

A Revision of Liquid-Liquid Flow Patterns in Horizontal and Slightly Inclined Pipes

Roberto Ibarra^a, Omar K. Matar^b, Christos N. Markides^c

Department of Chemical Engineering, Imperial College London, London SW7 2AZ, UK

^a r.ibarra-hernandez13@imperial.ac.uk

^b o.matar@imperial.ac.uk

^c c.markides@imperial.ac.uk

Abstract

This paper presents a review of co-current flow of two immiscible liquids in horizontal and slightly inclined pipes. Liquid-liquid flows are present in a wide variety of industrial processes, such as chemical, pharmaceutical, and food processing. However, this phenomenon is mainly studied in the oil industry, especially for the analysis of oil-water mixtures encountered in long transportation pipelines from the wellhead to processing facilities. The hydrodynamic behaviour of liquid-liquid flows is more complex than gas-liquid flows due to the density ratio, viscosity ratio, interfacial forces and pipe wettability. This means that a significant number of different flow patterns can be obtained from different fluid properties and pipe characteristics. Furthermore, the flow pattern classification of liquid-liquid flows is an arbitrary process in which several authors have used their own classification complicating comparison and analysis of

flow pattern maps. In this paper, a unified flow pattern classification for liquid-liquid flow is proposed. This classification enables the direct comparison of flow pattern maps for further analysis.

Keywords: Horizontal liquid-liquid flow; inclined liquid-liquid flow; flow pattern map; flow pattern classification

1. Introduction

A number of studies in liquid-liquid flows have been performed over the last 50 years. This has allowed the development of flow pattern maps for specific flow conditions, fluid properties and pipe characteristics. Some authors have attempted to develop correlations and mechanistic models to characterise the behaviour of these types of flows. However, this is a difficult task due to the complex phenomenon of liquid-liquid flows in pipes. The present review discusses the study of co-current flow of two immiscible liquids in horizontal and inclined pipes. This phenomenon is of great interest in a variety of industrial sectors, especially the oil industry in which mixtures of oil and water commonly flow together in transportation pipelines.

Flow patterns depend on three basic parameters: flow velocity; pipe characteristics, which are defined as pipe diameter, pipe roughness, and inclination angle; and fluid properties, which are based on fluid density, viscosity, surface tension, and wettability. The density ratio has a significant effect in two-phase flow systems. Phases tend to flow at different velocities when the density difference between the phases is significant. Furthermore, gravity enhances the separation of the phases in the pipe. This behaviour is encountered in gas-liquid systems where the density of the gas phase is much lower than the liquid phase, resulting in well-structured flow patterns. On the other hand, liquid-liquid systems have a density ratio close to unity and a viscosity ratio that can vary from 0.3 to 10,000 (Valle, 2000). Interfacial forces become more important for liquid-liquid systems due to wetting characteristics, surface tension and phase inversion. These mechanisms make liquid-liquid flows a complex phenomenon, which complicates the development of predictive tools.

Gas-liquid mixtures have been extensively studied, resulting in large data sets used to develop predictive tools for a wide range of conditions. A number of empirical correlations and mechanistic models are currently available for gas-liquid flows, such as Hagedorn and Brown (1965), Beggs and Brill (1973), Taitel and Dukler (1976), and Barnea (1987), which are widely used and provide accurate results. In contrast, liquid-liquid flows have not been rigorously modelled, mainly due to the assumption that liquid-liquid flows behave as homogeneous mixtures (Torres-Monzón, 2006). However, experimental data have revealed that liquid-liquid flows present a complex hydrodynamics, making the homogeneous model only applicable for a limited range of conditions.

One of the first studies in liquid-liquid flow was carried out by Russell et al. (1959) where three flow patterns were identified by visual observations, namely, stratified flow, bubble flow and mixed flow. A number of studies have been conducted after Russell et al. (1959) to characterise liquid-liquid flows, such as those by Charles et al. (1961), Hasson et al. (1970), Oglesby (1979), and Arirachakaran et al. (1989). However, these studies have been performed in horizontal pipes. A limited number of liquid-liquid studies have been focused on slightly inclined pipes (Oddie et al., 2003; Lum et al., 2006; Rodriguez and Oliemans, 2006; Atmaca et al., 2009; Kumara et al., 2009). The effect of pipe inclination on liquid-liquid systems results in flow pattern transitions at different conditions than in horizontal systems. Gravity acts in the direction of the flow for downward inclinations (i.e. denser fluid flows at higher velocities) and in the opposite direction for upward inclinations (i.e. denser fluid flows at slower velocities) (Kumara et al., 2009).

