental understanding of the physics of the flow, but it can also help develop existing numerical models (e.g. Biberg, 2007), which rely on the provision of accurate empirical parameters. PIV measurements can also facilitate the capture transient effects, removing the uncertainty of flow changes occurring between each measurement point. Furthermore, the velocity is measured through the fundamental parameters of distance and time,

without the need to take any indirect parametric routes to obtain the desired information (Vestol and Melaaen, 2007).

Limitations

PIV is considered as a spatial averaging diagnostic technique, where the velocity vectors are based on the average movement of all tracer particles within a defined interrogation window. The spatial averaging approach introduces some drawbacks. For example, the fluctuations in the average velocity of all particles differ from the fluctuations of individual particles. However, it is worth noting that both PIV and LDA have limits in spatial resolution (one technique necessarily superior to the other), with both relying on the appropriate use of seeding particles.

Since PIV measures the velocity specifically in the bulk of the phases and not at the interface, limited resolution can exist for the measurement of the interfacial velocity. In addition, the interrogation regions for vectors in the vicinity of the interface are not at consistent distances from the interface itself (André and Bardet, 2014).

Furthermore, PIV depends on the dynamic range of the flow within pipes, which makes it difficult to resolve the velocities in both the areas of high-velocity gradients (in the middle of the phase) and low-velocity gradients (near the wall).

Practical considerations

Although the fundamental concept of PIV is relatively simplistic; there are various factors that need to be considered to achieve rapid, reliable and accurate measurements. Firstly, the application of laser-based diagnostics in a multiphase pipe requires one to consider the distortion of the acquired images, which may occur due to differences in the refractive indices of the system (i.e. the fluids and pipe). Figure 2.18 illustrates an example of a non-matched refractive index system,

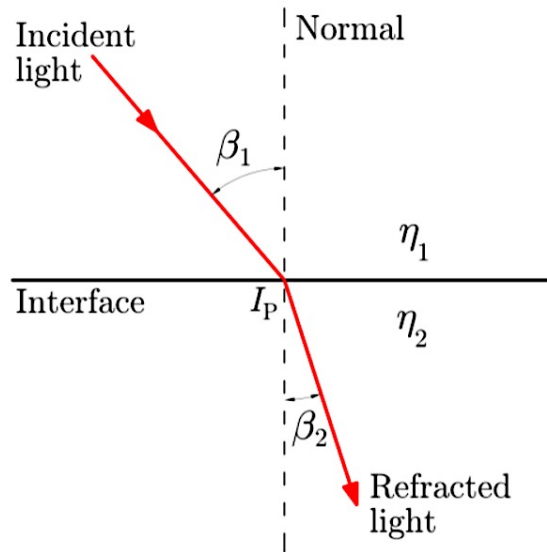


Figure 2.18: An illustration of Snell's law in a non-matched refractive index system (adapted from Ibarra, 2017). The normal of the incidence point, I_P .

where the refraction of laser light as it passes through the interface is interpreted by Snell's law, given by equation (2.117).

$$\eta_1 \cdot \sin\beta_1 = \eta_2 \cdot \sin\beta_2, \quad (2.117)$$

where η_1 and η_2 is the refractive index of phase 1 and phase 2, respectively; β_1 is the angle of incidence and β_2 is the angle of refraction.

Within liquid-liquid flows and liquid-solid flows, it is possible to match the refractive indices through the judicious selection of materials and fluids, and by carefully regulating their temperature and/or composition. Unfortunately, the selection of these fluids contains properties that are different to those encountered in industrial applications. Table 2.2 summarises the typical physical property ranges found in industrial light oils.

Table 2.2: Typical physical properties of industrial light oils.

Property	Range
Density ρ ($\frac{kg}{m^3}$)	810-830
Interfacial tension γ ($\frac{mN}{m}$)	35-45
Viscosity μ ($mPa \cdot s$)	3-12

Conan et al. (2007) used heptane and a glycerol solution (50% vol.) to match the refractive index of the test fluids in a 0.05m diameter horizontal acrylic pipe, where PIV was implemented to extract velocity and shear information near the wall and interface. Morgan et al. (2013) applied PIV and matched the refractive indices using Exxsol D80 and 81.7% wt. glycerol solution as the test fluids. Since the refractive indices were matched, they were able to obtain simultaneous flow information of both phases using a single laser sheet (this method is illustrated by 'Approach 1', in Figure 2.19).

In the PIV experiments of Kumara et al. (2010), the refractive indices of the test fluids were not matched when attempting to characterise oil-water flow structures in a 0.056m diameter stainless steel pipe. Due to the refraction of the laser light at the liquid-liquid interface, accurate information was therefore only accessible for one phase at a time i.e. by illuminating the flow with the laser light sheet from the top to the bottom of the pipe (for the oil phase), then bottom to top (for the water phase); thus, eliminating the possibility of obtaining simultaneous measurements ('Approach 2' in Figure 2.19)

For gas-liquid systems, any attempt at matching the refractive indices of the two phases fails, because of their considerable difference in the visible spectrum and low absorbance (André and Bardet, 2014). At X-ray and gamma-ray wavelengths, both water and gases have a refractive index close to unity; however, the implementation is much too complex and expensive for a practical set-up. Again, the difference in the refractive indices prevents a simultaneous measurement of both phases. Nevertheless, it can be overcome through the implementation of a secondary laser light sheet of a different wavelength, to provide an independent illumination source from both sides of the interface. In gas-liquid flows, this PIV technique has recently been

applied by Belden and Techet (2011), who used this configuration to obtain simultaneous quantitative flow measurements of the air-water interface for breaking waves (‘Approach 3’ in Figure 2.19). Although it is not possible to match the refractive indices of two phases within gas-liquid flows, one can still match the test fluid with the pipe material to minimise the refraction of light at the liquid-wall interface, which would simplify the laser system setup and processing of images. In addition, the use of a calibration target (i.e. a graticule) can be inserted into the test pipe.

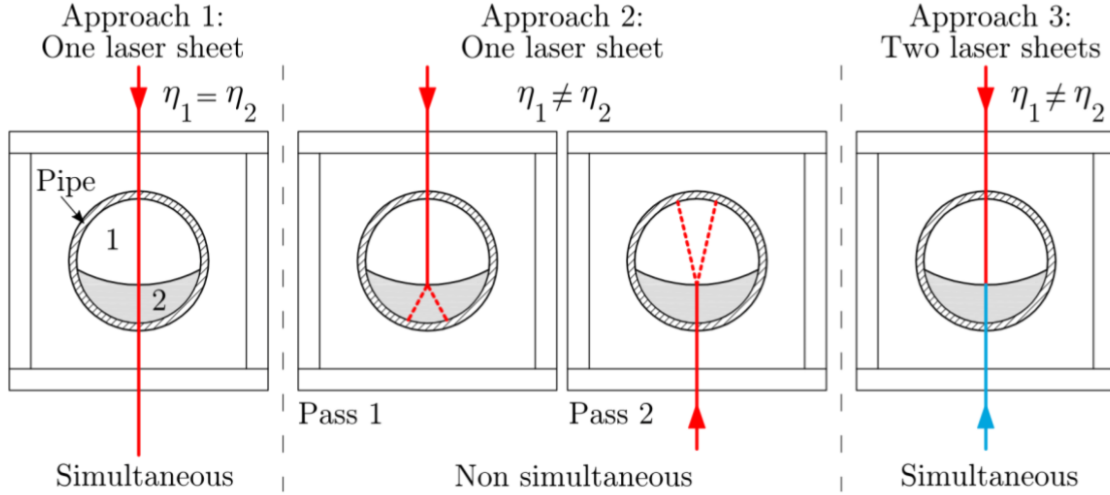


Figure 2.19: Three different approaches for the implementation of PLIF and PIV in two-phase pipe flow systems (Ibarra, 2017). Simultaneous measurements are possible for a fully refractive index matched system (Approach 1) or through the implementation of a secondary laser sheet (Approach 3).

To minimise optical distortions, two other methods may be applied within pipe systems, aside from the matching of refractive indices (Steenbergen, 1996). The first is by reducing the thickness of the pipe wall. However, this method is constrained by various factors including the pipe material, the maximum pressure inside the pipe, the optical quality of the pipe and the manufacturing process. The second method involves the installation of a correction box with flat surfaces filled with one of the test fluids (that ideally, matches the refractive index of the pipe).

In PIV, one should notice that it is not the velocity of the actual flow measured, but rather, the velocity of the particles suspended in the flow. Therefore, the seeding particles can be considered to act as the velocity probes and are an important consideration to the PIV setup. Seeding particles must be small enough to accurately trace the flow, but large enough to scatter sufficient light for camera detection. In addition, the particles should be homogeneously dispersed, neutrally buoyant, non-toxic, non-abrasive, non-volatile and chemically inert (Ayati et al., 2014). Ideally, their presence should also cause negligible interference to the flow field. Furthermore, the selection of the fluorescent dye used for the seeding particles must account for the absorption and emission spectra. To maximise the emission of light from the seeded particles, the laser light wavelength should closely match the absorption peak of the fluorescent dye.

Imaging considerations are also important to the PIV setup. If the spanwise surface slope of stratified flow is close enough to zero, both phases can be captured from the side with a single camera (Techet and McDonald, 2005). However, precisely resolving the near-surface velocity and surface profile is not possible due to the meniscus near the wall. Hence, one cannot optically access the gas-liquid interface using a horizontally placed camera (Sanchis and Jensen, 2011). André and Bardet (2014) note that this problem may be overcome through the use of two cameras, imaging each phase at an angle with respect to the optical axis, allowing the actual free surface and the near-wall meniscus to appear at distinct locations in the image. An example of this setup is illustrated in Figure 2.20.

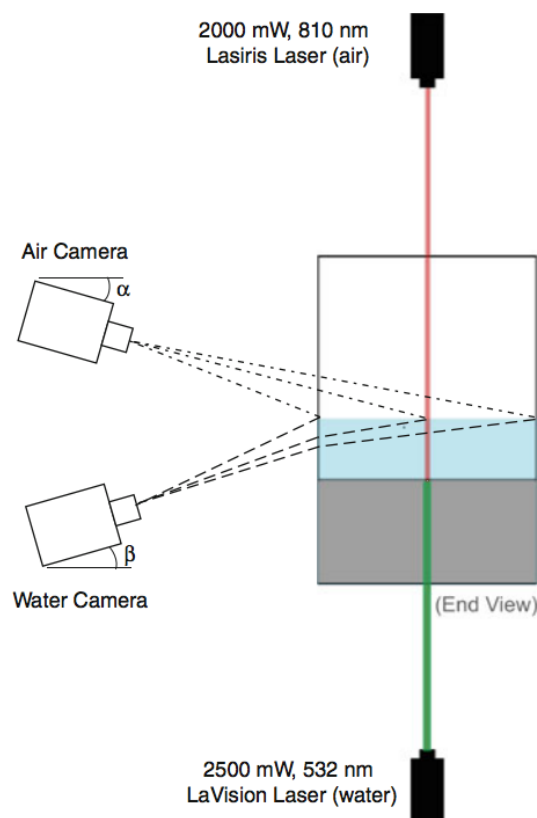


Figure 2.20: Schematic of an angled camera PIV setup used by Belden and Techet (2011) for two-phase air-water flows.

2.3.2 PIV studies in gas-liquid stratified pipe flows

Table 2.3 provides a summary of all previous PIV studies applied in gas-liquid horizontal stratified flows. In the following part of the review, the experimental setup used in each of these works is initially outlined, followed by a discussion and critique of the most important results obtained regarding the instantaneous velocity and turbulence measurements. Where possible, certain gaps within these works are also disclosed, setting the framework for the novelty element of the present project.

LITERATURE REVIEW

Table 2.3: Summary of previous experimental studies employing PIV in gas-liquid stratified pipe flows

Authors	Test fluids	Pipe diameter	Pipe length	Pipe material	Phases measured	Location of measurement	Seeding method
Vestol and Melaaen (2007); Vestol et al. (2017)	Air-water Exxsol D60 oil-water	56 mm	14 m, 15 m	Stainless steel	Both gas and liquid.	Pipe centre in a vertical plane	Liquid phase seeded with solid polyamide tracer particles; $\overline{d_p} = 20 \mu m$ Gas phase seeded with oil droplets; $\overline{d_p} = 2 \mu m$
Birvalski et al. (2014, 2015, 2016)	Air-water	50 mm	10.3 m	PMMA	Liquid only	Pipe centre in a vertical plane	Liquid phase seeded with Lefranc & Bourgeois FlasheVinyl, Fluorescent Light Orange Colour; $\overline{d_p} = 5\text{-}20 \mu m$
Ayati et al. (2014, 2015, 2016)	Air-water	100 mm	31 m	PVC	Both gas and liquid	260D downstream from pipe inlet and 50D upstream from pipe outlet in a vertical plane	Liquid phase seeded with commercial polyamide particles from Dantec Dynamics; $\overline{d_p} = 50 \mu m$ Gas-phase seeded using small water droplets; $\overline{d_p} = 6 \mu m$

2.3.2.1 Vestol and Melaaen (2007); Vestol et al. (2017)

The first to apply PIV to gas-liquid stratified pipe flows were Vestol and Melaaen (2007), who measured the local velocity and turbulence profiles in a 14m long stainless steel horizontal pipe, with a 56 mm internal diameter, using air and water as the test fluids. A range of pipe inclinations (-5° to $+5^\circ$), mixture velocities ($5.0 - 15 \text{ m/s}$) and liquid fractions ($0.00010 - 0.0010$) were investigated in their experiments. Polyamide particles were used to seed the liquid phase whilst oil droplets were used to seed the gas phase, using average particle diameters of $20\mu\text{m}$ and $2\mu\text{m}$, respectively. All PIV measurements were performed in the vertical plane at the pipe centre. The authors reported difficulties in maintaining valid measurements in the liquid phase due to optical disturbances from the wavy interface and in some flows, the liquid film was too narrow to obtain accurate velocity profiles. For stratified wavy flows with entrainment (Figure 2.21) and flows in the transition region (Figure 2.22), liquid droplets and/or a liquid film covered the pipe wall and restricted the view in the gas phase. Consequently, the flow was optically inaccessible and measurements were not possible (one should keep in mind that accurate PIV cannot be performed for more than 1-2% dispersed phase fractions) In addition, turbulence measurements in the gas phase failed due to the small size of air droplets used as tracer particles.

In the liquid phase, the axial velocity profiles were S-shaped, displaying larger gradients near the wall and interface compared to the midsection. Axial turbulent fluctuations and their gradients also appeared to be largest near the wall and interfacial areas, but lowest in the middle of the liquid phase. Furthermore, increasing liquid fractions and increasing downward pipe inclinations was seen to increase the liquid velocity (although it was still negligible compared to the gas phase velocity) and increase the level of axial turbulent fluctuations. For the gas phase, the axial velocity profiles were similar to what is expected for single phase flows, with larger gradients seen near the interface and wall compared to the midsection. However, the profiles were relatively unsymmetrical with the maximum axial velocity value shifting closer to the upper wall of the pipe, due to the presence of the liquid phase. Increasing downward pipe inclinations resulted in a thinner liquid layer, increasing the area for gas to flow, decreasing the velocity. Increasing the liquid fraction caused the reverse effect, increasing the gas velocity.

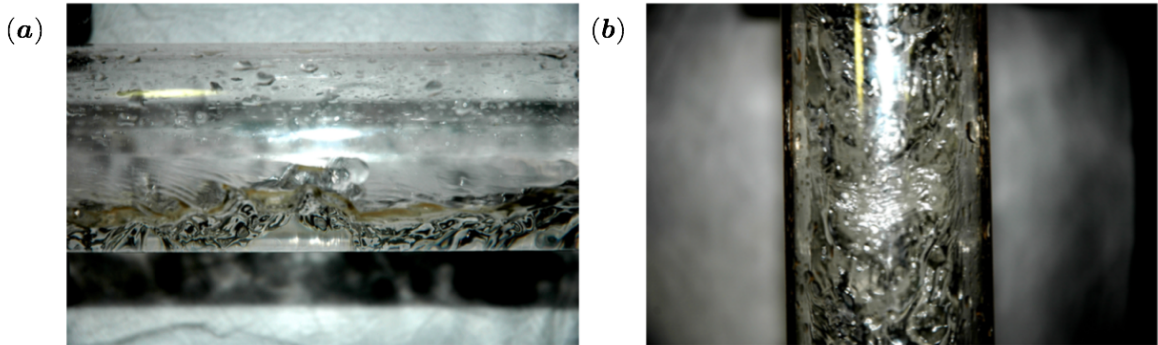


Figure 2.21: Side view (a) and top view (b) images of the stratified wavy flow pattern with entrainment (Vestol and Melaaen, 2007).

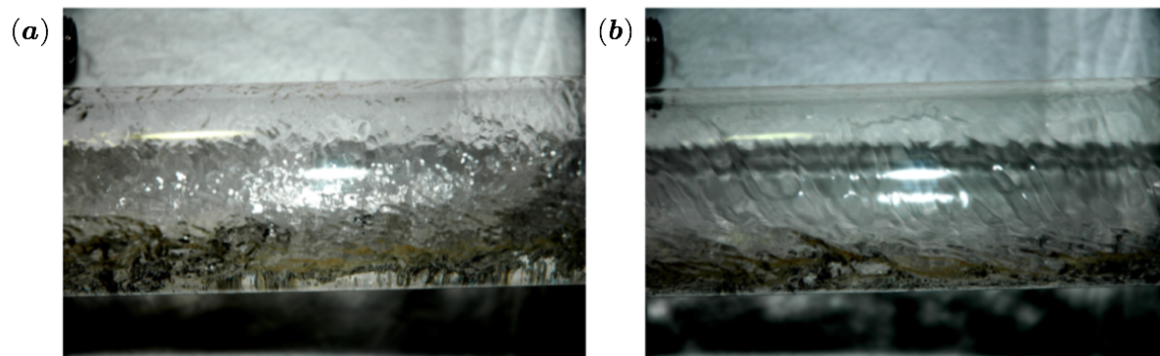


Figure 2.22: Side view images of the transition flow regime. The pipe section from (a) is partly covered with liquid droplets and partly covered by a liquid film whilst (b) shows a pipe fully covered by a continuous liquid film (Vestol and Melaaen, 2007).

To date, the latest PIV study that has been applied in gas-liquid stratified pipe flows is that of Vestol et al. (2017), who produced detailed velocity and turbulence profile measurements for both the gas and liquid phases. The position of the interface was also measured using single beam gamma densitometry. Their experiments were now performed in a 15 m long, 56 mm in diameter stainless steel pipe, using Exxsol D60 oil, water, and air as the test fluids. Their measurements were performed using a fixed mixture velocity (defined as the sum of the gas and liquid flow rates divided by the area) of 5 m/s, with the same range of liquid fractions (0.00010 – 0.0010) and pipe inclinations (-5° to $+5^\circ$) as their previous study. An identical seeding method was also used. The experimental setup is illustrated in Figure 2.23.

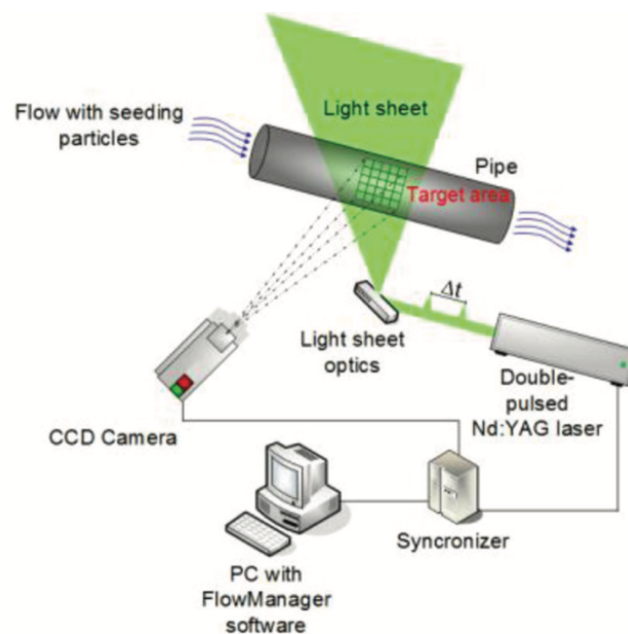


Figure 2.23: PIV experimental setup used by Vestol et al. (2018)

The results gas and liquid phase results were very similar to their previous results for air-water flows, regarding the shape of the velocity and turbulent profiles seen; as well as the effect

of the increasing liquid fractions and increasing downward pipe inclinations. However, their results were now to include gas-phase turbulence measurements (which failed in their preceding paper). As expected, significantly higher turbulence occurred in the gas phase compared to the liquid phase, with the axial turbulent fluctuations being highest near wall and interface, but lowest in middle of the phase. In addition, an increase in the liquid fraction caused the gas-phase axial turbulent fluctuations to be comparatively much larger at the interface than at the wall. A summary of the general results obtained for air-water flows from both papers is provided in Table 2.4.

Table 2.4: Summary table of the general gas and liquid phase results obtained by Vestol and Melaaen (2007) and Vestol et al. (2017), applicable for air-water stratified flows.

Phase	Axial velocity profile	Axial turbulent profile	Effect of increasing liquid fractions	Effect of increasing downward pipe inclinations
Liquid	Gradients largest near the wall and interface, lowest in the middle of the phase	Gradients largest near the wall and interface, lowest in the middle of the phase	Liquid velocity and turbulent fluctuations increase.	Liquid velocity and turbulent fluctuations increase.
Gas	Gradients largest near the wall and interface, lowest in the middle of the phase	Gradients largest near the wall and interface, lowest in the middle of the phase	Gas velocity and turbulent fluctuations increase.	Gas velocity and turbulent fluctuations decrease.

Along with their newly founded gas-phase results for air-water flows, both gas and liquid phase results were presented for oil-air flows. The liquid film for the oil (Exxsol D60) was slightly thinner than for water, causing the gas velocities to be lower and liquid velocities to be higher for the air-oil case. For air-oil flows, the shape of the velocity and axial turbulent profiles for both phases were very similar to the corresponding air-water case results outlined in Table 2.4.

2.3.2.2 Birvalski et al. (2014, 2015, 2016)

Birvalski et al. (2014) studied air-water flows in a horizontal PMMA pipe, with an internal diameter of 50 mm and a length of 10.3 m. The overall aim was to obtain detailed velocity measurements and wave characteristics of the liquid layer. The authors used planar PIV combined with a profile detection technique to measure the velocity field below the moving interface, where a phase averaging procedure (based on the wave phase) was applied to decompose the velocity field into three components: time-averaged velocity, wave-induced fluctuations, and turbulence induced fluctuations. Detailed interfacial information was also presented using data obtained for the instantaneous interface position.

For their setup, the use of a correction box filled with water (covering roughly a quarter of the pipe circumference) was fixed to the test section to correct optical distortions. The liquid phase was seeded with fluorescent light orange particles, with average particle diameters ranging from 5-20 μm . Two cameras were implemented to view the centre plane of the pipe, below and above the interface. The camera positioned below the test section pointed upwards at an angle of 16° to record the seeding particles, whilst the camera positioned above the test section pointed downwards at an angle 7.3° to record the position of the interface (Figure 2.24).

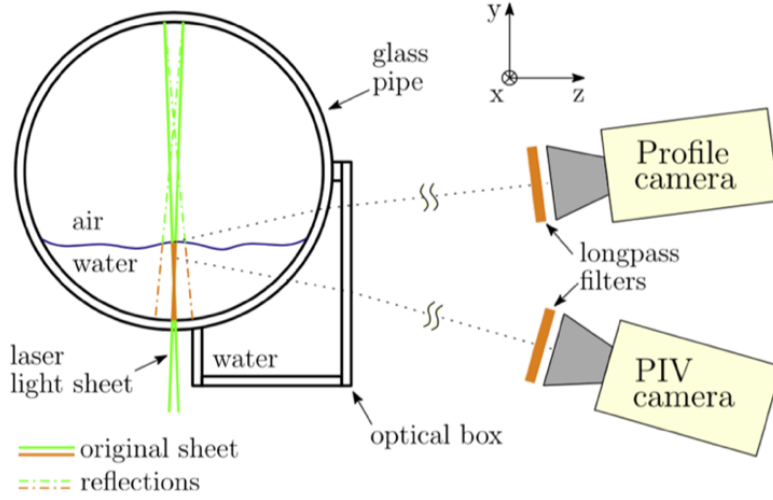


Figure 2.24: Schematic view of the test section used by Birvalski et al. (2014).

Their results were collected through a combination of 8 different air and water flow rates, split into stratified-smooth (A-D) and stratified-wavy cases (E-H). Each case was designated in accordance with the demarcations set out in the flow map of Barnea et al. (1982), as shown in Figure 2.25.

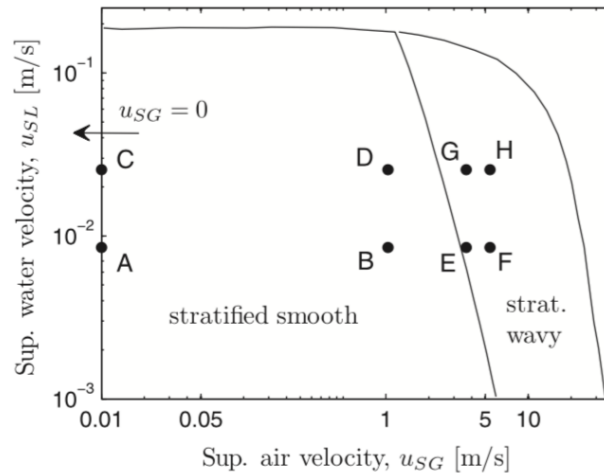


Figure 2.25: Flow map of Barnea et al. (1982) for air-water flow in a 51 mm diameter horizontal pipe. The measurement points (A-H) of Birvalski et al. (2014) are overlaid.

Referring to Figure 2.25, let us first summarise the noteworthy results obtained for the stratified smooth cases (A-D). Cases A and B in the stratified smooth zone were both laminar, displaying almost parabolic axial velocity profiles and negligible radial velocity values. For both cases, the total stresses linearly decreased as a function of the scaled liquid height ($\frac{y}{h_L}$), with case A having zero shear stress at the interface ($\frac{y}{h_L} = 1$), compared to case B with a non-zero interfacial shear stress (as air shears the liquid phase). Transitional case C was composed of fluctuating laminar and turbulent patches, where the interface height decreased and then sharply increased with the onset of turbulence. Case D was representative of fully turbulent non-wavy flow, where the turbulent contribution formed the major part of the total stress, which also decreased as a function of the scaled liquid height. Again, a non-zero value was measured at the interface, due to the air flowing above the liquid layer. Furthermore, the obtained Reynolds stresses (axial, radial and shear) for case D compared well with single phase pipe flow experiments performed by Eggels et al. (1994), especially in the near wall region, with expected deviations near the interface.

For the stratified-wavy cases (E-H), an interfacial profile analysis was first performed. All waves were asymmetric, containing troughs steeper than crests, which are characteristic features of capillary waves (McCormick, 2010). However, the turbulent cases were observed to be more symmetric, each closely resembling a sinusoidal profile. In addition, the measured wavelengths were well predicted by the linear wave theory and classified as capillary-gravity waves. A velocity analysis was then performed for all wavy cases, in a Eulerian coordinate system using a phase averaging procedure. The wave-induced fluctuations for the laminar cases were non-existent at the wall but reached a peak at the interface where wave-induced motion was most dominant. However, for the turbulent cases, wave-induced fluctuations existed both at the interface and near the wall. In addition, the aforementioned asymmetry in the wave profile resulted in asymmetric wave-induced velocities i.e. the velocity magnitude was seen to be larger below the trough than under the crest. Moreover, turbulent fluctuations were presented from the applied velocity decomposition. The two areas of highest fluctuation intensity occurred near the wall and below the interface, agreeing with the claims made by Vestol and Melaaen (2007), who through their cautions, were seemingly unsettled with their turbulence results. Close to the wall, axial turbulent fluctuations were also seen to be independent of the wave phase, suggesting the presence of waves do not influence the properties of turbulence.

Birvalski et al. (2015) used PIV to investigate the laminar-turbulent transition and wave-turbulence interaction in stratified gas-liquid pipe flow in the liquid phase only. Overall, the presence of waves was seen to increase the Reynolds numbers at the end of the laminar-turbulent transition. At the same time, the transition to turbulence caused the waves to transfer from 2D small-amplitude (capillary-gravity) waves to 3D small amplitude (gravity-capillary) waves.

Birvalski et al. (2016) carried out an experimental study with the objective of investigating the interfacial characteristics and velocities of both the gas and liquid phases for two distinct stratified flow subregimes: ‘3D small amplitude (SA)’ and ‘2D large amplitude (LA)’ waves. Compared to their previous study, they extended their optical measurements with a second PIV system (Figure 2.26), to measure the velocity field of both phases simultaneously. To the best of the author’s knowledge, this study presented the first valid attempt to obtain simultaneous PIV measurements in the flow of air and water, using two laser light sheets.

The 3D SA waves were characterised by a relatively short wavelength and low amplitude waves, with the wave steepness (calculated as the wave height divided by the wavelength) increasing significantly with increasing gas velocities. On the other hand, the 2D LA waves had longer wavelengths and higher amplitudes, but the wave steepness remained relatively constant with increasing liquid velocities. The 3D SA waves were classified as capillary-gravity waves, whilst the 2D LA waves were classified as gravity waves.

Differences between 3D SA and 2D LA waves were also observed in the results obtained for the time and phase-averaged liquid velocities. Overall, the 3D SA wave pattern experienced linear velocity profiles near the wall (in the laminar sublayer) and transitioned into the classical log-law at large enough values of the liquid height (in the bulk). This contrasted with what was seen for 2D LA waves, where all cases deviated from the log-law at all heights at which the log law is valid. Instead, a nearly flat velocity profile occurred near the bulk region, which was reasoned to the strong mixing of momentum caused by the characteristically high and long dimensions of 2D LA waves.

In contrast to the liquid phase, the gas phase velocities did not show a substantial difference between the two stratified flow subregimes. The only exception was the shape of the gas velocity profiles, which was relatively symmetric for 3D SA waves, but asymmetric for 2D LA waves, with the maximum axial velocity value shifting closer to the upper wall of the pipe. Both wave patterns enhanced the turbulent fluctuations in the near-interface region, with the fluctuations becoming higher with an increase in the wave height or wave steepness.

As part of their conclusions, the authors arrived at an important recommendation for future studies aiming to model the velocity profiles and the resulting shear stresses. Since the phases (i.e. their velocities and shear stresses) were coupled to the interfacial conditions, any future studies must consider the flow in the entire cross-section of the pipe (and ideally also in the third direction).

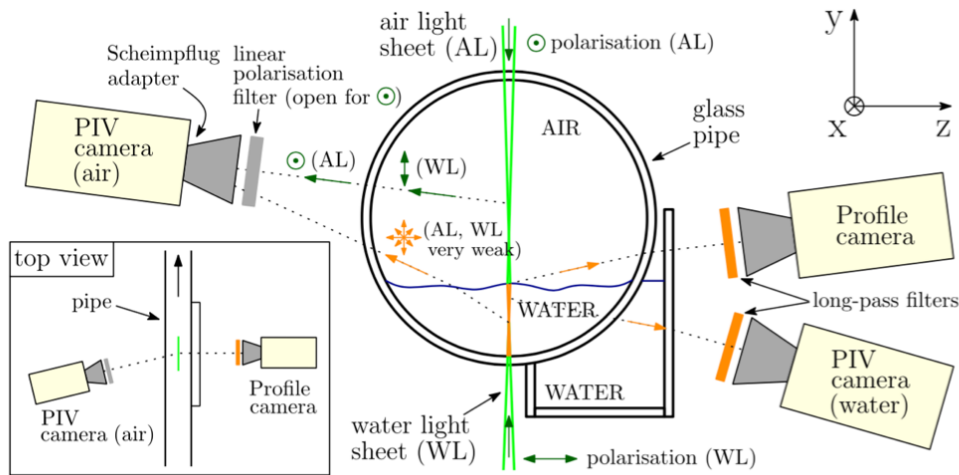


Figure 2.26: Schematic view of the test section used by Birvalski et al. (2016).

2.3.2.3 Ayati et al. (2014, 2015, 2016)

Ayati et al. (2014) performed simultaneous PIV measurements of stratified turbulent air-water flow in a 31 m long, 100 mm in diameter PVC pipe, to provide information on the velocity and turbulence of both the gas and liquid phases.

The authors claimed novelty through their gas phase seeding approach, using small water droplets as the tracer particles with average diameters of $6\mu\text{m}$. The liquid phase was seeded using commercial polyamide particles with $\overline{d_p} = 50\mu\text{m}$. The PIV measurements were performed in a vertical plane located $260D$ downstream from the pipe inlet and $50D$ upstream from the pipe outlet (Figure 2.27). To map both phases including the interface, two cameras were positioned 15cm above and below the pipe centreline, pointing at 15° upward and downward angles. Their main results were presented through a qualitative comparison between two stratified flow cases based on the interfacial pattern: (1) the smooth/flat interface and (2) the wavy interface.

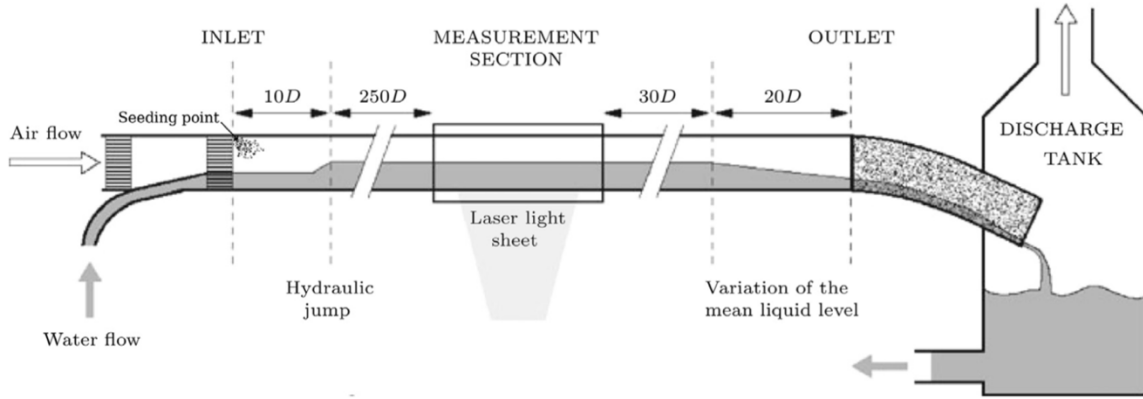


Figure 2.27: Experimental PIV setup of Ayati et al. (2014).

For the stratified smooth case, the mean velocity profile in the liquid layer was deemed to resemble an S-shaped turbulent Couette profile, where the velocity gradient is highest near the wall and interface but lowest in the middle of the phase. Here, the interface was considered to act like a moving wall and the bottom wall as a stagnant wall. Corresponding to the behavior of turbulent Couette flow (as described by Bech et al., 1995), the highest axial turbulent fluctuations occurred near the wall, linearly decreased within the main flow region and increased again near the interface. In the gas phase, the mean velocity profile was characterized by turbulent Poiseuille flow, where the gas-liquid interface was also perceived by the analogy of a slowly moving wall. Here, an almost symmetrical time-averaged velocity profile was observed. In addition, the axial turbulent profile presented a considerably higher peak near the wall than the near the interface. An analysis of the instantaneous profiles also indicated that relatively steady flow conditions existed for all smooth cases.

The second interfacial pattern concerning the stratified wavy case caused a redistribution of the mean velocity profile in the liquid layer. An increase in the mean velocity occurred in the lower region of the liquid layer, whilst a decrease occurred in the upper region (up until the wave crest), straightening the shape of the velocity profile. Throughout the liquid layer, a considerable

increase in the axial turbulent fluctuations was evident, especially in the region close to the wall. For the gas phase, the mean velocity profiles for the wavy cases were no longer symmetric, lowering in magnitude in the boundary region close to the interface. At the same time, the lower (interfacial) axial turbulent fluctuation peak appears larger than the upper (wall) peak. The authors attribute this to the analogy where the gas phase perceives the interface to act as a rough wall, where the additional local roughness of the interface enhances turbulent activity in the vicinity of that region (see Lakehal et al. (2003), Berthelsen and Ytrehus (2005), Biberg (2007) etc.).

In subsequent work, Ayati et al. (2015) performed simultaneous two-phase PIV measurements to provide instantaneous velocity and turbulence measurements, using the same experimental setup in their previous work. If one was to consider the experimental setup used in Birvalski et al. (2016), illustrated in Figure 2.26, where two laser light sheets were applied, it is easy to understand how simultaneous results could have been extracted. However, such a setup did not exist in either works of Ayati et al. (2014, 2015); therefore, it remains unclear why ‘simultaneous’ measurements were claimed by the authors.

Generally, a replica of their previous results (from Ayati et al., 2014) for the mean velocity profile and axial turbulent fluctuations were obtained. However, compared to their preceding paper, their findings were upgraded to include information on the vertical (radial) fluctuations and the Reynold stresses. The collection of results obtained from both papers is summarised in Table 2.5.

Table 2.5: Summary of the general liquid and gas-phase velocity and turbulence results of Ayati et al. (2014, 2015), for stratified smooth vs. wavy cases.

Measurements	Stratified-smooth (liquid)	Stratified-wavy (liquid)	Stratified-smooth (gas)	Stratified-wavy (gas)
Mean axial velocity profile	‘S’ shaped Turbulent Couette	S-shaped profile straightens	Relatively symmetric resembling Turbulent Poiseuille profile	Lowers in magnitude close to the interface
Intensity of axial turbulence	Largest near the wall and interface, lowest in the middle of the phase	Increases throughout the liquid layer (especially near the wall)	Higher peak near the wall than near the interface.	Higher peak near the interface than near the wall.
Radial turbulent fluctuations	Zero at the interface	Increases near the interface	Zero at the interface	Increases near the interface.
Reynold stresses	Little variation below and above the interface.	More variation occurs than for smooth flow	Little variation below and above the interface	More variation occurs than for smooth flow

For the smooth case, the vertical fluctuations in both the gas and liquid layers decayed to zero towards the interface, and little variation occurred in the Reynold stresses in the region slightly above and below the interface. However, in wavy flows, the dynamic interfacial boundary condition allowed the vertical fluctuations in the liquid layer to grow significantly towards the interface. A higher vertical fluctuation near the interface also occurred in the gas-phase due to the presence of waves. Furthermore, for both phases, in the regions close to the interface, more variation in the Reynold stresses was seen to occur when fully developed 2D waves were present.

Ayati et al. (2016) extended their work to explore the effect of interfacial waves on the turbulence structure of stratified air/water pipe flow. The velocity field was measured using PIV and vortical structures were visualised by applying the swirling strength method. The intensity, size and frequency of waves were shown to be strongly dependent on the two-phase flow rate combination and their presence were shown to influence the level of turbulent activity. Overall, an increase in the gas flow rate resulted in a stronger presence of waves, increasing the level of turbulence i.e. larger eddy populations.

2.3.3 Summary

In this section of the review, the relevant spatiotemporal laser-based techniques applicable to the present project were first discussed, where PIV was presented in terms of its working principle, the advantages/disadvantages over other techniques (e.g. LDA), and the practical considerations relevant to the setup. The latter represented an important part of the review, where the refractive index, imaging and seeding considerations were identified to be some of the most crucial implementation factors for the present work. To facilitate the required simultaneous PIV measurement of both the gas and liquid phases, it was clear that a two-line laser system must be used. To the best of the author's knowledge, the work of Birvalski et al. (2016) presents the only previous attempt to implement such a setup, for the specific case of gas-liquid stratified pipe flow.

Having provided a perspective of PIV, the relevant studies were then discussed in depth, in terms experimental setups used and the results extracted for gas-liquid stratified pipe flows. Generally, the velocity and turbulence measurements from the considered papers harmonised well with one another, providing a good benchmark to experimentally validate some of the results that will be obtained for the present study. These measurements have been studied as functions of varying liquid fractions and pipe inclinations (e.g. Vestol and Melaaen, 2007; Vestol et al., 2017), or upon transition from smooth to wavy flow (e.g. Birvalski et al., 2014; Ayati et al., 2014, Ayati et al., 2015).