A number of measurement techniques have been used to characterise liquid-liquid flows, such as quick closing valves, impedance probes, conductivity probes, conductance probes, differential pressure transducers, gamma densitometer, and high-speed photography. Currently, high accuracy images and detailed flow information can be obtained with the implementation of advance visualisation techniques, namely, Planar Laser Induced Fluorescence (PLIF), Particle Image Velocimetry (PIV) and Particle Tracking Velocimetry (PTV). Morgan et al. (2012,2013) used laser-based techniques to study the co-current flow of two initially stratified immiscible liquids in horizontal pipes, both of circular (Morgan et al., 2013) and square (Morgan et al., 2012) cross-section, obtaining information on phase distribution, in-situ phase fraction, interfacial level and droplet size distribution.

2. Liquid-Liquid Flow Pattern Classification and Flow Pattern Map

Several authors have used different flow pattern classifications for the flow of two immiscible liquids in a pipe. These flow patterns have been obtained from experimental investigations carried out at different conditions, namely, fluid properties, flow velocities, pipe material and test section configuration (e.g. inlet design and pipe inclination). Complex configurations are encountered for liquid-liquid flows, such as dual dispersions, and dual dispersions with stratified layers. As a result, a large number of different definitions arise which complicates the flow pattern classification. This is in contrast to gas-liquid flows in which the flow pattern classification is clearly defined. However, four main flow patterns can be distinguished in liquid-liquid flows, namely: (1) stratified flow, where both liquids flow as separated layers; (2) dispersed flow, droplets of one phase into the other; (3) intermittent flow; and (4) annular flow, one of the liquids in the core and the other in the annulus. Each of these four main patterns can be sub-divided into more specific flow configurations.

2.1 Horizontal Experimental Studies

One of the first liquid-liquid flow pattern classifications was performed by Russell et al. (1959) in which three flow patterns were identified. The experimental investigations were carried out in a 1-in. horizontal pipe of 8 m long. The fluids used were tap water and mineral oil with a density of 835 kg/m³ and viscosity of 18 mPa.s. For a fixed water superficial velocity, U_{sw} , and increasing input oil fraction, $\phi_{in,o}$, defined as the oil volumetric flow rate divided by the total volumetric flow rate $\phi_{in,o} = Q_o / (Q_o + Q_w)$, the flow patterns observed were: (1) bubble flow, where oil droplets move at the top of the pipe; (2) stratified flow, where the lighter liquid flows at the top of the pipe; and (3)

mixed flow. Russell et al. (1959) found that as increasing the flow rate, turbulence also increases promoting the formation of droplets.

Charles et al. (1961) performed similar experiments to those of Russell et al. (1959) in a 8.78 m long test section (1-in. pipe). Oil with viscosities 6.29, 16.8 and 65 mPa.s were used. The oil density closely matched the water density ($\rho_o = 988 \text{ kg/m}^3$). Five different flow patterns, as shown in **Figure 1**, were observed: (1) water drops in oil, (2) oil in water concentric, (3) oil slugs in water, (4) oil bubbles in water, and (5) oil drops in water. Charles et al. (1961) did not observe stratified flow. This can be attributed to the density ratio between both liquids in which gravity forces tend to move the heavier phase to the bottom of the pipe. From the experiments conducted with different oil viscosities, Charles et al. (1961) found that the flow patterns observed were similar, i.e., the oil viscosity has little effect on the flow pattern of two immiscible liquids in a pipe. However, the flow pattern map obtained with the more viscous oil presented some differences, as shown in **Figure 2** and **Figure 3**, in which flow pattern transitions occurred at different flow conditions. These differences were attributed to surface tension forces for high viscosity fluids. In addition, Charles et al. (1961) found a transition from oil to water continuous for the experiments with the most viscous oil.

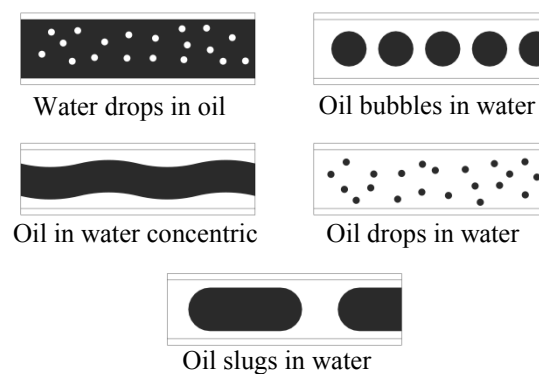


Figure 1: Flow patterns observed in 1-in. pipe (adapted from Charles et al., 1961).