2.4 CFD

Within the realms of mathematical modelling, the use Computational Fluid Dynamics (CFD) presents another method to solve and analyse fluid flow problems. In CFD calculations, a set of governing partial differential equations, along with the appropriate boundary conditions is discretised onto a 2D or 3D grid, and the resulting equations are solved using numerical methods.

Recent advances in the numerical solution of the Navier-Stokes equations and the capabilities of high-speed computers have resulted in a substantial focus on the application of CFD in two-phase flow problems. Indeed, this application has sparked a growing interest in the oil and gas industry in recent years, with some researchers considering CFD to be the most sophisticated modelling technique.

To predict the transport phenomena in steady and transient stratified flows, a variety of commercial codes e.g. OLGA, PLAC, TACITE and non-commercial codes e.g. PRESBAL TRIOMPH are available. These are mostly one-dimensional in nature, applying the two-fluid model to solve separate mass, momentum, and energy conservation equations for each phase, along with the suitable closure relations for the wall and interfacial shear stresses.

In the following section of the review, a brief outline of the common modelling approaches is presented, before a discussion and summary of all previous numerical gas-liquid stratified flow studies within the available literature.

2.4.1 Modelling approaches

Generally, there are two main approaches to modelling multiphase flow: the Euler-Euler approach and the Euler-Lagrange approach. In the former, both phases are treated as continuous, and in the latter, one phase is treated as continuous and the other as discrete.

Under the Euler-Euler approach, three models can be classified. These are briefly summarised herein:

- **Volume of Fluid (VOF)** - In the VOF model, a single set of governing equations are solved for the mixture. It has been developed with the aim of capturing and tracking the interface between two or more immiscible fluids. To facilitate this, an additional equation is numerically solved for the secondary phase and is responsible for the interface tracking. The VOF method is advantageous in being relatively simple to implement, mass conserving, numerically stable and computationally economic. Hence, it is among the most widely used approaches.
- **Mixture** - More complexity is introduced within this model as the two fluids can be interpenetrating (Ambrose, 2015). A single set of governing equations are still used for the mixture, but the phases do not necessarily have the same velocities and momentum transfer can exist between the phases. The mixture model is also computationally economic and numerically stable.
- **Eulerian multiphase** - The most complex Euler-Euler approach is the Eulerian model. In this model, the governing equations are solved for each phase, and the phases themselves are coupled using interphase transfer coefficients. It is widely regarded as

the most accurate model among Euler-Euler approaches, but it is the most computationally expensive.

In the Euler-Lagrange approach, the governing equations of the flow are solved for the continuous fluid phase whilst the dispersed phase is tracked with a Lagrangian formulation to form its discrete phase trajectories (Taher Ali, 2017). This approach was developed for multiphase flow problems under the assumption that the volume fraction of the dispersed phase occupies no more than 10% of the flow. Thus, the major limitation of the Euler-Lagrange model is its inapplicability at non-negligible volume fractions of the second phase.

2.4.2 Numerical gas–liquid stratified pipe flow studies

Initial works employing CFD techniques to simulate, in particular, stratified turbulent-turbulent gas-liquid flows were restricted mainly to flows inside a rectangular channel (Akai et al., 1981; Issa, 1988; Srichai et al., 1995). Over the last two decades or so, considerable efforts have been made to computationally simulate the more complicated pipe flow geometry of such flows. Early attempts were performed by Shoham and Taitel (1984), who modelled the pipe flow domain in a bipolar coordinate system. Later studies carried out by Issa (1988), Newton and Behnia (2000), Meknassi et al. (2000) and Duan et al. (2014), have since adopted the same approach. Shoham and Taitel (1984) applied an exact solution to their two-dimensional model for the liquid phase only, applying the eddy viscosity theory to model the turbulent viscosity, with the gas phase being treated as bulk flow. Their results were reported for air-water systems in a 25.4 mm internal diameter pipe, showing acceptable agreement with the mechanistic model of Taitel and Dukler (1976).

Issa (1988) applied a more advanced CFD approach for channel and pipe flow cases, solving the two-dimensional momentum equations for both the gas and liquid phases. The effect of turbulence was considered using the $k - \varepsilon$ turbulent model and all calculations were made with the assumption of a smooth interface. The pipe flow results were compared with the model predictions of Taitel and Dukler (1976) and Shoham and Taitel (1984), and the experimental results of Cheremisinoff & Davis (1979), Agrawal et al. (1973), Govier & Omer (1962), Hoogendoorn (1959) and Bergelin & Gazley (1949). Generally, the results presented for the pressure gradient and the liquid holdup showed a good correlation between the data and predictions.

Newton and Behnia (2000) carried out a numerical calculation of the axial pressure gradient, liquid holdup, and the flow and turbulence fields for smooth-stratified gas-liquid pipe flows. The authors extended the work of Issa (1988), using a larger pipe diameter of 50 mm. The phases were coupled through the velocity, and the shear stresses at the interface were assumed equal. A low Reynolds number $k - \varepsilon$ formulation was applied to model the turbulent viscosity. Calculations for the pressure gradient and liquid holdup were compared with the mechanistic model of Taitel and Dukler (1976) and the experimental data of Newton and Behnia (1996), showing reasonable agreements. In addition, the interfacial and wall shear stress profiles were estimated with a higher degree of success than Issa (1998).

Meknassi et al. (2000) numerically modelled the stratified-wavy flow regime in horizontal pipes, where the axial momentum equations were solved for each phase, and the coupling was also achieved through the velocity and interfacial shear stresses. To consider the effect of

turbulence, the classical $k - \varepsilon$ turbulence model was implemented. Numerical gas and liquid velocity profiles showed satisfactory agreement with the experimental profiles of Strand (1993) and Lopez (1994), up until the onset of secondary flows. The concept of interfacial roughness to account for gas-liquid interactions was also validated through their simulations.

Newton and Behnia (2001) developed a numerical model of stratified-wavy gas-liquid pipe flow, extending their previous work performed for stratified-smooth flows. Steady axial momentum equations were solved for both phases, together with a low Reynolds number $k - \varepsilon$ turbulence model for the eddy viscosity. Special boundary conditions were used to account for the interfacial roughness caused by the presence of waves. Predictions for the pressure drop and liquid holdup showed fair agreement with their own experimental data as well as a variety of mechanistic models (Taitel and Dukler, 1976); Andritsos and Hanratty, 1987; Spedding and Hand, 1997). Overall, the model over predicted the pressure drop and under predicted the liquid hold up, with absolute average errors of 20% and 19%, respectively. For flows characterised by unsteady roll waves, the calculated gas and liquid wall shear stresses were overestimated by the numerical model. Flows with steady interfacial conditions were more successful, closely matching those given by the Blasius equations used for single phase flow, as observed by Kowalski (1987).

Gao et al. (2003) performed a numerical study of smooth-stratified oil-water two-phase turbulent flow, using a 55.75 mm internal diameter and 8 m long horizontal tube. A modified VOF model was implemented, and the continuum surface force (CSF) model was used to account for the effect of surface tension. Results for the pressure drop, slip ratio, local phase fraction profile and axial velocity profile were presented, showing reasonable agreement with experimental data from the literature. Through extensive calculations and analysis of the numerical results, a correlation was proposed for the pressure drop, which was represented as a function of the Martinelli parameter (X) and the ratio of superficial velocities. An expression was also proposed for the mean liquid holdup.

Ghorai and Nigam (2006) applied the VOF model and the commercial CFD package FLUENT to investigate the flow profiles and interfacial phenomena in stratified air-water two-phase flow, using a horizontal pipe with an internal diameter of 0.1 m and length of 35 m. Turbulence was modelled using the RNG $k - \varepsilon$ model. The computed pressure drops and numerical velocity profiles showed satisfactory agreement with the experimental results of Strand (1993) and Lopez (1994). A correlation was proposed for the ratio of the interfacial friction factor f_i to the wall friction factor f_w for stratified-wavy flow, which was represented as a function of the gas superficial velocity U_{SG} to the liquid superficial velocity U_{SL} :

$$\frac{f_i}{f_w} = 1.204 \left(\frac{U_{SG}}{U_{SL}} \right)^{0.245}, \quad (2.118)$$

valid in the range of $600 < Re_L < 10000$, and $8000 < Re_G < 87000$. Using the experimental data of the same aforementioned authors, equation (2.118) predicted the interfacial friction factor within an error of $\pm 10\%$.

Lu et al. (2007) carried out numerical simulations using the VOF method, with the aim of characterising flow regime transitions from stratified to slug flow, in the laminar flow regime. Only one-half of the pipe cross section was modelled, with symmetry being assumed about the mid-plane. The authors tested their results against the experiments they performed for oil-gas

flow in a horizontal pipe, using a 1 m long pipe with a 0.125 m internal diameter. Their numerical results seemingly compared well with their own experimental findings, however, the comparisons were all done qualitatively. Namely, this involved testing contours of the predicted phase distributions against photographs taken of the observed flow regimes.

Sidi-Ali and Gatignol (2010) conducted a numerical study to determine the interfacial friction factor in horizontal stratified two-phase flow, simulating the same experimental conditions of Strand (1993). The flow domain comprised the gas-phase passage only (hence only the gas phase was solved for), whilst the liquid layer was considered as a rough moving flat wall. The gas flow was treated as fully turbulent, and the standard $k - \varepsilon$ turbulent model was used to calculate the turbulence viscosity. The axial and radial velocity profiles computed for the gas phase, using their analogy, were highly congruent with the experimental profiles of Strand (1993), even more so than the numerical results of Meknassi et al. (2000). Furthermore, through their approach, two friction factor correlations were derived. The authors concluded that the most valid gas-wall friction factor correlation is that of Taitel and Dukler (1976), given by equation (2.21), and claim that the most accurate interfacial friction factor correlation is their own, given by equation (2.113).

Duan et al. (2014) formulated a numerical model for smooth-stratified gas-liquid flow and heat transfer in a pipeline, adopting a similar modelling approach to Meknassi et al. (2000) and Newton and Behnia (2001). Steady axial momentum equations were solved for each phase, along with a low Reynolds number $k - \varepsilon$ turbulence model for the eddy viscosity. Predictions for the axial pressure drop and the liquid holdup showed reasonable agreement with the experimental results of Espedal (1998) and the mechanistic model of Taitel and Dukler (1976). The gas-phase velocity field compared well with measurements at a position somewhat far from the interface ($\sim 15\%$ of the gas height). However, the velocity field in the liquid phase, along with predictions near the interface was not presented. Thus, it is difficult to evaluate the model's validity of predicting the flow field near the interface, bearing in mind the inherent difficulty of this particular task. Nevertheless, average values for the interfacial shear stress, along with the wall shear stresses compared well with the experimental values of Espedal (1998).

De Schepper et al. (2008) were the first to use the code FLUENT to predict the flow regimes observed in an experimental gas-liquid and vapour-liquid horizontal flow map (the Baker chart). Simulations were performed in a horizontal tube with a diameter of 0.08 m and a length of 7 m, using a 3D computational domain. The authors concluded that all horizontal flow regimes appearing in the Baker chart can be simulated through the VOF model implemented within the CFD code.

Alizadehdakhel et al. (2009) adopted a similar modelling approach to De Schepper et al. (2008), performing CFD simulations as well as experiments in a 2 cm diameter and 6m length tube. As part of the various flow regimes examined, photographs for stratified-wavy flows were presented, showing reasonable qualitative agreement with predicted contour plots of the interface. In addition, the predicted pressure drop compared well to the experimental measurements, despite not including turbulence effects.

Parvereh et al. (2010) numerically and experimentally studied different two-phase flow regimes in horizontal and vertical tubes, using a transparent pipe with a diameter of 2 cm and length of 4 m. The VOF model and the code FLUENT was used to capture the interface of the

stratified-wavy, slug, plug and annular flow regimes. Again, a qualitative validation of the flow regimes was achieved, using experimentally captured photographs obtained from Electrical Resistance Tomography (ERT) measurements. However, no other measurements e.g. the pressure drop were reported.

Kou et al. (2011) used the VOF model and FLUENT code to perform numerical simulations in a horizontal pipe with a diameter of 8 cm a length of 2 cm. In contrast to aforementioned VOF/FLUENT studies, Kou et al. (2011) did account for the effects of turbulence, using the $k - \varepsilon$ turbulence model. No comparisons with experimental data were included in their study. Instead, the validation was limited to the qualitative approach of matching the captured flow regimes with the flow regime map of Mandhane et al. (1974). Thus, the overall reliability of their proposed model is uncertain.

Taher Ali (2017) performed CFD simulations based on the VOF model for various conditions of gas-liquid turbulent flows in horizontal pipes. The predictive accuracy of the simulations was tested against common mechanistic models for stratified two-phase pipe flow, and against the experimental measurements of Strand (1993). Reasonable quantitative agreements were demonstrated. Since the proposed model does not require prior knowledge of the flow regime or any specific empirical information, it shows good promise for the general applicability of two-phase pipe flow designs.

2.4.3 Summary

CFD has become an active area of research over the past two decades or so, with the considerable focus being placed on handling two-phase flow problems. With the wealth of information numerical calculations can provide, CFD methods are in principle, more general and advanced than other techniques involving say, empirical correlations or mechanistic models. On the other hand, there remain many issues that must be addressed before one can reliably adopt CFD techniques to the design of multiphase flow systems.

One of the issues associated with computational modelling of two-phase flows is the ability to handle a dynamically changing interface, due to the discontinuity of fluid properties and complex flow field in that region (Yeoh and Tu, 2010).

Modelling the effects of turbulence and mixing presents another important challenge, since many of the flows of in industrial multiphase pipelines are indeed, turbulent in nature. Research exploring the performance of different turbulent models in the open literature are sparse, with the recent study of Taher Ali (2017) being one the few exceptions.

One evident reoccurrence within some of the reviewed numerical studies was their limited validation against experimental data for the prediction of flow regimes. Many of the comparisons were made qualitatively (e.g. Lu et al., 2007; De Schepper et al., 2008; Parvreh et al., 2010; Kou et al., 2011), in which contours of the predicted phase distributions were compared with experimental photographs. The limited number of quantitative comparisons may serve to highlight the difficulties with gathering detailed information on local flow parameters experimentally. Nevertheless, quantitative comparisons were found in some studies e.g. Meknassi et al. (2000), Newton and Behnia (2001), Sidi-Ali and Gatignol (2010).

2.5 Conclusion

There remain many challenges associated with the fundamental understanding of multiphase flow patterns. Despite the plethora of works, a considerable amount of discrepancies was evident when comparing different flow pattern maps.

Experimentally, PIV studies have been limited to measurements performed in a single plane i.e. a laser sheet cutting vertically through the pipe. Such measurements cause the main velocity component to become normal to the plane of the laser light sheet, which generates an error larger than that in the plane of the laser light sheet.

Almost all predictive methods for modelling gas-liquid stratified flows in the literature are one-dimensional, based on the momentum balances of the two phases. The two-fluid modelling approach is the most commonly applied, but as previous discussions highlighted, it is critically reliant on having accurate closure laws for the wall and interfacial shear stresses. In the context of mechanistic modelling, a circumferential variation of the wall shear stress has been obtained in several experiments, both in the liquid-phase (Kowalski, 1987; Newton and Behnia, 1996) and the gas-phase (Rosant, 1994; Paras et al., 1994; Vlachos et al., 1997; Shaha, 1999). However, these measurements are typically time-averaged results, but the wall shear stress is, in fact, a time-varying quantity, which will be effected by wave phenomena that cause fluctuations over time. Therefore, it is important that one understands how shear stress measurements could be effected by flow/wave dynamics.

One of the issues associated with computational modelling of two-phase flows is the ability to handle a dynamically changing interface, due to the discontinuity of fluid properties and complex flow field in that region (Yeoh and Tu, 2010). Modelling the effects of turbulence and mixing presents another important challenge, since many of the flows of in industrial multiphase pipelines are indeed, turbulent in nature. Research exploring the performance of different turbulent models in the open literature are sparse, with the recent study of Taher Ali (2017) being one the few exceptions.

Considering the outcomes of the review, the novelty element of the present project lies will rely on the provision of space/time-resolved information on the interface location, velocity profiles in both phase (including turbulence quantities) and wall/interface stresses all measured simultaneously and around the circumference of the pipe. Emphasis will be placed on the gas-phase and near-interface regions, where our understanding of the underlying physics remains somewhat poor.

3 Experimental Methods

3.1 TOWER facility

Experimental investigations will be performed in the flow facility known as TOWER, shown in Figure 3.1. The original purpose of the facility was built to conduct experiments for liquid-liquid flows. However, during the recommissioning stage, a multitude of modifications were made to extend its use for the study of gas-liquid flows, where high-speed images and pressure drop measurements were performed for 127 data sets under different air and water flow rates. To date, the rig now has provisions to also carry out air-oil experiments.

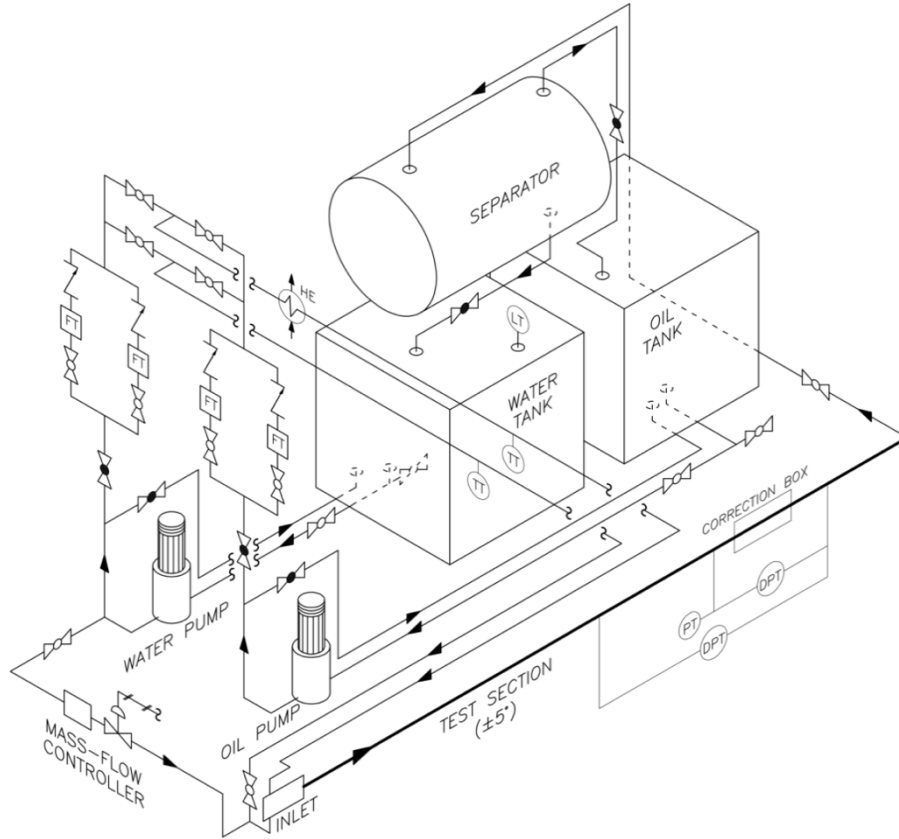


Figure 3.1: Schematic of the TOWER flow facility (FT-flow transmitter, TT-temperature transmitter, PT-pressure transmitter, DPT-differential pressure transmitter, LT-level transmitter, HE-heat exchanger. Adapted from Ibarra (2017).

The flow facility will be used in four sections: (1) storage, (2) pump and metering, (3) inlet section, and (4) test section. For clarity, we shall detail the use of each section below specifically in the context of air-oil flows.

3.1.1 Storage and pipelines

After oil and/or water flows through the test section, the liquid can initially be stored inside a horizontal liquid-liquid separator, using gravity as the driving force to obtain two clear liquids. The separator used in the flow facility had a total capacity of 450 L. It was originally equipped with a KnitMesh™ to accelerate the droplet coalescence for liquid-liquid flows, which has since been removed. The facility was modified such that one could also direct oil directly into the oil storage tank made (using a T-junction illustrated in Figure 3.2), without for oil to first pass through the separator. This is beneficial for future experiments where only air-oil flows will be studied.

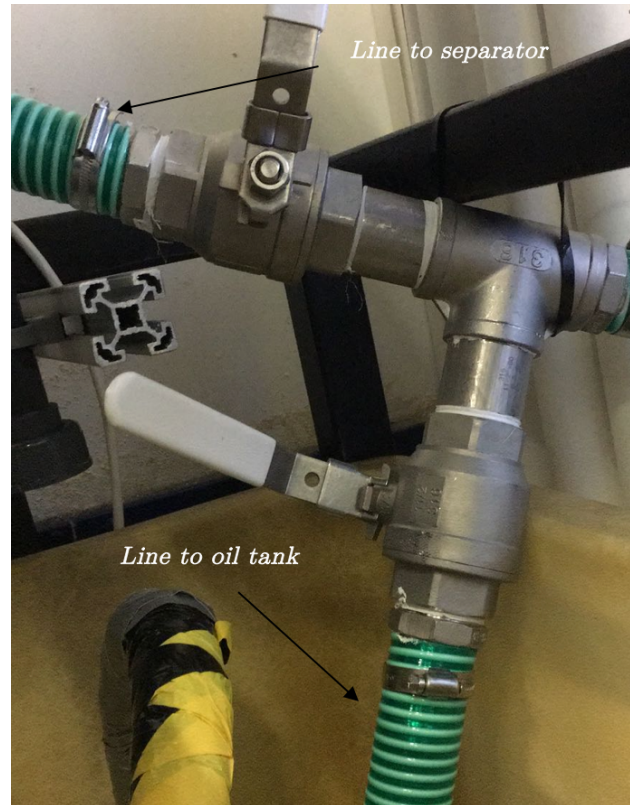


Figure 3.2: Illustration of the T-Junction design for the separator and oil tank lines.

After separation, both liquids can be transferred back to their respective storage tanks located below the separator, where the flow rates can be regulated by globe valves. Both storage tanks were made from fibreglass with a capacity of 680 L, which were linked to two vertical pumps using stainless steel pipes. In the original TOWER facility, PVC pipelines and connections were used. However, these were replaced for the purpose of future experiments taking place with low temperatures

3.1.2 Pump and metering

A Grundfos CRN10-5 pump deliver the oil to the test section. The oil pump consists of 5 stainless steel impellers installed in a vertical shaft. The pump also uses a magnetic drive for the

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mechanical connection between the impeller and the shaft of the motor; this is to eliminate leakage at the shaft.

The volumetric flow rate of the oil line is measured using two LFT stainless steel turbine flowmeters, rated at a maximum pressure of 250 bar, with an accuracy rating of $\pm 0.2\%$. Implementing two flowmeters with different measuring ranges reduces the experimental uncertainty in the investigated flow rates.

The flowmeters have a capacity of 2-20 L/min and 14-140 L/min, with sizes of 1/2 in. and 3/4 in, respectively. On each flowmeter, a Fluidwell totaliser model F110 was installed to display the instantaneous flow rate and to send analog outputs to the data acquisition card. Upstream the flowmeters, two globe valves are also used to regulate the flow rate through the main and recirculation lines.

In the original layout of the TOWER facility, the pump (A) in Figure 3.3 pumped water only, whilst the pump (B) pumped oil only. During recommissioning, the pipelines were exchanged such that pump (A) now only pumps oil, and pump (B) now only pumps water.

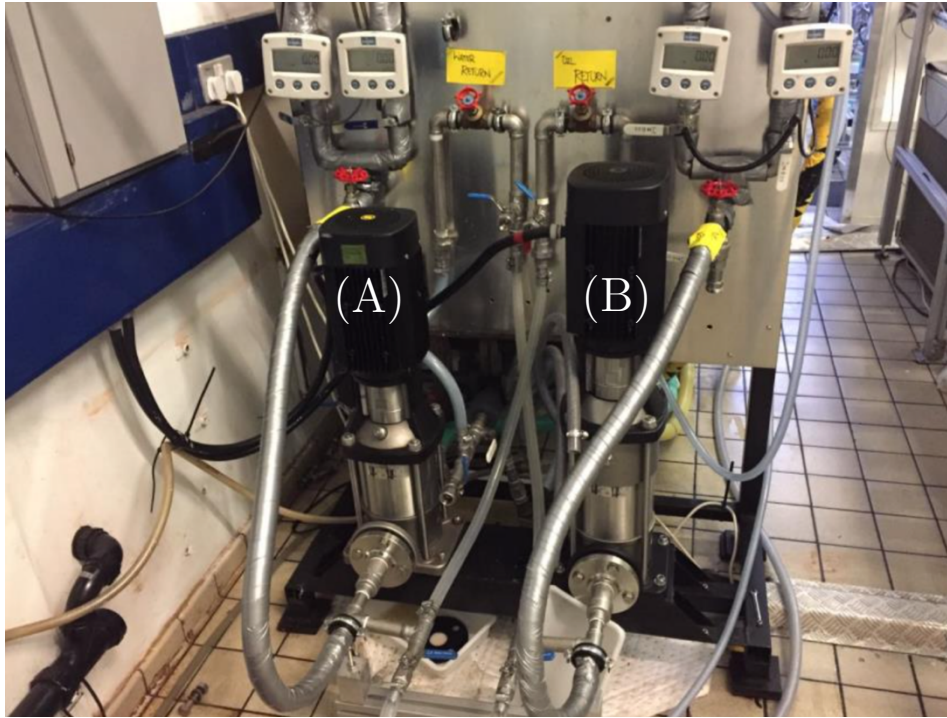


Figure 3.3: Grundfos pumps (A=oil; B=water) used in the TOWER facility, after recommissioning.

A gas line was also incorporated in the facility, where the flow rate is controlled by a gas flow meter via a software program. For the preliminary results achieved in this thesis, a maximum flow rate of 380 L/min was used for safety reasons.

3.1.3 Inlet section

The liquid and air phases are introduced from the bottom and top of the inlet section, respectively (Figure 3.4). The inlet has a 50mm internal diameter and a separation plate at a height of 15 mm from the bottom. The design consists of 3 meshes and 2 tube bundles. The

mesh has a square opening of length of 1 mm and wire thickness of 0.25 mm, corresponding to a 0.64% beta ratio. The tube bundle is made up of 180 and 60 holes at the top and bottom, respectively, and each hole has a diameter of 2.5 mm.

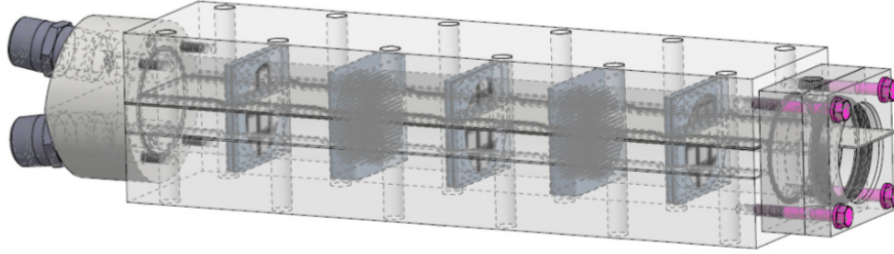


Figure 3.4: 3D schematic of the inlet design (Wright, 2015).

3.1.4 Test section

The test section is an ETFE 50 mm internal diameter pipe, which has an approximate length of 8.5m. The visualisation section is located 6 m downstream the inlet point and consists of a 2 m Perspex box containing silicone oil to minimise optical distortion.

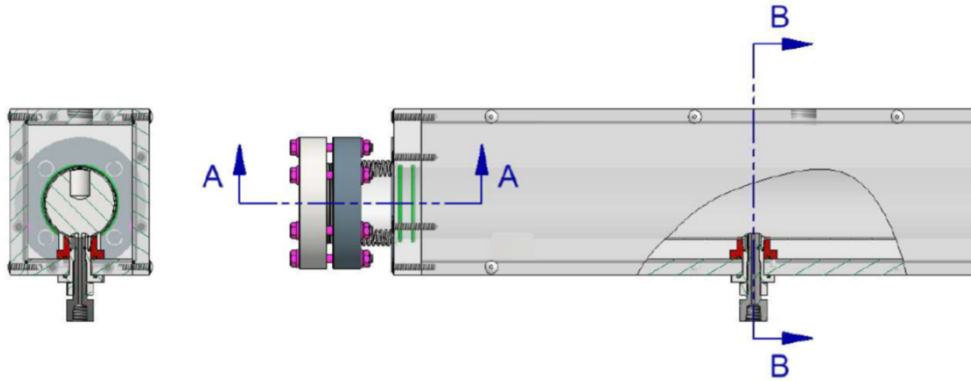


Figure 3.5: Test section visualisation box design (Wright, 2015).

The pressure drop in the test section was measured by three Differential Pressure Transmitters (DPTs) with an output of 4-20mA and an accuracy of $\pm 0.15\%$ of its full span. The measurement zone of each DP transmitter, along with the range and span is summarised in Table 3.1.

Table 3.1: Pressure drop measurement characteristics.

Sensor	Measurement zone (m) in the test section	Range (Pa)	Span (Pa)
DPT 1	2 to 6	-1000 to 4000	5000
DPT 2	4 to 6	-1000 to 4000	5000
DPT 3	6 to 8.1	-1000 to 4000	5000

It should be noted that the third pressure drop measurement (DP3) is the most significant as the flow is considered to be full developed in that location.

3.1.5 Cooling system

A cooling system (Figure 3.6) consisting of a chiller was incorporated as part of the TOWER facility for future temperature-sensitive experiments. A mixture of pure glycol and deionised water was added to the chiller, which circulates through into stainless-steel coils inside both the oil and water tanks. The mixture's freezing temperature was confirmed using a refractometer, and achieves a set temperature of -15°C after roughly two hours of cooling.



(a) Aqua cooling chiller.

(b) Refractometer

Figure 3.6: Cooling system

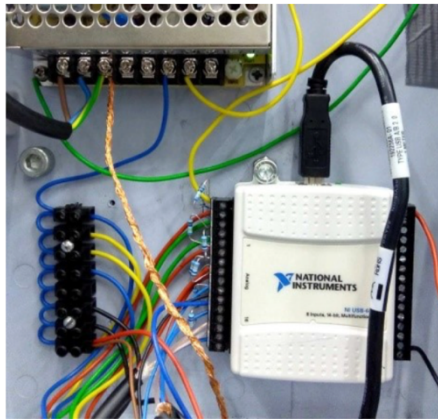
3.1.6 Instrumentation and data aquisition system

A National Instruments USB-6009 data acquisition card was used to convert the analog signals from the sensors installed in the flow facility to digital data. A single-ended configuration was used to connect the sensors to obtain a resolution of 13 bits. The LabView control panel designed by Ibarra (2017) was used to present the measured values of the sensors, as well as record data, operate and regulate the flow facility. Importantly, the control panel was also used to trigger the high-speed camera, and supplied with safety information to shut down both pumps in case of any equipment failures or pipe blockages.

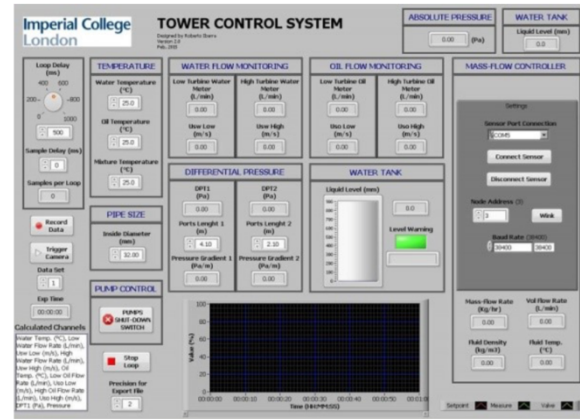
For the high-speed imaging, an OLYMPUS I-Speed 3 high-speed camera was used, which had a maximum resolution of 1280×2024 pixels, and a maximum frame rate of 2000 frames per second. The backside of the visualisation section was covered by a plain white A4 sheet of paper

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to prevent the transmission of light through the test section and decrease the dark areas of the acquired images.



(a) Data acquisition card



(a) LabView control panel

Figure 3.7: Data acquisition system.

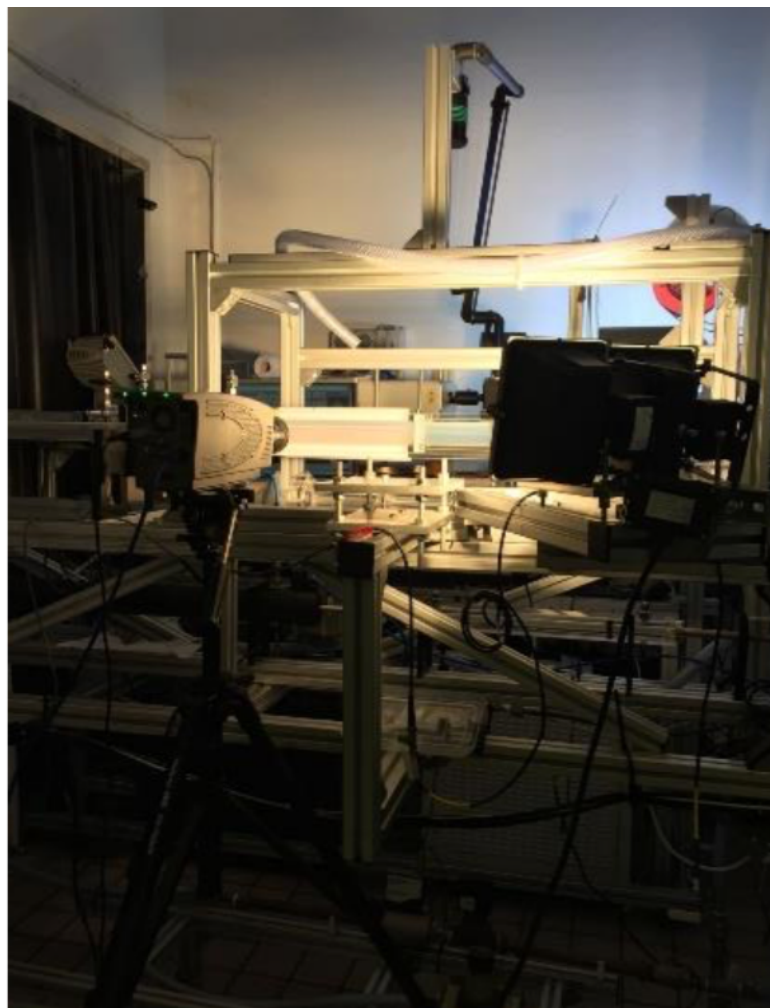


Figure 3.8: High-speed camera setup.

4 Preliminary results

The preliminary results achieved in this thesis and their subsequent analysis are focused around three major areas. The first concerns a phenomenological characterisation of flow structures using high speed images, where different flow structures are classified according to the descriptions in literature. From these phenomenological characterisations, the results are compared with well-known experimental flow pattern maps, where similarities are validated, and discrepancies are accounted for. Lastly, results of the pressure gradient are presented, analysed and again compared with works from literature.

The flow conditions chosen were limited to air-water flows, spanning an air flow rate and water flow rate range of 0-400 L/min and 5-65 L/min, respectively. A total of 127 different conditions were tested. The flow regime classification of each condition is outlined in Table 4.1. Classifications were made according to the most dominant regime observed (from a collation of high-speed images) near to a transition.

Table 4.1: Summary of 127 data sets. SS = Stratified Smooth, SW= Stratified-Wavy. Annular flows were non-present, due to safety constraints of the air flow rate (a maximum of 30% equal to 400 L/min).

	Air Flow Rate (%)					
Water Flow rate (L/min)	5	10	15	20	25	30
5	SS	SS	SS	SW	SW	SW
10	SS	SS	SW	SW	SW	SW
15	SS	SS	SW	SW	SW	SW
20	SS	SS	SW	SW	SW	SW
25	SS	SS	SW	SW	SW	SW
30	SW	SS	SW	SW	SW	SLUG
35	SW	SW	SW	SW	SLUG	SLUG
40	SW	SLUG	SLUG	SLUG	SLUG	SLUG
45	SLUG	SLUG	SLUG	SLUG	SLUG	SLUG
50	SLUG	SLUG	SLUG	SLUG	SLUG	SLUG
55	SLUG	SLUG	SLUG	SLUG	SLUG	SLUG
60	SLUG	SLUG	SLUG	SLUG	SLUG	SLUG
65	SLUG	SLUG	SLUG	SLUG	SLUG	SLUG

4.1 High-speed images

To date, high speed images have been performed for various air-water flows, and the resulting flow regimes have been phenomenologically characterised. Observationally classifying a flow regime can be somewhat ambiguous, as this method is subjective in the eyes of the observer. Weisman (1979) proposed a more precise method, where a flow pattern was defined based on the amplitude ratio of standard slug flow. However, the experimental conditions spanned in the present work could not achieve the flow rates necessary for the access of ‘standard slug flow’, therefore, an observational approach has been used.

For the experimental conditions, three flow regimes could be classified: stratified-smooth, stratified-wavy and slug (Figure 4.1). Separated flows could be clearly identified by two continuous layers that are separated by an interface, whilst mixed flows are defined by multiple interfaces where one phase is submerged in the other. In these experiments, the former occurs for stratified-smooth and stratified-wavy flow structures, and the latter for slug flow.

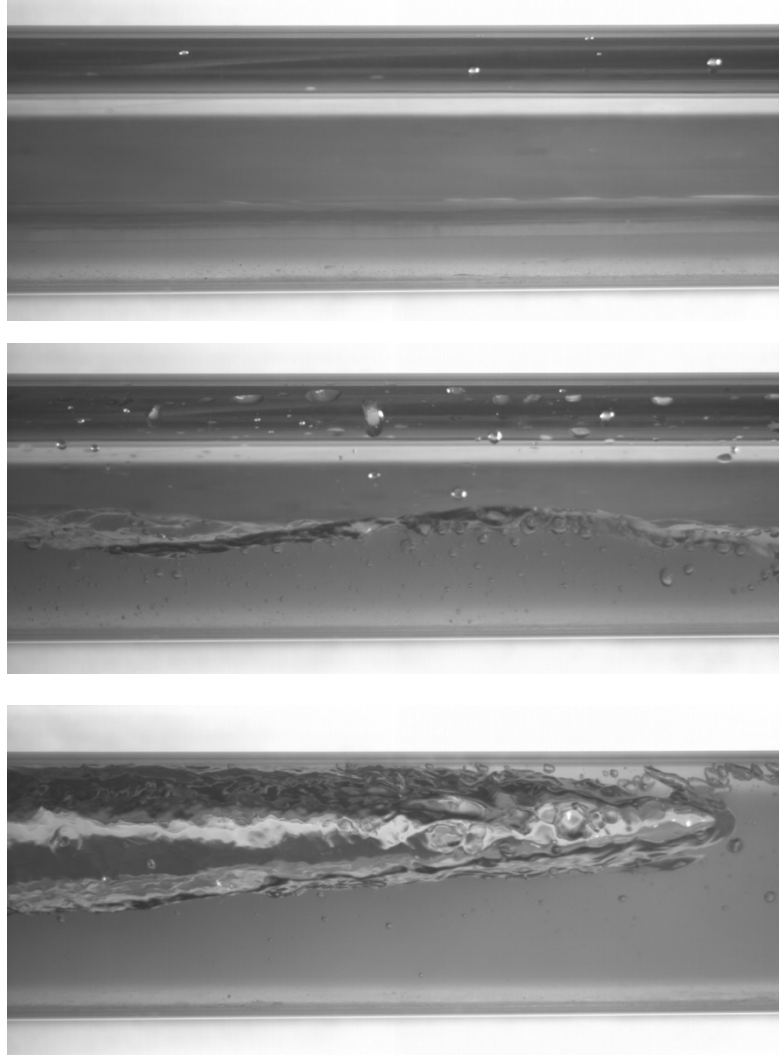


Figure 4.1: Phenomenological characterisation of flow regimes. Top: Stratified smooth (water flow rate=5L/min, air flow rate=0.00625 m³/s); Middle: Stratified-wavy (water flow rate= 30 L/min, air flow rate= 0.006 m³/s); Bottom: Slug flow (water flow rate= 40L/min, air flow rate= 0.0035 m³/s).

As mentioned, annular flows were not achieved due to limited air flow rate capacities. The maximum air flow rate was capped at 400 L/min due to safety concerns, as the ETFE pipe becomes more venerable from vibrational damage.

The phenomenon of a droplet impact was also observed, as illustrated in Figure 4.2. However, droplet breakup is not examined in detail in this thesis, due to difficulties in measuring droplet sizes, shapes and velocities.