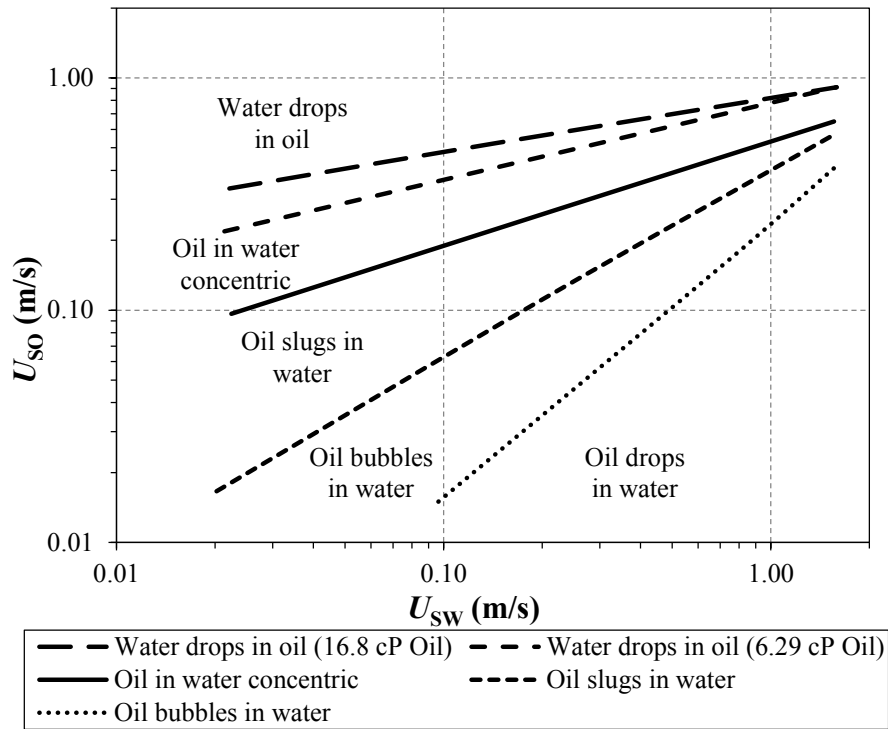


Figure 2: Flow pattern transitions for 1-in. oil-water flow with similar densities and oil viscosities of 6.29 and 16.8 mPa.s (adapted from Charles et al., 1961).

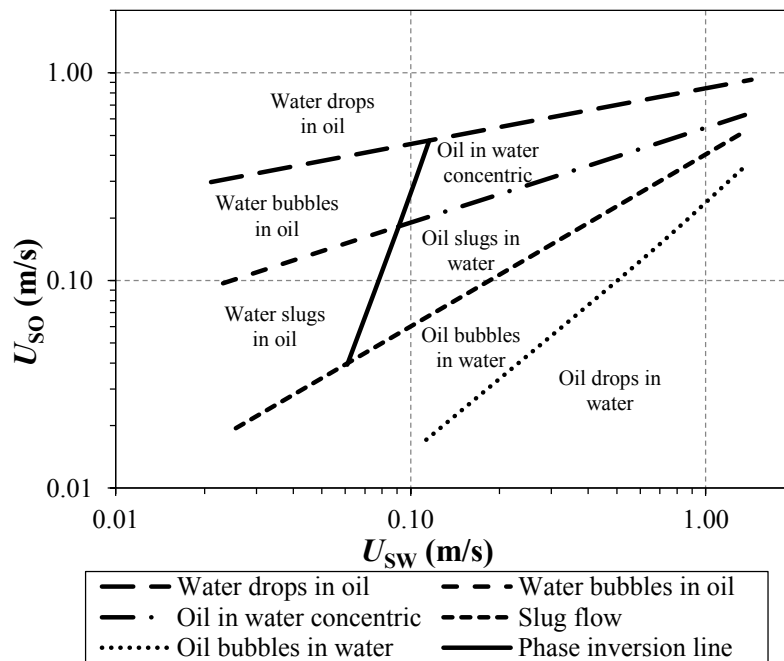


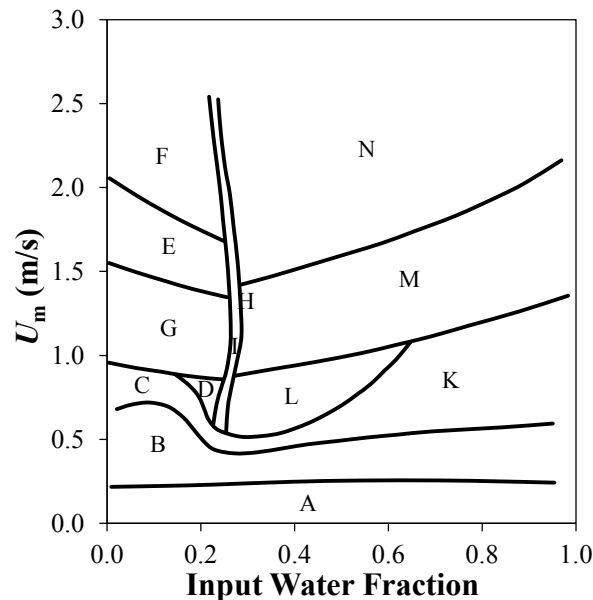
Figure 3: Flow pattern map for horizontal 1-in. oil-water flow with similar densities and oil viscosity of 65.0 mPa.s (adapted from Charles et al., 1961).

Hasson et al. (1970) studied initially concentric flow in a 12.6 mm internal diameter (ID) pipe of 2.7 m long using distilled water and a kerosene-perchloroethylene solution with equal densities (1020 kg/m^3) and viscosities of 0.8 mPa.s and 1.0 mPa.s, respectively. Water was injected in the core and the oil in the annulus. Hasson et al. (1970) used high speed photography to characterise the flow pattern, obtaining five different flow regimes: dispersion, slug, stratified layers, annular and mixed flow. Hasson et al. (1970) concluded that the flow patterns from initially concentric flow (i.e., annular flow) depend on: the flow rates, the break-up mechanism, and the wettability of the pipe (i.e. once the initially annular structure breaks). Two types of pipe materials were tested: hydrophobic and hydrophilic pipe. It was found that the pipe wettability has an effect on the flow pattern transition and the break-up mechanism. Hydrophobic pipes promote water continuous flows and hydrophilic pipes promote break-up of the annulus.

Oglesby (1979) performed experiments in a 41 mm internal diameter horizontal pipe using water and oils with viscosities of 32, 61 and 167 mPa.s. Fourteen flow patterns were identified (see **Table 1**). Phase inversion was observed at an input water fraction between 0.2 and 0.4 (vertical transition H and I in **Figure 4**). Oglesby (1979) observed annular flow with water in the core and oil in the annulus. This behaviour contradicts the minimum viscous dissipation principle which states that the liquid with the lower viscosity is expected to encapsulate the higher viscous liquid (Joseph et al., 1984). This principle is based on energy dissipation in which the lower viscosity liquid radially migrates to form a lubrication layer at the pipe wall.

Table 1: Flow pattern classification (Oglesby, 1979).

Category	Flow Pattern
Segregated	A- Stratified flow.
	B- Stratified flow with mixing at the interface.
Oil dominant	C- Dispersion of oil in water with a free oil layer at the top. The dispersion layer occupies less than half of the pipe cross sectional area.
	D- Dispersion of oil in water with a free oil layer at the top. The dispersion layer occupies more than half of the pipe cross sectional area.
	E- Non-homogeneous water in oil dispersion.
	F- Homogenous water in oil dispersion.
	G- Annular flow with water in the core and oil in the annulus.
	H- Water slugs in oil.
Water dominant	I- Oil slugs in water.
	J- Annular flow with oil in the core and water in the annulus.
	K- Dispersion of water in oil with a free water layer at the bottom. The dispersion layer occupies less than half of the pipe cross sectional area.
	L- Dispersion of water in oil with a free water layer at the bottom. The dispersion layer occupies more than half of the pipe cross sectional area.
	M- Non-homogeneous oil in water dispersion.
	N- Homogenous oil in water dispersion.