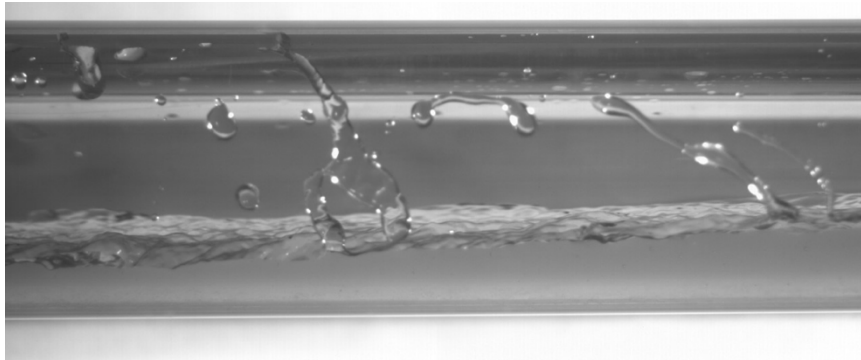


Figure 4.2: Stratified smooth with droplet impact (water flow rate=35L/min, air flow rate=0.0047 m³/s)

4.2 Flow regime mapping

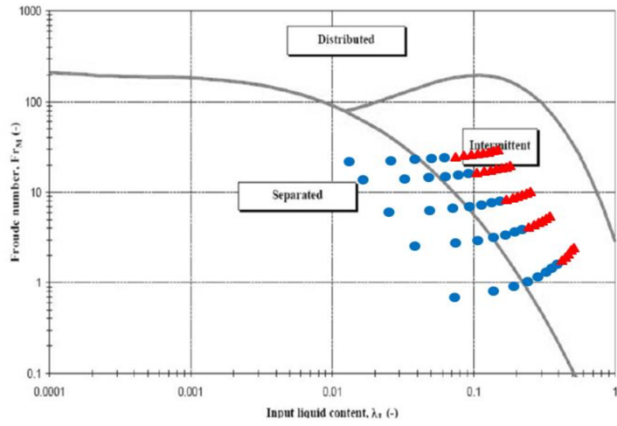
4.2.1 Performances

The performance of five flow pattern maps (chosen from section 2.1) was tested against the experimental results of this thesis. A total of 65 data points was superimposed on the five different flow pattern maps of Beggs and Brill (1973), Mandhane et al. (1974), Taitel and Dukler (1976), Weisman et al. (1979) and Spedding et al. (2008), shown in Figure 4.3. The method used to assess the accuracy of each was based on the number of correctly predicted points in an individual flow regime map, divided by the total number of observed points in the flow regime considered (in percentage form). The results are summarised in Table 4.2. Over the prescribed range of flow conditions, the Beggs and Brill serves as the best predictive tool with a 77% prediction accuracy. Table 4.2: Performance of five different flow pattern maps predicting the experimental dataset.

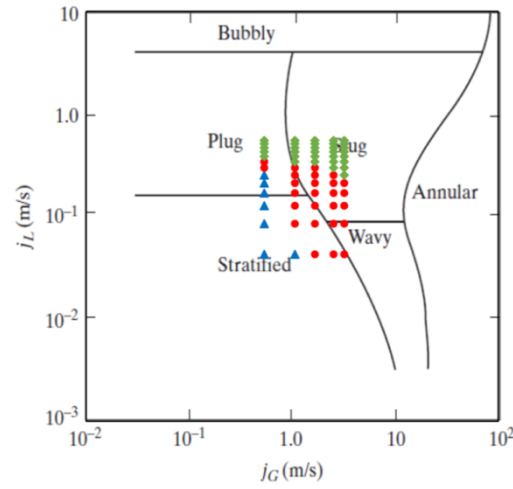
Table 4.2: Performance of five different flow pattern maps predicting the experimental dataset.

Flow Pattern Map	Prediction Accuracy
Beggs and Brill (1973)	77%
Mandhane et al. (1974)	52%
Taitel and Dukler (1976)	57%
Weisman et al. (1979)	71%
Spedding et al. (2008)	63%

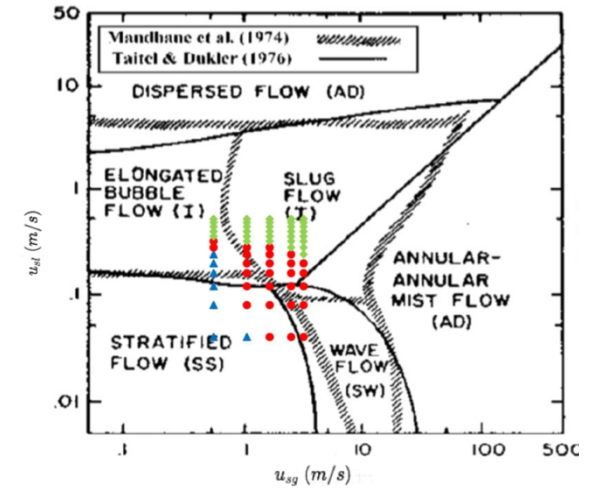
PRELIMINARY RESULTS



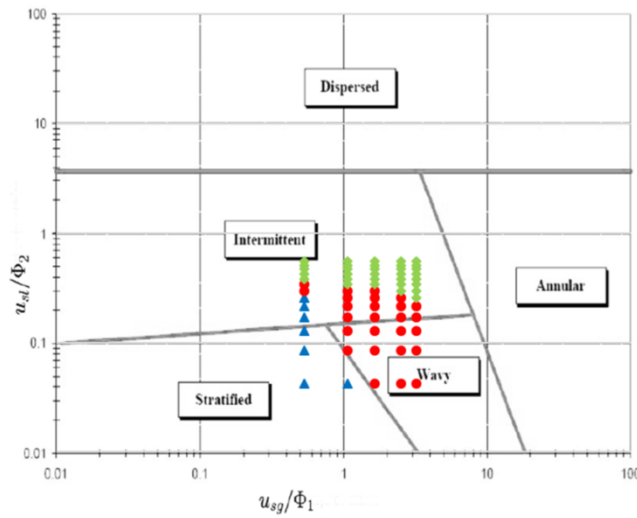
(a) Beggs and Brill (1973)



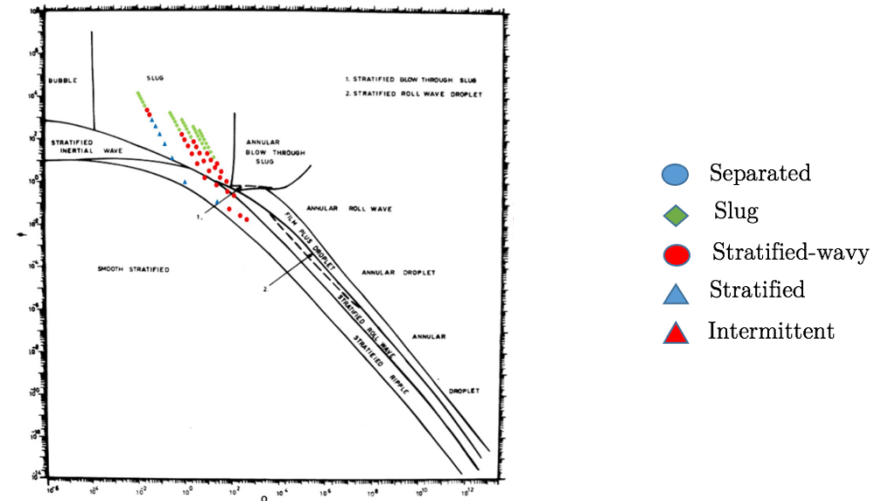
(b) Mandhane et al. (1974)



(c) Taitel and Dukler (1976)



(c) Weisman et al. (1979)



(e) Spedding et al. (2008)

Figure 4.3: Superimposed experimental data points on five different flow pattern maps.

4.2.2 Potential sources of error

Indeed, even the best performing flow regime map has a relatively low prediction accuracy. Due to the inadequate nature of conditions encountered in the flow facility, one leads to believe these inaccuracies stem from the experimental results themselves, rather than the flow regime maps used in the comparisons. A summary of the experimental issues that must be addressed for future experiments are summarised below.

Contaminated water

In many of the experimental runs, the water was seemingly contaminated with residual white particles (Figure 4.4), which may have remained in the water pump from a previous experimental campaign performed in the facility. Any impurities present will have influence the physical properties of water e.g. density, viscosity etc.; therefore, the resulting data points superimposed in Figure 4.3 are not truly valid for pure air-water flows. To help mitigate this problem in the future, a filter has now been installed in the line of the water pump.

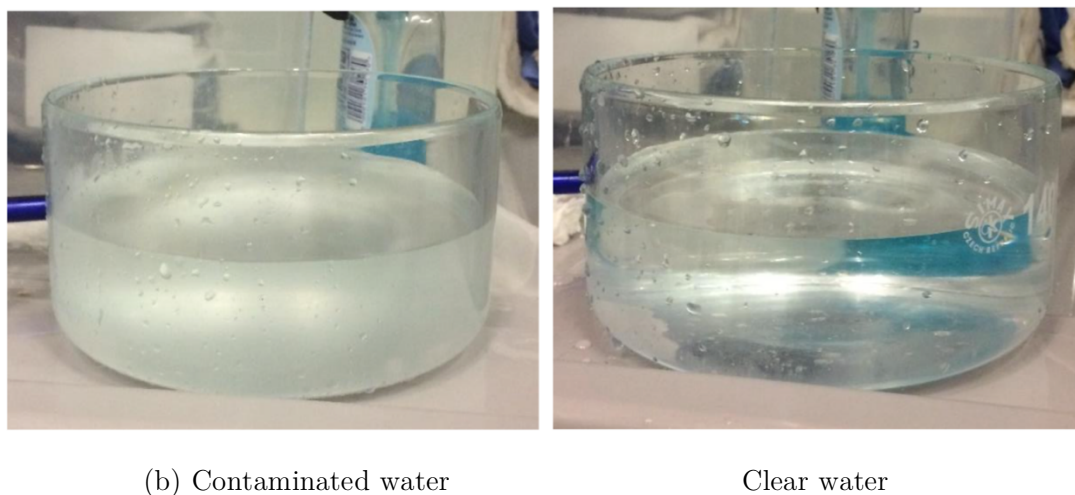


Figure 4.4: A samples of contaminated water taken from an experimental run, compared to that of clean water.

Inlet section leakage

Leakages exist in both the fittings connecting the hoses of air and water to the inlet section, which has occurred as a result of BSPT fittings being driven into BSPP inlet threads. For liquid-liquid flows, the impact is minimal, however, for gas-liquid flows where compressed air is used, the effect of this leak is more pronounced. Therefore, it is likely that the measured air-flow rate in the test section is significantly lower than the value that would have been attained without a leakage. The superimposed maps of Mandhane et al. (1974) and Taitel and Dukler (1976) provides some evidence of this, where in both maps, the x-axis represents the superficial gas velocity, and we notice the position of data points to be skewed leftwards. Also noteworthy are

the changes in the physical properties of air due to the leak, where a pressure drop could cause certain variables such as the density to change.



Figure 4.5: Inlet section wrapped with a plastic film to help minimise air leakage.

Pressure gauge

No pressure gauge exists in the air inlet section. Since the facility was originally designed for liquid-liquid flows only, this would not have been problematic as liquids are incompressible. However, air is compressible and it is important to know if a pressure difference causes a significant change in the air density to occur.

Flowmeter positioning

The flowmeter is positioned too closely to the elbow, a region where fluctuations in the flow rate are highest, causing measurement errors increase. Ideally, the flowmeters need to be positioned further away to allow the measurement of more steady flow.



Figure 4.6: Flow meter positioned closely to the elbow.

4.3 Pressure drop measurements

4.3.1 Validations

Pressure gradient measurements were performed in three different locations of the test section (Table 3.1). A validation of each DP transmitter was achieved by conducting a single-phase flow pressure drop measurement (Figure 4.7), and comparing the result to the following theoretical formula:

$$\frac{\Delta P}{\Delta L} = \frac{f}{2D} \cdot \rho U^2. \quad (4.1)$$

The Zigrand and Sylvester explicit correlation, (4.2), was used to calculate the friction factor:

$$\frac{1}{\sqrt{f}} = -2 \log \left\{ \frac{\varepsilon}{3.7D} - \frac{5.02}{Re} \log \left[\frac{\varepsilon}{3.7D} - \frac{5.02}{Re} \log \left(\frac{\varepsilon}{3.7D} + \frac{13}{Re} \right) \right] \right\}, \quad (4.2)$$

where ε , the roughness of the pipe (acrylic/glass) was taken as 0.0015 mm from manufacturer specifications.

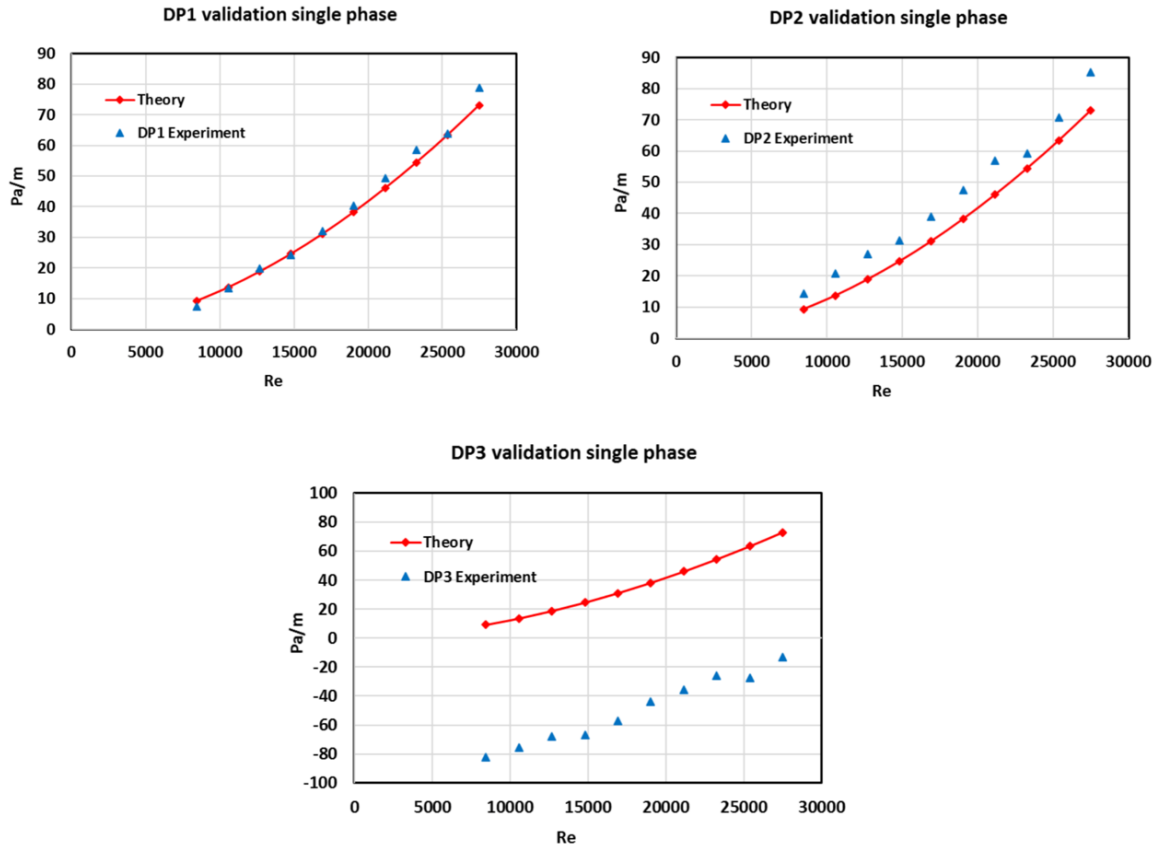


Figure 4.7: DP transmitter validation results.

DP1 acceptably matches with the theoretical predictions, however, an error is presented by DP2 and a relatively large one by DP3, indicating that an unsatisfactory calibration was

conducted. This could have occurred because of changes in the liquid density, changes in the pipe inclination and/or air bubbles being present in the lines.

To compromise for this error, offset values of $(-)$ 6 Pa and $(+)$ 87 Pa were obtained for DP2 and DP3, respectively, when a steady and non-flowing fluid is filled in the test section. With the addition of these offset values, the experimental results achieve a far better fit to the theoretical predictions (Figure 4.8).

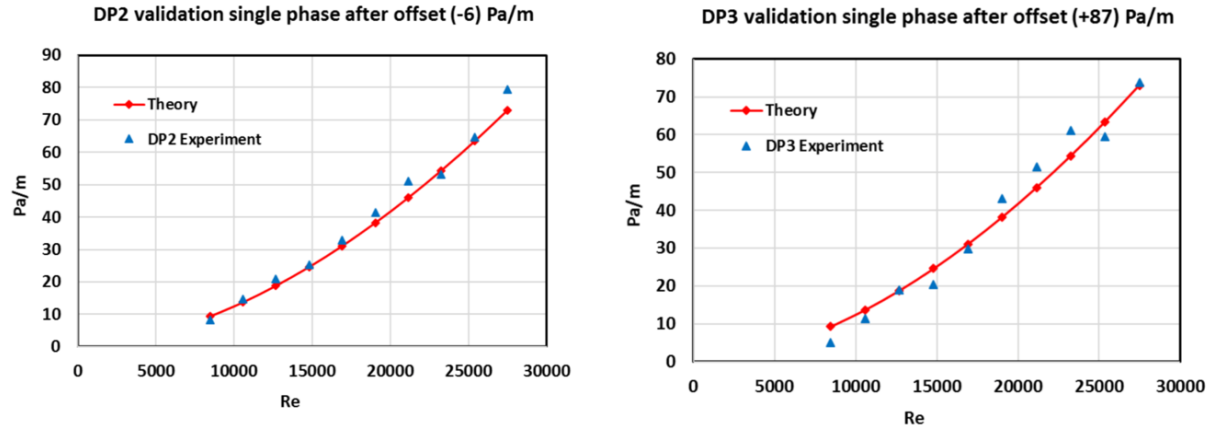
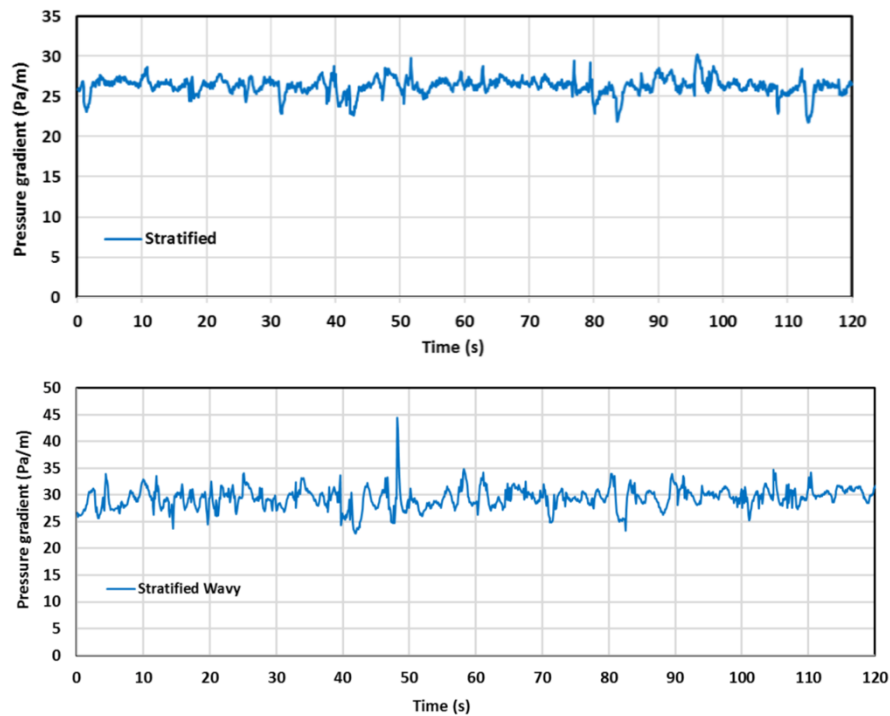


Figure 4.8: DP2 and DP3 transmitter validation results (after the addition of offsetting values).

4.3.2 Flow pattern pressure gradients

Pressure gradient vs. time

Different pressure gradient patterns were encountered for the stratified-smooth, stratified-wavy and slug flow regimes (Figure 4.9).