**Figure 4:** Flow pattern map for horizontal 41 mm ID oil-water flow (adapted from Oglesby, 1979).

Arirachakaran et al. (1989) conducted oil-water experimental investigations in horizontal pipes using two test sections: (i) a 1.5-in. pipe with oil viscosities of 4.7, 58.0, 84.0 and 115.0 mPa.s, and (ii) a 1-in. pipe with oil viscosities of 237 and 2116 mPa.s. Mixture velocities (U_m) were varied from 0.46 to 3.66 m/s and the input water fraction ($\phi_{in,w}$) from 0.05 to 0.9. Arirachakaran et al. (1989) classified the observed flow patterns as follows (see **Figure 5**):

1. Stratified (S): separate layers with possibility of mixing at the interface.
2. Mixed: dispersion of one phase into the other with possibility of pure layer, i.e., water dispersed with oil layer (MO) and oil dispersed with water layer (MW).
3. Annular (AO): water core with an oil annulus.
4. Intermittent: slugs of a continuous phase or an accumulation of droplets, i.e., oil slugs in water (IO) and water slugs in oil (IW).
5. Dispersed: homogeneous mixture, i.e., oil dispersion in water (DO) and water dispersion in oil (DW).

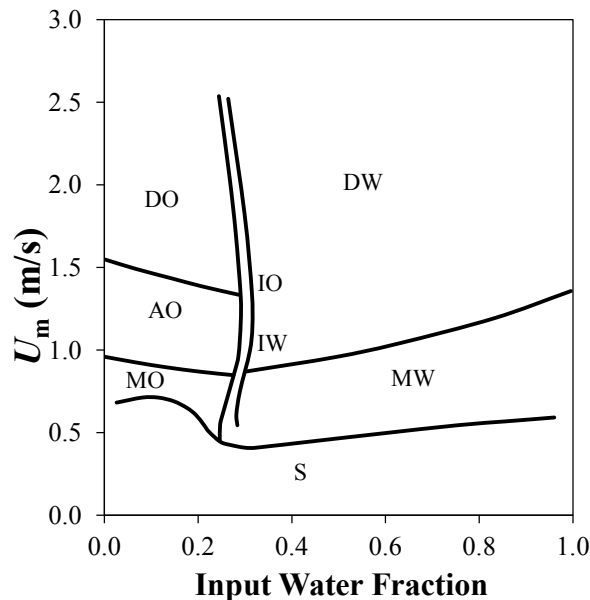


Figure 5: Flow pattern map for horizontal 1.5-in. oil-water flow with $\mu_o = 84.0$ mPa.s (adapted from Arirachakaran et al., 1989).

Arirachakaran et al. (1989) found that the oil viscosity has little effect on the flow pattern for water continuous flows. Annular flow with water in the annulus was not observed. It was suggested that the oils were not viscous and heavy enough to develop a stable oil core and water annulus. In addition to the construction of a flow pattern map, Arirachakaran et al. (1989) studied the phase inversion phenomena in oil-water flows, for which the phase inversion is found to be a function of the oil viscosity and the input water fraction in the fully laminar region for the oil phase as observed in **Figure 6**. The correlation was developed taking into account data from Russell et al. (1959), Charles et al. (1961), Guzhov et al. (1973) and Oglesby (1979).

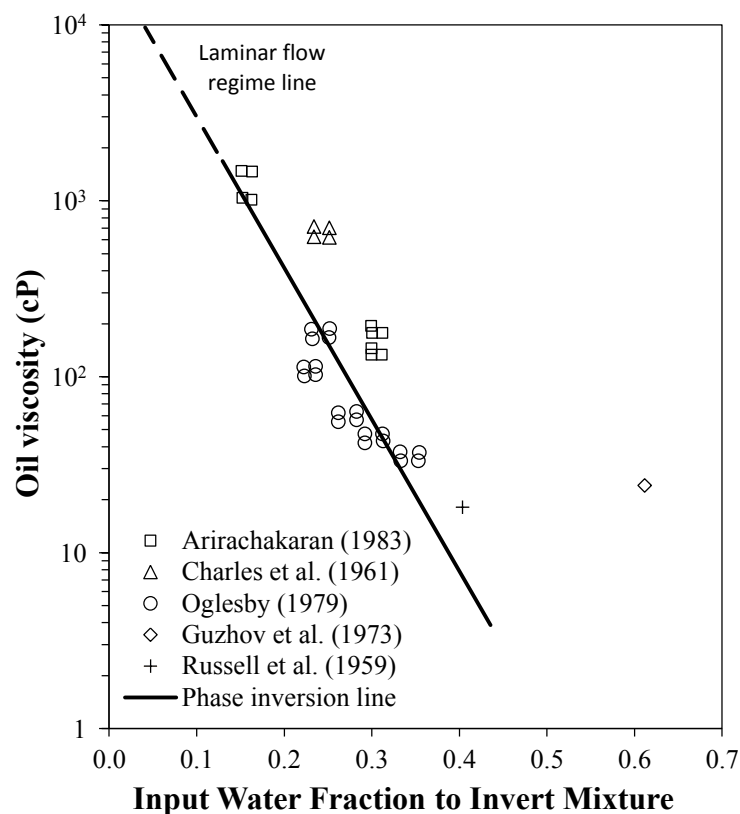


Figure 6: Phase inversion line correlation (adapted from Arirachakaran et al., 1989).

Nädler and Mewes (1995) classified dispersions and emulsion in different categories. Emulsion was defined as stable dispersions with a nearly homogeneous droplet size

distribution with only one continuous phase. On the other hand, dispersions were identified by the presence of a continuous layer (i.e. free of droplets) and a dispersed layer, as shown in **Figure 7**. Nädler and Mewes (1995) used water and a mineral white oil with $\mu_o = 20$ mPa.s and $\rho_o = 841$ kg/m³ in a 59 mm internal diameter Perspex horizontal pipe. Liquids were injected into the test section through a cone-shaped nozzle separated with baffle plates to prevent emulsions at the inlet.

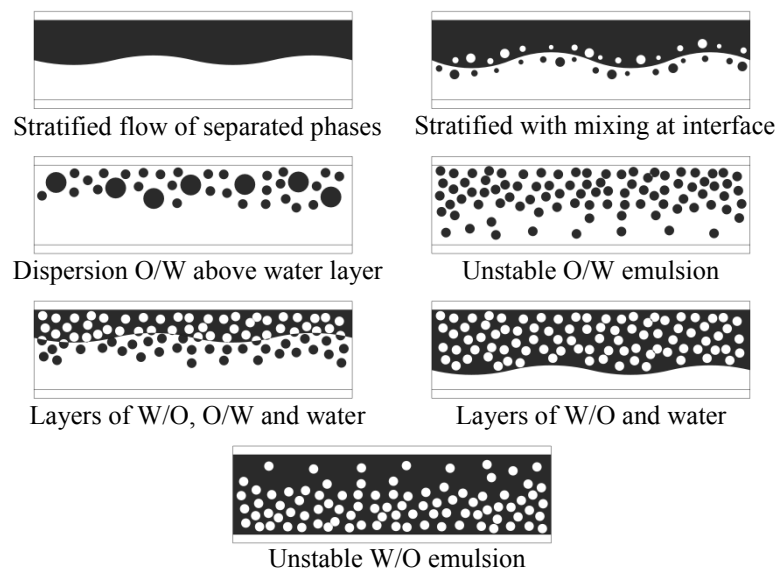


Figure 7: Oil-water flow patterns observed in horizontal 59 mm ID pipe (adapted from Nädler and Mewes, 1995).

Nädler and Mewes (1995) utilised emulsion and dispersion to identify two different behaviours. *Emulsion* was defined as a homogeneous dispersion, while dispersion consisted of a heterogeneous distribution of droplet of one phase in the other along the cross-section of the pipe.