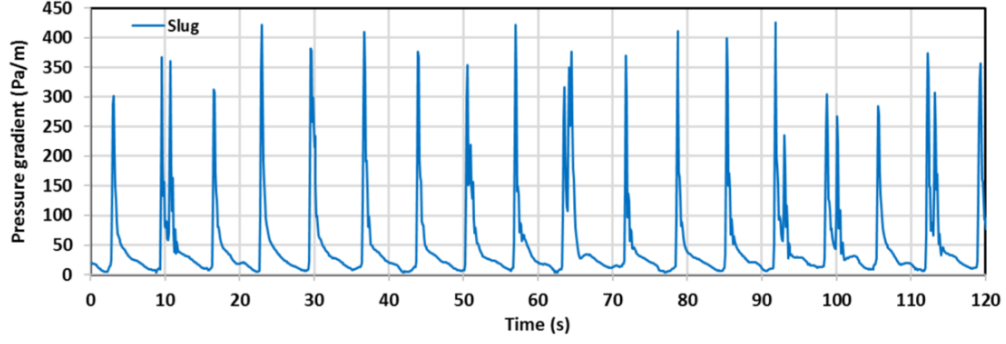


Figure 4.9: Stratified-smooth (Top), stratified-wavy (Middle) and Slug (Bottom) flow pattern pressure gradients vs. time.

For stratified-smooth flow, no significant variations in the pressure gradient occur. A greater amount of fluctuations is present for the stratified-wavy flow regime, which are a result of discontinuities occurring in the near-interface region.

The slug flow regime is characterised by its own unique pattern, where the pressure gradient increases sharply and subsequently drops in an intermittent fashion. This cycle repeats every 120 seconds, and is referred to as the ‘slug frequency’. To avoid vibrational damages in industrial pipelines, one must prevent the natural resonant frequency of the piping system from matching with the slug frequency.

Pressure gradient vs. water flow rate (with constant air flow rates)

Variations in the pressure gradient were investigated as a function of the water flow rate at constant air flow rates (Figure 4.10). Initially, the pressure gradient increases only moderately between stratified-smooth and stratified-wavy flows. Subsequently, in every case, a sudden rise in the pressure drop was noticed, signifying the transition period between the stratified-wavy and slug flow regimes. However, at a higher constant air flow rates, the transition to slug flow occurs earlier.

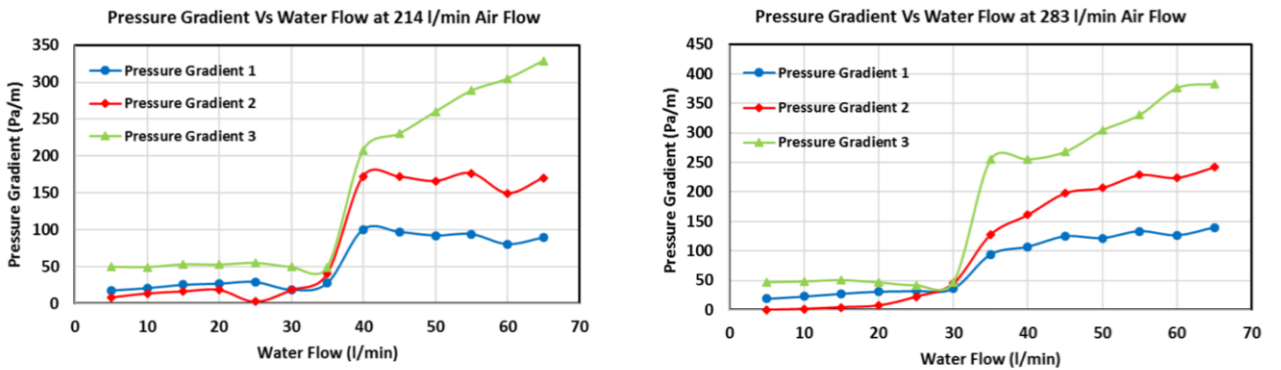


Figure 4.10: Pressure gradient vs. water flow rate (Left: 214 L/min, Right = 283 L/min).

Pressure gradient vs. air flow rate (with constant water flow rates)

The pressure gradient was also examined as a function of the air flow rate, whilst maintaining a constant water flow rate. Similar to the previous cases, shy increases in the pressure gradients were observed between stratified-smooth and stratified-wavy flows, until a sharp increase occurs with the onset of slug flow.

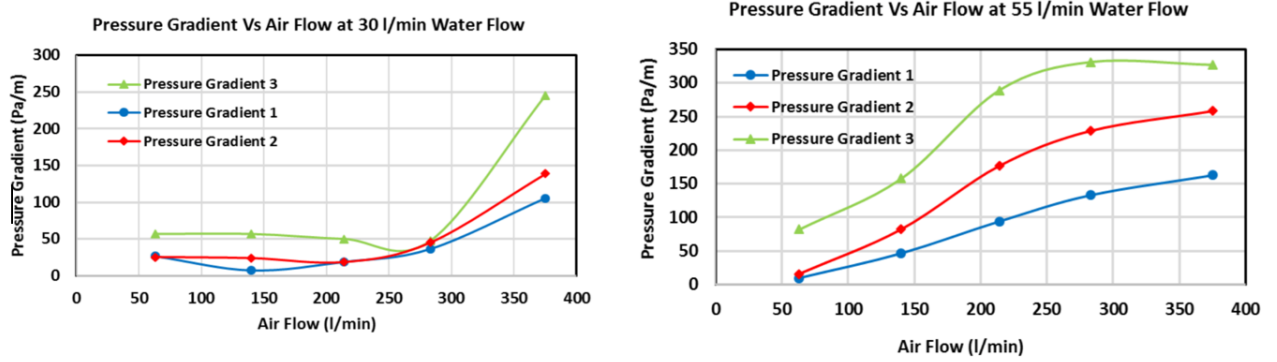


Figure 4.11: Pressure gradient vs. air flow rate (Left: 30 L/min, Right = 55 L/min).

4.3.3 Correlations

Theoretical pressure drop predictions were plotted against experimental pressure drop data in a parity plot, for the stratified-smooth, stratified-wavy and slug flow regimes (Figure 4.12). The error of each data point is defined as the vertical distance from the ideal value situated in the $y = x$ reference line. In what follows, the existing correlations used for evaluation in this study are described.

Lockhart and Martinelli (1949)

Based on the separated flow model, Lockhart and Martinelli proposed the following expression to determine the two-phase frictional pressure drop:

$$\left(\frac{dP}{dl}\right)_{2ph} = \phi_l^2 \left(\frac{dP}{dl}\right)_l, \quad (4.3)$$

where Chisholm (1967) calculates the two-phase multiplier ϕ_l , based on the liquid phase pressure drop:

$$\phi_l^2 = 1 + \frac{C}{X} + \frac{1}{X^2}. \quad (4.4)$$

The value of C depends on the regimes of the liquid and vapor, and the Martinelli parameter X is given by

$$X^2 = \frac{\left(\frac{dP}{dl}\right)_l}{\left(\frac{dP}{dl}\right)_g}, \quad (4.5)$$

with

$$\left(\frac{dP}{dl}\right)_l = f_l \frac{2G^2(1-x)^2}{d\rho_l} \quad (4.6)$$

and

$$\left(\frac{dP}{dl}\right)_g = f_g \frac{2G^2x^2}{d} \rho_g, \quad (4.7)$$

where f , ρ , x , G and D are friction factor, density, quality, mass flux and the hydraulic diameter, the subscripts g and l denote the gas phase and the liquid phase, respectively.

Chisholm (1972)

Chisholm calculates the two-phase frictional pressure drop using:

$$\frac{\Delta P_{2ph}}{\Delta P_{lo}} = 1 + (X^2 - 1)[Bx^{0.875}(1-x)^{0.875} + x^{1.75}], \quad (4.8)$$

where

$$X^2 = \frac{\left(\frac{dP}{dl}\right)_{go}}{\left(\frac{dP}{dl}\right)_{lo}}, \quad (4.9)$$

and the subscripts of go and lo denote that the whole mixture flows as vapour or liquid. The value of B depends on the value of X and the mass flux:

$$\begin{aligned} & \text{if } 0 < X < 9.5, \\ & B = \frac{55}{G^{0.5}} \text{ for } G \geq 1900 \frac{kg}{m^2s}, \\ & B = \frac{2400}{G} \text{ for } 500 < G < 1900 \frac{kg}{m^2s}, \\ & \text{and } B = 4.8 \text{ for } G < 500 \frac{kg}{m^2s}. \\ & \text{If } 9.5 < X < 28, \\ & B = \frac{520}{XG^{0.5}} \text{ for } G \leq 600 \frac{kg}{m^2s}, \\ & \text{and } B = \frac{21}{X} \text{ for } G > 600 \frac{kg}{m^2s}. \\ & \text{If } Y > 28, \\ & B = \frac{15000}{X^2G^{0.5}}. \end{aligned} \quad (4.10)$$

Friedel (1979)

Friedel developed his own correlation by introducing dimensionless numbers, the Froude number Fr , Weber number We , and Reynolds number Re .

$$\left(\frac{dP}{dl}\right)_{2ph} = \left(\frac{dP}{dl}\right)_{lo} \phi_{lo}^2, \quad (4.11)$$

$$\phi_{lo}^2 = E + \frac{3.24FX}{Fr^{0.045}We_l^{0.035}}, \quad (4.12)$$

where

$$\begin{aligned} Fr &= \frac{G^2}{gD\rho_{2ph}^2}, F = x^{0.78}(1-x)^{0.224}, We_l = \frac{G^2D}{\sigma\rho_l}, \\ X &= \left(\frac{\rho_l}{\rho_g}\right)^{0.91} \left(\frac{\mu_g}{\mu_l}\right)^{0.19} \left(1 - \frac{\mu_g}{\mu_l}\right)^{0.7}, \\ \text{and } E &= (1-x^2) + x^2 \frac{\rho_l f_{go}}{\rho_g f_{lo}}. \end{aligned} \quad (4.13)$$

Mishima and Hibiki (1996)

Using the Lockhart-Martinelli model, Mishima and Hibiki modified the constant C in equation (4.4), as follows:

$$C = 21(1 - e^{319D}). \quad (4.14)$$

Zhang and Mishima (2006)

In the correlation of Zhang and Mishima, the Laplace number is employed instead of the equivalent diameter:

$$C = 21 \left(1 - e^{-\frac{0.358}{La}}\right). \quad (4.15)$$

where

$$La = \frac{\left(\frac{\sigma}{g(\rho_l - \rho_g)}\right)^{0.5}}{d}. \quad (4.16)$$

A summary of the pressure drop prediction accuracies of each of the above theoretical models is compiled in Table 4.3.

In the DP1 transmitter measurement range (2m-6m), the Zhang and Mishima correlation serves as the best predictor of the experimental pressure drop data for the stratified-smooth flow regime, with an accuracy of 71%. The stratified-wavy, slug and overall flow regimes are unsatisfactorily predicted by all other models.

The Zhang and Mishima correlation is also superiorly predicts the pressure drop for the stratified-smooth regime in the DP2 transmitter measurement range (4m to 6m), attaining an accuracy of 71%. All other flow regimes within this measurement range are falsely predicted,

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apart from slug flow, where the Lockhart Martinelli model generates a relatively sound accuracy of 69%. For the final DP3 measurement span (6m-8.1m), mispredictions are also prevalent. The only exceptions being the Mishima and Hibiki correlation with an 81% accuracy of slug flow, and a 55% of the overall flow regime (also shared by Zhang and Mishima).

Table 4.3: Performances of theoretical models predicting experimental pressure drop data. A RAG analysis has been carried out, outlining whether a correlation would be expected to work for a given flow regime (according to the prescribed boundary conditions of the respective correlation). Green = Good accuracy expected, Amber = reasonable accuracy expected, Red = low accuracy expected.

Correlation	Flow regime	DP1 accuracy (%)	DP2 accuracy (%)	DP3 accuracy (%)
Lockhart Martinelli	Stratified	14	14	0
	Stratified-wavy	4	8	31
	Slug	3	69	59
Chisholm	Stratified	14	14	0
	Stratified-wavy	15	27	0
	Slug	19	6	0
Friedel	Stratified	14	0	29
	Stratified-wavy	0	0	8
	Slug	0	0	0
Mishima and Hibiki	Stratified	71	71	0
	Stratified-wavy	8	8	38
	Slug	0	59	81
Zhang and Mishima	Stratified	71	71	0
	Stratified-wavy	8	8	38
	Slug	0	63	81

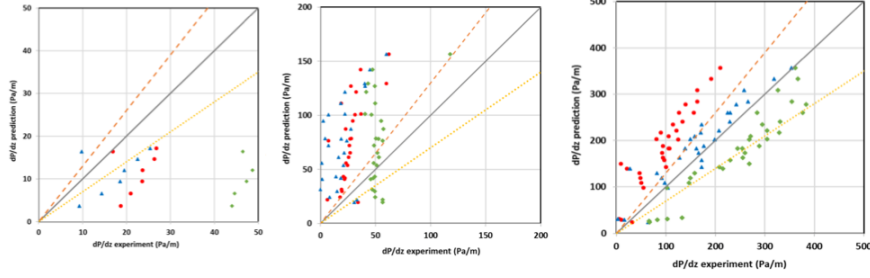
The different experimental rig configuration, fluids, pipe characteristics and environmental conditions implemented in the TOWER facility are all factors that could cause discrepancies between the predictions of empirical correlations and the experimental dataset.

However, a substantial degree of error was evident with every tested correlation, which leads one to believe that the inaccuracies stem from the experimental results themselves (due to the reasons described in section 4.2.2.), rather than predictions of the correlations.

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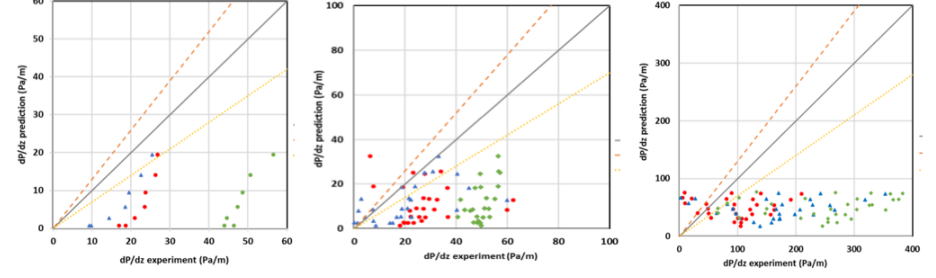
Lockhart and Martinelli (1949)

(a) Stratified smooth (b) Stratified-wavy (c) Slug



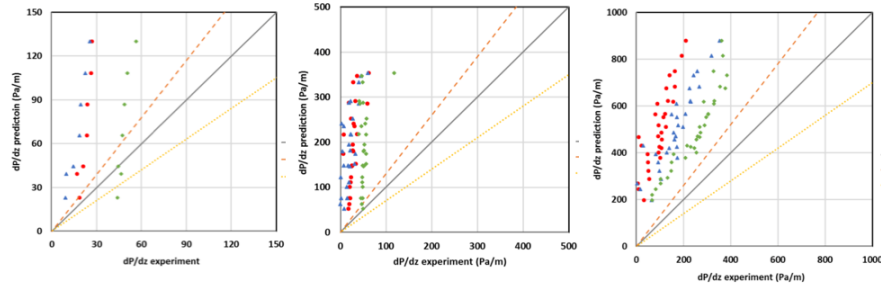
Chisholm (1972)

(a) Stratified smooth (b) Stratified-wavy (c) Slug



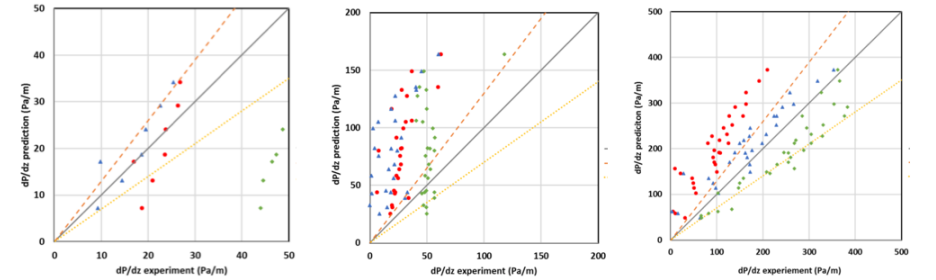
Friedel (1979)

(a) Stratified smooth (b) Stratified-wavy (c) Slug



Mishima and Hibiki (1996)

(a) Stratified smooth (b) Stratified-wavy (c) Slug



Zhang and Mishima (2006)

(a) Stratified smooth (b) Stratified-wavy (c) Slug

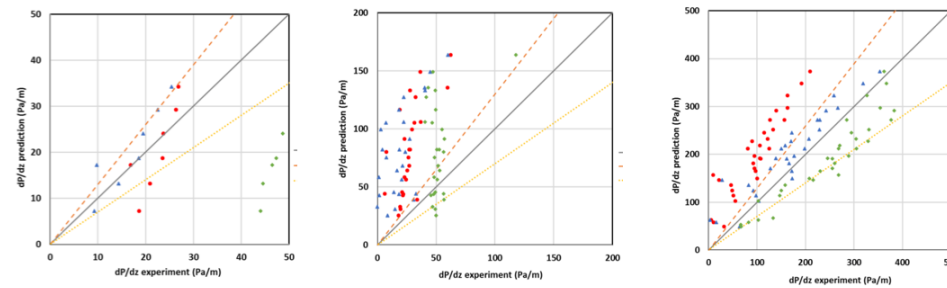


Figure 4.12: Parity plots of theoretical pressure drop predictions vs. experimental pressure drop data for stratified-smooth, stratified-wavy and slug flow regimes. In each graph, the maximum and minimum error bounds are specified at $\pm 30\%$.

5 Conclusions and further work

The outcomes of a comprehensive literature review established that the provision of spatiotemporally resolved information on the interface location, and wall/interface stresses, would satisfy the novelty element of future work, if measured simultaneously and circumferentially around the pipe. In addition, an emphasis should be placed on the gas-phase and near-interface regions, where our understanding of the underlying physics remains largely inconclusive.

A full recommissioning of the TOWER facility was carried out, which was originally constructed for liquid-liquid flow experiments only. The facility has now been modified to extend its application to gas-liquid flow experiments, where a cooling system has been incorporated to enable low-temperature two-phase flow experiments. Leak tests were also scanned throughout the flow facility and all relevant sections were insulated to reduce the amount of heat transferred to the system.

The preliminary experimental results achieved in this thesis were focused around three areas. Firstly, high-speed images were used to phenomenologically characterise flow structures, which were classified according to the descriptions found in literature. The performances of five different flow pattern maps were then tested, where a total of 65 data points was superimposed on each map. In general, flow maps that used generalised axes coordinates were deemed the most accurate e.g. the map of Beggs and Brill (1973), which uses the dimensionless Froude number and liquid holdup parameters. Lastly, results of the pressure gradient were presented as a function of time, air flow rate and water flow rate. The accuracy of five different theoretical models were also tested, which were seen to unsatisfactorily predict the experimental pressure drop data.

For future work, the high-speed images, flow regime maps, and pressure drop measurement results in this thesis must be repeated for air-oil flows. Quantitative, high-resolution information should then be obtained regarding: (i) the spatiotemporal distribution of the two phases within the stratified flow regime using planar laser-induced fluorescence (PLIF) and (ii) the full velocity distribution in both phases (in the liquid phase in the first instance, and if time permits since this is riskier, also in the gas phase) using particle image velocimetry (PIV).

Circumferential wall shear stress information and the interfacial stresses at various axial stations can then be derived from the PIV data, over a range of superficial gas and liquid velocities (within the stratified flow regime). The shear stress information obtained using the PIV data should then be validated against the data obtained from overall pressure drop information (with pressure transducers) as well as shear stress probes (subject to the cost of purchasing this system within the available project budget). Furthermore, CFD simulations could also be performed using OPENFOAM, where the experimental data will be used to inform and validate shear stress calculations.

Appendix

TOWER risk assessment

Special hazards

The following hazards have specific risk assessment requirements and have a departmental approval process.

Table 0.1: List of special hazards.