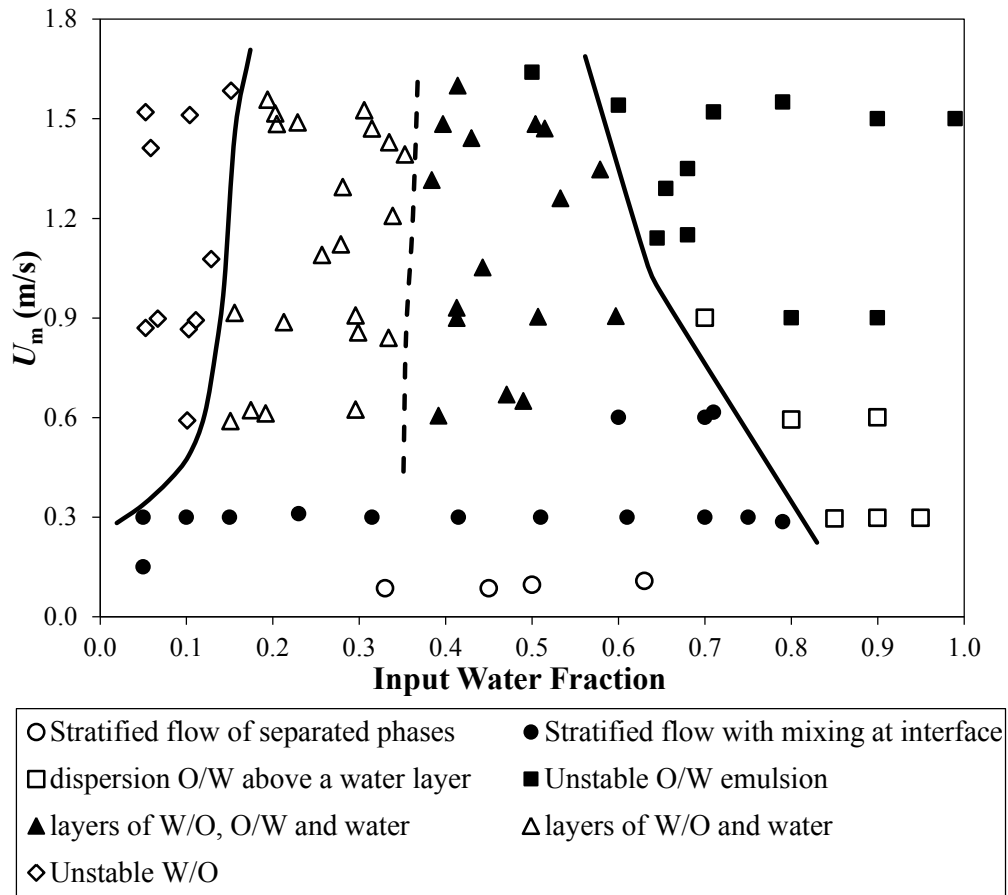


Figure 8: Flow pattern map for horizontal 59 mm ID oil-water flow with $\mu_o = 20$ mPa.s (adapted from Nädler and Mewes, 1995).

Trallero (1995) proposed a standardised flow pattern classification based on previous studies and acquired data. Experiments were conducted in a 50.13 mm internal diameter horizontal pipe of 15.54 m long. Mixtures velocities (U_m) were varied from 0.25 to 3.0 m/s and input water fraction ($\phi_{in,w}$) from 0 to 1. The fluids used were water and mineral oil with $\mu_o = 28.8$ mPa.s, $\rho_o = 884$ kg/m³ and interfacial tension of 36.0 mN/m. The first attempt to use camera, differential pressure transducers and conductance probes to study liquid-liquid flows was done by Trallero (1995). Conductance probes were used to measure the local average phase continuity. Trallero (1995) observed six flow patterns as shown in **Figure 9**. At low flow velocities, segregated flows are encountered. For

stratified flow (ST) both liquids flow as separate layers with the heavier phase at the bottom of the pipe. As increasing the flow velocity, droplets appear at the interface. This flow pattern is defined as stratified flow with mixing at the interface (ST&MI). As the flow velocity increases further, turbulence also increases leading to droplet formation where a transition to dispersed flow patterns is observed. This dispersion is divided into water continuous or oil continuous. For water continuous, a dispersion of oil in water with a water layer (Do/w & w) and oil in water emulsion (o/w) was observed for high input water fraction. For oil continuous, two patterns were identified: a dual dispersion of water in oil and oil in water (Dw/o & D o/w), and water in oil emulsion (w/o) which was only observed for very low input water fraction (i.e. $\phi_{in,w} < 0.1$). The flow pattern map developed by Trallero (1995) is shown in **Figure 10**.

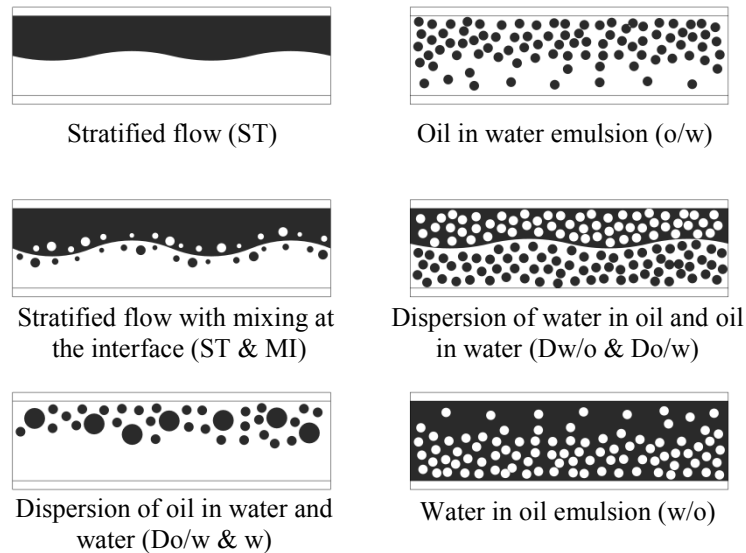


Figure 9: Oil-water flow patterns observed by Trallero (1995).