Special Hazard	Action(s) completed
Lasers (Class 4)	Attend the 'Introduction to Laser Safety' course. Conduct a laser risk assessment
Hazardous substances (Eosin Y dye, Rhodamine B, Rhodamine 6G)	Conduct a COSHH/DSEAR risk assessment
Gases or Cryogenic substances (Neon)	Conduct a gas/cryogenics risk assessment
Manual handling or Heavy lifting	Obtain guidance/approval from the Departmental Safety Officer

General hazards

The following hazards have general risk assessment and local approval requirements.

Table 0.2: List of general hazards.

General Hazard	Hazard explanation and/or Location
Pressurised equipment	Compressed air supply, used for numerous items including 2 air assisted valves.
Electrical	2 Phase and 3 phase pumps. 2x High speed cameras. 1 PC and 2 monitors. 2x Halogen lamps. Cu Vapour Laser. NdYLF laser
Water	Water is used for the flow system and as a coolant. The lab is equipped with a spill kit.
Structural Failure	The Perspex, glass and ETFE test section is positioned on an aluminium frame (1.2 m above the ground). The rigidity of the frame

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	should ensure that no structure failure should occur.
Trip hazards	Pipes and wires occur throughout the lab. These are limited via passing through conduits or overhead.
Working at height	Climbing up a ladder to view inside the separator. Collecting lab equipment from shelves.
Falling objects	

Standard Operating Procedure (SOP)

The following table is a summary of the overall risk assessment on the Standard Operating Procedure (SOP).

Table 0.3: Risk assessment on the Standard Operating Procedure (SOP). Note: Severity Scale (1=minor; 2=serious; 3=major; 4=fatality), Probability Scale (1=Very unlikely; 2=Unlikely, 3=Possible; 4=Likely).

Standard Operating Procedure	Risk involved	Controls in place	Risk evaluation (severity x probability)
Check all valves are initially closed.	Some valve could be left open. Potentially leading to a spillage.	Manual valves are in place and it is the responsibility of the user to check if they are in the correct position.	3=1x3 (LOW)
Check volume in the storage tanks. Volume should be at least half of the tank capacity.	Tank could be empty, potential pump overheating / failure. Potential fire risk	Tanks are regularly checked. An electronic sensor for the water tank height is also present and is also monitored.	4=4x1 (LOW)
Fully open valves: V19,V20,V30,V35,V36	Some valves can remain closed. This can lead to pressure build-up, pump and /or pipe failure. Potentially leading to a spillage.	Manual valves are in place and it is the responsibility of the user to check if they are in the correct position.	2=1x2 (LOW)

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Select the flow meter to be used and open the corresponding valve at the water and oil lines (e.g. for the oil phase open valve V32 or V33).	Incorrect or no meter is selected. Fluids would just be recirculated and so not a hazardous	Manual valves are in place and it is the responsibility of the user to check if they are in the correct position.	3=1x3 (LOW)
Select the injection configuration. If water is injected from the bottom of the test section and oil from the top, open valves V24 and V27.	Incorrect valve selection. Fluids would just be recirculated and or sent into test section upside down so not hazardous	Manual valves are in place and it is the responsibility of the user to check if they are in the correct position.	3=1x3 (LOW)
Select either the 32mm or 50mm test sections via valve V2.	Wrong line could be selected Leading to spillage if 1 line is being serviced	Manual valves are in place and it is the responsibility of the user to check if they are in the correct position.	4=2x2 (LOW)
If selecting the 32mm test section open values V32, V6 and either V7 (turbine meters) or V8 (coriolis meter).	Incorrect valve selection. Fluids would just be recirculated	Manual valves are in place and it is the responsibility of the user to check if they are in the correct position.	3=1x3 (LOW)
If selecting the 50 mm test section open valves V4, V9 and either V10 (turbine meters) or V11 (coriolis meter).	Incorrect valve selection. Fluids would just be recirculated	Manual valves are in place and it is the responsibility of the user to check if they are in the correct position.	3=1x3 (LOW)

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Open valves V1, V16	Incorrect valve selection. Fluids would just be recirculated	Manual valves are in place and it is the responsibility of the user to check if they are in the correct position.	3=1x3 (LOW)
If the 50 mm test section is selected and jet are to be used open valves V21, V42, V15	Pump could be starved, or lead to pressure build-up, pump and /or pipe failure. Overheating/failure. Potential fire risk.	Manual valves are in place and it is the responsibility of the user to check if they are in the correct position.	3=3x1 (LOW)
Switch on instruments and sensors.		System should be in a failsafe condition when not enabled	3=1x3 (LOW)
Open and run LabVIEW control panel.		System should be in a failsafe condition when LabVIEW not running	3=1x3 (LOW)
Switch on oil pump, water pump and jet pump (if needed)		A pump being left off should be fine.	1=1x1 (LOW)
Reach desired flow rate by first opening valves oil valve V34 and water valve V31 (turbine meter) or V43 (coriolis meter).	If valves are not opened accordingly, pressure build-up can occur.	Manual valves are in place and it is the responsibility of the user to check if they are in the correct position.	3=3x1 (LOW)
In the case of the turbine meters slowly open V34 and V31 until flow is reached.	If valves are not opened accordingly, pressure build-up can occur.	Manual valves are in place and it is the responsibility of the user to check if they are in the correct position.	3=3x1 (LOW)

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In the case of the coriolis meter, open V43 fully and set the desired flow within the labview control system.	If valves are not opened accordingly, pressure build-up can occur.	Manual valves are in place and it is the responsibility of the user to check if they are in the correct position.	3=3x1 (LOW)
If higher flow rates are required but can't be reached, slowly close valve V35 (for oil) and valve V30 (for water).	If valves are not opened accordingly, pressure build-up can occur.	Manual valves are in place and it is the responsibility of the user to check if they are in the correct position.	3=3x1 (LOW)
If the 50 mm test section is used with jets, set the desired flow rate on the LabVIEW in jet mode, then switch back to recirculation mode and use valve V14 to set same pressure as occurs in jet mode. Toggle jetting and recirculation mode as needed via LabVIEW.	If valves are not opened accordingly, pressure build-up can occur.	Manual valves are in place and it is the responsibility of the user to check if they are in the correct position. Pressure will be monitored via LabVIEW and jet pumps will be shut down if excessive.	3=3x1 (LOW)

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Maintain a constant level in the water tank by adjusting valve V31. Simultaneously, monitor the oil-water interface in the separator (i.e. interface should be in the middle of the separator) by opening valves V40 and V16 accordingly.	If valves are not opened accordingly, pressure build-up can occur	Manual valves are in place and it is the responsibility of the user to check if they are in the correct position.	3=3x1 (LOW)
Turn off all pumps.	Tank could become empty, potential pump overheating / failure.	LabVIEW should automatically stop pumps once closed, limiting the chance this could happen	3=3x1 (LOW)
Close all valves, excluding V30, V35, V16, V15	Some valve could be left open. Potentially leading to a spillage.	Manual valves are in place and it is the responsibility of the user to check if they are in the correct position.	3=1x3 (LOW)
Close LabVIEW control panel.	Failure to close LabVIEW could leave some systems in automatic control if the electronics also remain on. Potentially leading to a spillage or mechanical hazard	Requires multiple user errors so unlikely	3=3x1 (LOW)
Switch off all instruments and sensors	Failure to switch of instruments and sensor could leave some systems in automatic control if the electronics also remain on. Could cause a spillage or mechanical hazard	Requires multiple user errors so unlikely	3=3x1 (LOW)

References

- Adrian, R. (1991). Particle-Imaging Techniques For Experimental Fluid-Mechanics. *Annual Review of Fluid Mechanics*, 23(1), pp.261-304.
- Agrawal, S., Gregory, G. and Govier, G. (1973). An analysis of horizontal stratified two phase flow in pipes. *The Canadian Journal of Chemical Engineering*, 51(3), pp.280-286.
- Akai, M., Inoue, A. and Aoki, S. (1981). The prediction of stratified two-phase flow with a two-equation model of turbulence. *International Journal of Multiphase Flow*, 7(1), pp.21-39.
- Al-Sheikh, J., Saunders, D. and Brodkey, R. (1970). Prediction of flow patterns in horizontal two-phase pipe flow. *The Canadian Journal of Chemical Engineering*, 48(1), pp.21-29.
- Ali, I. (2017). *CFD Prediction of Stratified and Intermittent Gas-Liquid Two-Phase Turbulent Pipe Flow Using RANS*. Ph.D thesis. University of Manchester.
- Alizadehdakhel, A., Rahimi, M., Sanjari, J. and Alsairafi, A. (2009). CFD and artificial neural network modeling of two-phase flow pressure drop. *International Communications in Heat and Mass Transfer*, 36(8), pp.850-856.
- Allen, M. and Hanson, R. (1986). Planar Laser-Induced-Fluorescence Monitoring Of OH In A Spray Flame. *Optical Engineering*, 25(12).
- Alves, G. (1953). Cocurrent Liquid-Gas Flow in a Pipeline Contractor. *Chem Engng Prog*, 50, pp.449-456.
- Ambrose, S. (2015). *The rise of Taylor bubbles in vertical pipes*. Ph.D thesis. Imperial College London.
- André, M. and Bardet, P. (2014). Velocity field, surface profile and curvature resolution of steep and short free-surface waves. *Experiments in Fluids*, 55(4).
- Andreussi, P. and Persen, L. (1987). Stratified gas-liquid flow in downwardly inclined pipes. *International Journal of Multiphase Flow*, 13(4), pp.565-575.
- Andritsos, N. (1986). *Effect of pipe diameter and liquid viscosity on horizontal stratified flow*. Ph.D thesis. University of Illinois, Urbana.
- Andritsos, N. (1992). Statistical analysis of waves in horizontal stratified gas-liquid flow. *International Journal of Multiphase Flow*, 18(3), pp.465-473.
- Andritsos, N. and Hanratty, T. (1987). Influence of interfacial waves in stratified gas-liquid flows. *AIChE Journal*, 33(3), pp.444-454.
- Andritsos, N. and Hanratty, T. (1987). Interfacial instabilities for horizontal gas-liquid flows in pipelines. *International Journal of Multiphase Flow*, 13(5), pp.583-603.
- Ayati, A., Kolaas, J., Jensen, A. and Johnson, G. (2014). A PIV investigation of stratified gas-liquid flow in a horizontal pipe. *International Journal of Multiphase Flow*, 61, pp.129-143.

REFERENCES

- Ayati, A., Kolaas, J., Jensen, A. and Johnson, G. (2015). Combined simultaneous two-phase PIV and interface elevation measurements in stratified gas/liquid pipe flow. *International Journal of Multiphase Flow*, 74, pp.45-58.
- Ayati, A., Kolaas, J., Jensen, A. and Johnson, G. (2016). The effect of interfacial waves on the turbulence structure of stratified air/water pipe flow. *International Journal of Multiphase Flow*, 78, pp.104-116.
- Azzopardi, B. (2010). *Chemical Engineering and Chemical Process Technology*. 3rd ed. United Kingdom: Eolss Publishers, pp.97-129.
- Baker, O. (1954). Simultaneous Flow of Oil and Gas. *Oil and Gas Journal*, 53, pp.185-195.
- Bech, K., Tillmark, N., Alfredsson, P. and Andersson, H. (1995). An investigation of turbulent plane Couette flow at low Reynolds numbers. *Journal of Fluid Mechanics*, 286(-1), p.291.
- Beggs, D. and Brill, J. (1973). A Study of Two-Phase Flow in Inclined Pipes. *Journal of Petroleum Technology*, 25(05), pp.607-617.
- Belden, J. and Techet, A. (2010). Simultaneous quantitative flow measurement using PIV on both sides of the air–water interface for breaking waves. *Experiments in Fluids*, 50(1), pp.149-161.
- Bell, K., Taborek, J. and Fenogilo, F. (1970). Interpretation of horizontal in-tube condensation heat transfer correlations with a two-phase flow regime map. *Chem. Eng. Progr., Symp. Ser. 66: No. 102*, 150-63.
- Bergelin, O. and Gazeley, C. (1949). Cocurrent gas-liquid Flow. I. Flow in horizontal tubes,. New York, NY, USA: ASME Heat Transfer and Fluid Mechanics Institute, pp.5–18.
- Biberg, D. (1998). A simple friction model for two-phase stratified pipe flow. Lyon, France: Proc. of the 3rd International Conference on Multiphase Flow.
- Biberg, D. (2007). A MATHEMATICAL MODEL FOR TWO-PHASE STRATIFIED TURBULENT DUCT FLOW. *Multiphase Science and Technology*, 19(1), pp.1-48.
- Birvalski, M. (2015). *Experiments in stratified gas-liquid pipe flow*. Ph.D thesis. University of Belgrade.
- Birvalski, M., Tummers, M. and Henkes, R. (2016). Measurements of gravity and gravity-capillary waves in horizontal gas-liquid pipe flow using PIV in both phases. *International Journal of Multiphase Flow*, 87, pp.102-113.
- Birvalski, M., Tummers, M., Delfos, R. and Henkes, R. (2014). PIV measurements of waves and turbulence in stratified horizontal two-phase pipe flow. *International Journal of Multiphase Flow*, 62, pp.161-173.
- Birvalski, M., Tummers, M., Delfos, R. and Henkes, R. (2015). Laminar–turbulent transition and wave–turbulence interaction in stratified horizontal two-phase pipe flow. *Journal of Fluid Mechanics*, 780, pp.439-456.

REFERENCES

- Brauner, N. and Maron, D. (1993). The role of interfacial shear modelling in predicting the stability of stratified two-phase flow. *Chemical Engineering Science*, 48(16), pp.2867-2879.
- Brennen, C. (2005). *Fundamentals of multiphase flow*. Pasadena, California: Cambridge University Press.
- Chaouki, J. (1997). *Non-invasive monitoring of multiphase flows*. Amsterdam [u.a.]: Elsevier.
- Chen, J. and Spedding, P. (1981). An extension of the Lockhart-Martinelli theory of two phase pressure drop and holdup. *International Journal of Multiphase Flow*, 7(6), pp.659-675.
- Chen, R. and Fan, L. (1992). Particle image velocimetry for characterizing the flow structure in three-dimensional gas-liquid-solid fluidized beds. *Chemical Engineering Science*, 47(13-14), pp.3615-3622.
- Chen, X., Cal, X. and Brill, J. (1997). Gas-Liquid Stratified-Wavy Flow in Horizontal Pipelines. *Journal of Energy Resources Technology*, 119(4), p.209.
- Cheremisinoff, N. and Davis, E. (1979). Stratified turbulent-turbulent gas-liquid flow. *AIChE Journal*, 25(1), pp.48-56.
- Churchill, S. (1977). Friction Factor Equations Spans All Fluid-Flow Regimes. *Chemical Engineering Journal*, 84, pp.91-92.
- Colebrook, C. (1939). Turbulent flow in pipes, with particular reference to the transition region between the smooth and rough pipe laws. *Journal of the Institution of Civil Engineers*, 11(4), pp.133-156.
- De Schepper, S., Heynderickx, G. and Marin, G. (2008). CFD modeling of all gas-liquid and vapor-liquid flow regimes predicted by the Baker chart. *Chemical Engineering Journal*, 138(1-3), pp.349-357.
- del Corral, N. (2014). *Analysis of Two-Phase Flow Pattern Maps*. [online] Brno University of Technology Faculty of Mechanical Engineering Energy Institute. Available at: http://www.energetickéforum.cz/ext/2pf/maps/Documents/Analysis_of_maps.pdf [Accessed 7 May 2018].
- Duan, J., Gong, J., Yao, H., Deng, T. and Zhou, J. (2014). Numerical modeling for stratified gas-liquid flow and heat transfer in pipeline. *Applied Energy*, 115, pp.83-94.
- Duns, H. and Ros, N. (1963). Vertical flow of gas and liquid mixtures in wells. In: *Proc. of 6th World Petroleum Congress*.
- Eaton, B., Knowles, C. and Silberbrg, I. (1967). The Prediction of Flow Patterns, Liquid Holdup and Pressure Losses Occurring During Continuous Two-Phase Flow In Horizontal Pipelines. *Journal of Petroleum Technology*, 19(06), pp.815-828.
- Eck, B. (1973). *Technische Stromungslehre*. New York: Springer.

REFERENCES

- Eggels, J., Unger, F., Weiss, M., Westerweel, J., Adrian, R., Friedrich, R. and Nieuwstadt, F. (1994). Fully developed turbulent pipe flow: a comparison between direct numerical simulation and experiment. *Journal of Fluid Mechanics*, 268(-1), p.175.
- Emamzadeh, M. (2012). *Modelling of annular two-phase flow in horizontal and vertical pipes including the transition from the stratified flow regime*. Ph.D thesis. Imperial College London.
- Espedal, M. (1998). *An experimental investigation of stratified two-phase pipe flow at small inclinations*. Ph.D thesis. Norwegian University of Science and Technology (NTNU).
- Fabre, J., Suzanne, C. and Masbernat, L. (1987). EXPERIMENTAL DATA SET NO. 7: STRATIFIED FLOW, PART I: LOCAL STRUCTURE. *Multiphase Science and Technology*, 3(1-4), pp.285-301.
- Fernandino, M. and Ytrehus, T. (2006). Determination of flow sub-regimes in stratified air–water channel flow using LDV spectra. *International Journal of Multiphase Flow*, 32(4), pp.436-446.
- Fernandino, M. and Ytrehus, T. (2008). Effect of Interfacial Waves on Turbulence Structure in Stratified Duct Flows. *Journal of Fluids Engineering*, 130(6), p.061201.
- Gao, H., Gu, H. and Guo, L. (2003). Numerical study of stratified oil–water two-phase turbulent flow in a horizontal tube. *International Journal of Heat and Mass Transfer*, 46(4), pp.749-754.
- Gazley, C. (1949). *INTERFACIAL SHEAR AND STABILITY IN TWO-PHASE FLOW*. Ph.D thesis. University of Delaware.
- Ghorai, S. and Nigam, K. (2006). CFD modeling of flow profiles and interfacial phenomena in two-phase flow in pipes. *Chemical Engineering and Processing: Process Intensification*, 45(1), pp.55-65.
- Goldstein, S. (1965). *Modern developments in fluid dynamics*. New York: Dover Publications.
- Govier, G. and Omer, M. (1962). The horizontal pipeline flow of air-water mixtures. *The Canadian Journal of Chemical Engineering*, 40(3), pp.93-104.
- Govier, G., Aziz, K. and Schowalter, W. (1973). The Flow of Complex Mixtures in Pipes. *Journal of Applied Mechanics*, 40(2), p.404.
- Graebel, W. (2001). *Engineering Fluid Mechanics*. Milton: Taylor & Francis.
- Grauso, S., Mastrullo, R., Mauro, A., Thome, J. and Vanoli, G. (2013). Flow pattern map, heat transfer and pressure drops during evaporation of R-1234ze(E) and R134a in a horizontal, circular smooth tube: Experiments and assessment of predictive methods. *International Journal of Refrigeration*, 36(2), pp.478-491.

REFERENCES

- Grolman, E. and Fortuin, J. (1996). Transient Gas-Liquid Flow in Upward Sloping Pipes, Approaching the Wavy-to-Slug Flow Transition. *Journal of Fluids Engineering*, 118(4), p.729.
- Hagiwara, Y., Esmailzadeh, E., Tsutsui, H. and Suzuki, K. (1989). Simultaneous measurement of liquid film thickness, wall shear stress and gas flow turbulence of horizontal wavy two-phase flow. *International Journal of Multiphase Flow*, 15(3), pp.421-431.
- Hamersma, P. and Hart, J. (1987). A pressure drop correlation for gas/liquid pipe flow with a small liquid holdup. *Chemical Engineering Science*, 42(5), pp.1187-1196.
- Hand, N. (1991). *Gas liquid co-current flow in a horizontal pipe*. Ph.D thesis. Faculty of Engineering, The Queen's University of Belfast.
- Hand, N. and Spedding, P. (1991). *Gas-liquid co-current flow data in horizontal pipes at atmospheric pressure, report CE/1/91*. Department of Chemical Engineering, The Queen's University of Belfast.
- Hanson, R., Seitzman, J. and Paul, P. (1990). Planar laser-fluorescence imaging of combustion gases. *Applied Physics B Photophysics and Laser Chemistry*, 50(6), pp.441-454.
- Hart, J., Hamersma, P. and Fortuin, J. (1989). Correlations predicting frictional pressure drop and liquid holdup during horizontal gas-liquid pipe flow with a small liquid holdup. *International Journal of Multiphase Flow*, 15(6), pp.947-964.
- Hassan, Y., Blanchat, T., Seeley, C. and Canaan, R. (1992). Simultaneous velocity measurements of both components of a two-phase flow using particle image velocimetry. *International Journal of Multiphase Flow*, 18(3), pp.371-395.
- Hoogendoorn, C. (1959). Gas-liquid flow in horizontal pipes. *Chemical Engineering Science*, 9(4), pp.205-217.
- Hoogendoorn, C. and Buitelaar, A. (1961). The effect of gas density and gradual vaporization on gas-liquid flow in horizontal pipes. *Chemical Engineering Science*, 16(3-4), pp.208-221.
- Huntington, R. and White, P. (1958). Horizontal Co-Current Two-Phase Flow of Fluid in Pipe Lines. *The Petroleum Engineer*, 27(9), p.40.
- Ibarra, R. (2017). *Horizontal and low-inclination oil-water flow investigations using laser-based diagnostic techniques*. Ph.D thesis. Imperial College London.
- Ishii, M. and Grolmes, M. (1975). Inception criteria for droplet entrainment in two-phase concurrent film flow. *AIChE Journal*, 21(2), pp.308-318.
- Issa, R. (1988). Prediction of turbulent, stratified, two-phase flow in inclined pipes and channels. *International Journal of Multiphase Flow*, 14(2), pp.141-154.
- Jayanti, S. (1991). *Interfacial friction in horizontal stratified flow*. MPS Report no.6. Department of Chemical Engineering, Imperial College London.

REFERENCES

- Jenkins, R. (1947). *Two-phase, two-component flow of air and water..* M.S. University of Delaware.
- Jensen, J. (2004). Flow measurements. In: Proceedings of ENCIT2004, XXVI, No. 4. pp.400–419.
- Johnson, H. and Abou-Sabe, A. (1952). Heat Transfer and Pressure Drop for Turbulent Flow of Air-Water Mixtures in a Horizontal Pipe. *Trans ASME*, 74, pp.977-987.
- Johnson, R. (2016). *Handbook of Fluid Dynamics, Second Edition*. s.l: CRC Press.
- Kadambi, V. (1982). Stability of annular flow in horizontal tubes. *International Journal of Multiphase Flow*, 8(4), pp.311-328.
- Kang, H. and Kim, M. (1993). The relation between the interfacial shear stress and the wave motion in a stratified flow. *International Journal of Multiphase Flow*, 19(1), pp.35-49.
- Kawajl, M., Anoda, Y., Nakamura, H. and Tasaka, T. (1987). Phase and velocity distributions and holdup in high-pressure steam/water stratified flow in a large diameter horizontal pipe. *International Journal of Multiphase Flow*, 13(2), pp.145-159.
- Knowles, C. (1965). *The Effects of Flow Patterns of Pressure Loss in Multiphase Horizontal Flow*. M.S thesis. The University of Texas, Austin.
- Kokal, S. and Stanislav, J. (1989). An experimental study of two-phase flow in slightly inclined pipes—II. Liquid holdup and pressure drop. *Chemical Engineering Science*, 44(3), pp.681-693.
- Kosterin, S. (1949). An Investigation of the Influence of Diameter and Inclination of a Tube on the Hydraulic Resistance and Flow Structure of Gas-Liquid Mixtures. *Izvest. Akad, Nauk, USSR*, 12, pp.1824-1830.
- Kou, J., Gong, S. and Yang, W. (2011). Numerical simulation research on flow pattern of gas-water two-phase flow in horizontal pipeline. In: *Mechanic Automation and Control Engineering (MACE), IEEE*. pp.484-487.
- Kowalski, J. (1987). Wall and interfacial shear stress in stratified flow in a horizontal pipe. *AIChE Journal*, 33(2), pp.274-281.
- Krasiakova, L. (1952). Some Characteristics of Movements of Two-Phase Mixtures in a Horizontal Pipe. *Zhur Tech Fig 22, AERE Lib/Trans 695*, p.656.
- Kumara, W., Halvorsen, B. and Melaaen, M. (2010). Particle image velocimetry for characterizing the flow structure of oil–water flow in horizontal and slightly inclined pipes. *Chemical Engineering Science*, 65(15), pp.4332-4349.
- Lamari, M. (2002). *An experimental investigation of two-phase (air-water) flow regimes in a horizontal tube at near atmospheric conditions*. Ottawa: National Library of Canada = Bibliothèque nationale du Canada.

REFERENCES

- Langsholt, M., Nordsveen, M., Lunde, K., Nesic, S. and Enerhaug, J. (1997). Wall Shear Stress and Mass Transfer Rates-Important Parameters in CO₂ Corrosion. In: *8th International Conference on Multiphase Production (Multiphase '97)*..
- Liao, J., Ohkawa, K. and Frepoli, C. (2015). A horizontal stratified gas-liquid two-phase flow model for the two-fluid model in the W COBRA/TRAC-TF2 PWR safety analysis code. *Nuclear Engineering and Design*, 295, pp.239-250.
- Lin, P. and Hanratty, T. (1986). Prediction of the initiation of slugs with linear stability theory. *International Journal of Multiphase Flow*, 12(1), pp.79-98.
- Lin, P. and Hanratty, T. (1987). Detection of slug flow from pressure measurements. *International Journal of Multiphase Flow*, 13(1), pp.13-21.
- Lin, P. and Hanratty, T. (1987). Effect of pipe diameter on flow patterns for air-water flow in horizontal pipes. *International Journal of Multiphase Flow*, 13(4), pp.549-563.
- Liu, L. (2005). *Optical and computational studies of liquid-liquid flows*. Ph.D thesis. Imperial College London.
- Liu, Y., Zhang, H. and Wang, J. (2007). Estimation of Liquid Wall and Interfacial Shear Stress in Horizontal Stratified Gas-liquid Pipe Flow. AIP Conference Proceedings (American Institute of Physics) 914, 610.
- Lopez, D. (2018). *Ecoulements diphasiques à phases séparées à faible contenu de liquide*. Ph.D thesis. National Polytechnic Institute of Toulouse.
- Lorencez, C., Nasr-Esfahany, M., Kawaji, M. and Ojha, M. (1997). Liquid turbulence structure at a sheared and wavy gas-liquid interface. *International Journal of Multiphase Flow*, 23(2), pp.205-226.
- Lu, G., Wang, J. and Jia, Z. (2007). Experimental and Numerical Investigations on Horizontal Oil-Gas Flow. *Journal of Hydrodynamics, Ser. B*, 19(6), pp.683-689.
- Mandhane, J., Gregory, G. and Aziz, K. (1974). A flow pattern map for gas-liquid flow in horizontal pipes. *International Journal of Multiphase Flow*, 1(4), pp.537-553.
- McCormick, M. (2010). *Ocean engineering mechanics*. Cambridge University Press.
- Meknassi, F., Benkirane, R., Liné, A. and Masbernat, L. (2000). Numerical modeling of wavy stratified two-phase flow in pipes. *Chemical Engineering Science*, 55(20), pp.4681-4697.
- Melling, A. (1997). Tracer particles and seeding for particle image velocimetry. *Measurement Science and Technology*, 8(12), pp.1406-1416.
- Melton, L. and Verdick, J. (1985). Vapor/Liquid Visualization for Fuel Sprays. *Combustion Science and Technology*, 42(3-4), pp.217-222.
- Morgan, R., Markides, C., Hale, C. and Hewitt, G. (2012). Horizontal liquid-liquid flow characteristics at low superficial velocities using laser-induced fluorescence. *International Journal of Multiphase Flow*, 43, pp.101-117.

REFERENCES

- Newton, C. and Behnia, M. (1996). Estimation of gas wall shear stress in horizontal stratified gas-liquid pipe flow. *AIChE Journal*, 42(8), pp.2369-2373.
- Newton, C. and Behnia, M. (2000). Numerical calculation of turbulent stratified gas-liquid pipe flows. *International Journal of Multiphase Flow*, 26(2), pp.327-337.
- Newton, C. and Behnia, M. (2001). A numerical model of stratified wavy gas-liquid pipe flow. *Chemical Engineering Science*, 56(24), pp.6851-6861.
- Newton, C., Behnia, M. and Reizes, J. (1999). The effect of liquid viscosity on gas wall and interfacial shear stress in horizontal two-phase pipe flow. *Chemical Engineering Science*, 54(8), pp.1071-1079.
- Ng, T. (2002). *Interfacial structure of stratified pipe flow*. Ph.D thesis. Imperial College London.
- Nicholson, M., Aziz, K. and Gregory, G. (1978). Intermittent two phase flow in horizontal pipes: Predictive models. *The Canadian Journal of Chemical Engineering*, 56(6), pp.653-663.
- Oliemans, R. (1987). Modelling of gas-condensate flow in horizontal and inclined pipes. Dallas, Texas: Pipeline Engineering Symposium.
- Olive, N., Zhang, H., Wang, Q., Redus, C. and Brill, J. (2003). Experimental Study of Low Liquid Loading Gas-Liquid Flow in Near-Horizontal Pipes. *Journal of Energy Resources Technology*, 125(4), p.294.
- Omgba-Essama, C. (2004). *Numerical modelling of transient gas-liquid flows (application to stratified & slug flow regimes)*. Ph.D thesis. Cranfield University.
- Ottens, M., Hoefsloot, H. and Hamersma, P. (2001). Correlations Predicting Liquid Hold-up and Pressure Gradient in Steady-State (Nearly) Horizontal Co-Current Gas-Liquid Pipe Flow. *Chemical Engineering Research and Design*, 79(5), pp.581-592.
- Paras, S. and Karabelas, A. (1992). Measurements of local velocities inside thin liquid films in horizontal two-phase flow. *Experiments in Fluids*, 13(2-3), pp.190-198.
- Paras, S., Vlachos, N. and Karabelas, A. (1994). Liquid layer characteristics in stratified—Atomization flow. *International Journal of Multiphase Flow*, 20(5), pp.939-956.
- Parvareh, A., Rahimi, M., Alizadehdakhel, A. and Alsairafi, A. (2010). CFD and ERT investigations on two-phase flow regimes in vertical and horizontal tubes. *International Communications in Heat and Mass Transfer*, 37(3), pp.304-311.
- Pawloski, J. (2001). *A study of air-oil two-phase flow in a horizontal straight pipe*.
- Pawloski, J., Ching, C. and Shoukri, M. (2004). Measurement of Void Fraction and Pressure Drop of Air-Oil Two-Phase Flow in Horizontal Pipes. *Journal of Engineering for Gas Turbines and Power*, 126(1), p.107.
- Petalas, N. and Aziz, K. (2000). A Mechanistic Model for Multiphase Flow in Pipes. *Journal of Canadian Petroleum Technology*, 39(06).

REFERENCES

- Rosant, J. (1994). Liquid-wall shear stress in stratified liquid/gas flow. *Journal of Applied Electrochemistry*, 24(7), pp.612-618.
- Rouhani, S. and Sohal, M. (1983). Two-phase flow patterns: A review of research results. *Progress in Nuclear Energy*, 11(3), pp.219-259.
- Royal Dutch Shell (2007). GAS/LIQUID SEPARATORS - TYPE SELECTION AND DESIGN RULES. [online] Available at: http://razifar.com/cariboost_files/Gas-Liquid_20Separators_20-_20Type_20Selection_20and_20Design_20Rules.pdf [Accessed 7 May 2018].
- Russell, T., Etschells, A., Jensen, R. and Arruda, P. (1974). Pressure drop and holdup in stratified gas-liquid flow. *AIChE Journal*, 20(4), pp.664-669.
- Sanchis, A. and Jensen, A. (2011). Dynamic masking of PIV images using the Radon transform in free surface flows. *Experiments in Fluids*, 51(4), pp.871-880.
- Schicht, H. (2018). Flow Patterns for Adiabatic Two-Phase Flow of Water and Air Within a Horizontal Tube. *Verfahrenstechnik*, 3, pp.153-172.
- Schlichting, H. (1960). *Boundary layer theory*. New York: McGraw-Hill.
- Schubring, D., Ashwood, A., Shedd, T. and Hurlburt, E. (2010). Planar laser-induced fluorescence (PLIF) measurements of liquid film thickness in annular flow. Part I: Methods and data. *International Journal of Multiphase Flow*, 36(10), pp.815-824.
- Scott, D. (1963). Properties of Co-Current Gas-Liquid Flow. *Advances in Chemical Engineering*, 4, pp.199-277.
- Seitzman, J. and Hanson, R. (1993). Two-line planar fluorescence for temporally resolved temperature imaging in a reacting supersonic flow over a body. *Applied Physics B Photophysics and Laser Chemistry*, 57(6), pp.385-391.
- Shaha, J. (1999). *Phase interactions in transient stratified flow*. Ph.D thesis. Imperial College London.
- Shoham, O. and Taitel, Y. (1984). Stratified turbulent-turbulent gas-liquid flow in horizontal and inclined pipes. *AIChE Journal*, 30(3), pp.377-385.
- Sidi-Ali, K. and Gatignol, R. (2010). Interfacial friction factor determination using CFD simulations in a horizontal stratified two-phase flow. *Chemical Engineering Science*, 65(18), pp.5160-5169.
- Simpson, H., Rooney, D., Gratton, E. and Al-Samarrel, F. (1977). Two-Phase Flow in Large Diameter Horizontal Lines. European Two-Phase Flow Group Meeting Paper H6.
- Sinai, Y. (1983). A charnock-based estimate of interfacial resistance and roughness for internal, fully-developed, stratified, two-phase horizontal flow. *International Journal of Multiphase Flow*, 9(1), pp.13-19.

REFERENCES

- Spedding, P. and Chen, J. (1981). A simplified method of determining flow pattern transition of two-phase flow in a horizontal pipe. *International Journal of Multiphase Flow*, 7(6), pp.729-731.
- Spedding, P. and Hand, N. (1990). Prediction of holdup and pressure loss from the two- phase momentum balance for stratified type flows. Proc. of ASME-FED, Advances in gas- liquid flows, 99, HTD-vol. 188, pp.73-87.
- Spedding, P. and Hand, N. (1997). Prediction in stratified gas-liquid co-current flow in horizontal pipelines. *International Journal of Heat and Mass Transfer*, 40(8), pp.1923-1935.
- Spedding, P. and Nguyen, V. (1980). Regime maps for air water two phase flow. *Chemical Engineering Science*, 35(4), pp.779-793.
- Spedding, P. and Spence, D. (1993). Flow regimes in two-phase gas-liquid flow. *International Journal of Multiphase Flow*, 19(2), pp.245-280.
- Spedding, P., Cooper, R. and McBride, W. (2008). A Universal Flow Regime Map for Horizontal Two-Phase Flow in Pipes. *Developments in Chemical Engineering and Mineral Processing*, 11(1-2), pp.95-106.
- Srichai, S. (1994). *High Pressure Separated Two-Phase Flow*. Ph.D thesis. Imperial College London.
- Srichai, S., Jayanti, S. & Hewitt, G. F. (1995). CFD techniques for separated two-phase flows. In: *Proceedings of the First Asian CFD Conference*. pp.1025-1031.
- Steenbergen, W. (1996). Reduction of beam refraction in optical pipe flow experiments by use of sheet-fabricated pipe walls. *Experiments in Fluids*, 22(2), pp.165-173.
- Strand, O. (1993). *An Experimental Investigation of Stratified Two-Phase Flow in Horizontal Pipes*. Ph.D thesis. Department of Mathematics, University of Oslo, Norway.
- Taitel, Y. and Dukler, A. (1976). A model for predicting flow regime transitions in horizontal and near horizontal gas-liquid flow. *AIChE Journal*, 22(1), pp.47-55.
- Techet, A. and McDonald, A. (2005). High Speed PIV of Breaking Waves on Both Sides of the Air- Water Interface. In: *6th International Symposium on Particle Image Velocimetry*. pp.1-14.
- Thermal Fluids Central. (2010). *Two-Phase Flow Patterns in Horizontal Tubes*. [online] Available at: https://www.thermalfluidscentral.org/encyclopedia/index.php/Two-Phase_Flow_Patterns_in_Horizontal_Tubes [Accessed 7 May 2018].
- Tzotzi, C. and Andritsos, N. (2013). Interfacial shear stress in wavy stratified gas-liquid flow in horizontal pipes. *International Journal of Multiphase Flow*, 54, pp.43-54.
- Tzotzi, C., Bontozoglou, V., Andritsos, N. and Vlachogiannis, M. (2011). Effect of Fluid Properties on Flow Patterns in Two-Phase Gas-Liquid Flow in Horizontal and Downward Pipes†. *Industrial & Engineering Chemistry Research*, 50(2), pp.645-655.

REFERENCES

- Ullmann, A., Goldstein, A., Zamir, M. and Brauner, N. (2004). Closure relations for the shear stresses in two-fluid models for laminar stratified flow. *International Journal of Multiphase Flow*, 30(7-8), pp.877-900.
- Vestøl, S. and Melaaen, M. (2007). PIV and gamma measurements of stratified unprocessed gas flow in a horizontal and near horizontal test pipe. In: *Proc. 13th Int. Conf. Multiphase Prod. Technol.* pp.237–250.
- Vestøl, S., Kumara, W. and Melaaen, M. (2017). Particle image velocimetry measurements of stratified gas-liquid flow in horizontal and inclined pipes. *International Journal of Computational Methods and Experimental Measurements*, 6(2), pp.411-422.
- Vieira, R., Kesana, N., Torres, C., McLaury, B., Shirazi, S., Schleicher, E. and Hampel, U. (2014). Experimental Investigation of Horizontal Gas-Liquid Stratified and Annular Flow Using Wire-Mesh Sensor. *Journal of Fluids Engineering*, 136(12), p.121301.
- Vlachos, N., Paras, S. and Karabelas, A. (1993). Liquid Layer and Wall Shear Stress Characteristics in Stratified/Atomization Flow. In: *30th Meeting European Two-Phase Flow Group*.
- Vlachos, N., Paras, S. and Karabelas, A. (1997). Liquid-to-wall shear stress distribution in stratified/atomization flow. *International Journal of Multiphase Flow*, 23(5), pp.845-863.
- Vlachos, N., Paras, S. and Karabelas, A. (1999). Prediction of holdup, axial pressure gradient and wall shear stress in wavy stratified and stratified/atomization gas/liquid flow. *International Journal of Multiphase Flow*, 25(2), pp.365-376.
- Voulgaropoulos, V. (2017). *Dynamics of Spatially Evolving Dispersed Flows*. Ph.D thesis. University College London.
- Weisman, J. and Kang, S. (1981). Flow pattern transitions in vertical and upwardly inclined lines. *International Journal of Multiphase Flow*, 7(3), pp.271-291.
- Weisman, J., Duncan, D., Gibson, J. and Crawford, T. (1979). Effects of fluid properties and pipe diameter on two-phase flow patterns in horizontal lines. *International Journal of Multiphase Flow*, 5(6), pp.437-462.
- Westerweel, J. (1997). Fundamentals of digital particle image velocimetry. *Measurement Science and Technology*, 8(12), pp.1379-1392.
- Whalley, P. (1987). *Boiling, condensation, and gas-liquid flow*. Oxford: Forlag.
- Whalley, P. (1987). Flooding, slugging and bottle emptying. *International Journal of Multiphase Flow*, 13(5), pp.723-728.
- Xiao, J. (1990). *A comprehensive mechanistic model for two-phase flow in pipelines*. MSc thesis. Department of Petroleum Engineering, University of Tulsa.
- Yadigaroglu, G. and Hewitt, G. (2018). *Introduction to multiphase flow*. Cham: Springer.

REFERENCES

- Yeh, Y. and Cummins, H. (1964). LOCALIZED FLUID FLOW MEASUREMENTS WITH AN He-Ne LASER SPECTROMETER. *Applied Physics Letters*, 4(10), pp.176-178.
- Zadrazil, I., Matar, O. and Markides, C. (2014). An experimental characterization of downwards gas-liquid annular flow by laser-induced fluorescence: Flow regimes and film statistics. *International Journal of Multiphase Flow*, 60, pp.87-102.
- Zhou, F. and Li, W. (1999). Interfacial shear stress and friction factor of stratified flow. In: *Proc. of 2nd International Symposium on Two-phase Flow Modelling and Experimentation*, 2. pp.1263-1268.