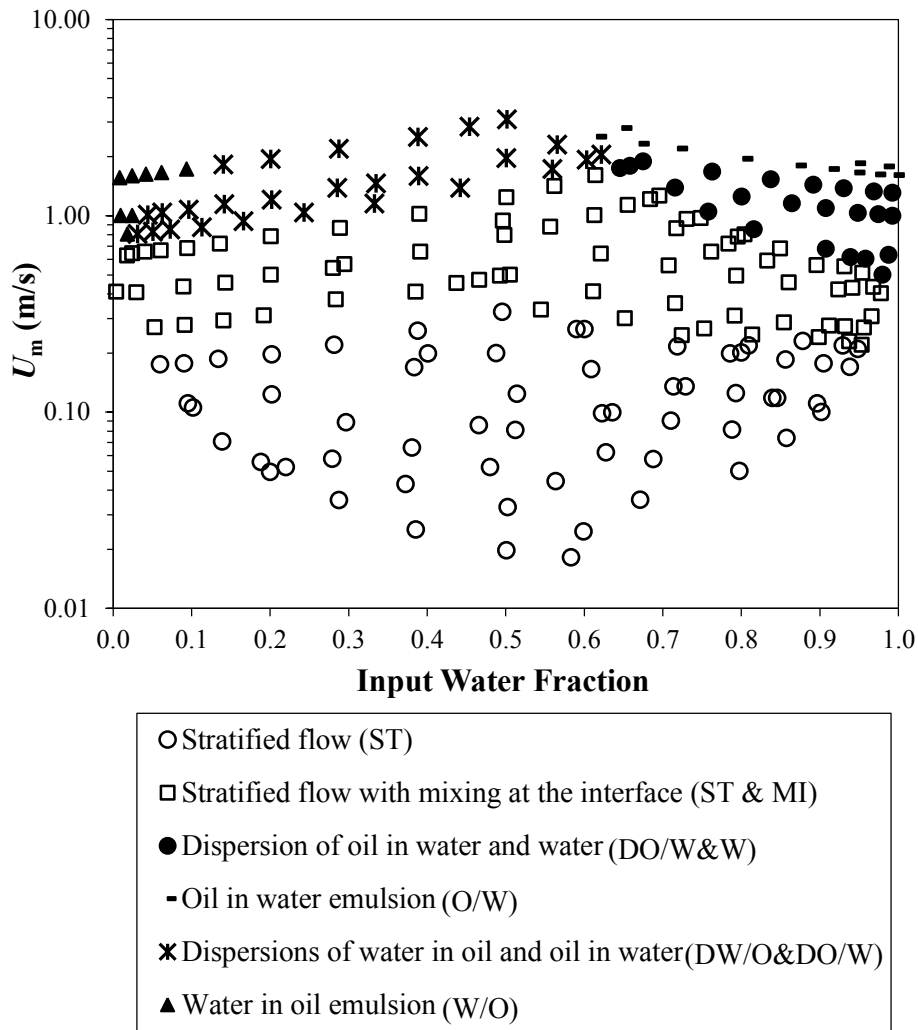


Figure 10: Flow pattern map for horizontal 50.13 mm ID oil-water flow at different mixture velocities and input water fraction (f_w) (adapted from Trallero, 1995).

Angeli (1996) and Angeli and Hewitt (2000) studied oil-water flows using a 1-in. stainless steel and acrylic horizontal pipe. Exxsol D80 was used as the oil phase with a viscosity of 1.6 mPa.s and a density of 801 kg/m³. Mixture velocities were varied from 0.2 to 3.9 m/s and input water fraction from 0.06 to 0.86. As increasing mixture velocity, six flow patterns were observed: (1) stratified wavy flow pattern (SW); (2) stratified wavy with drops (SWD); (3) three layer flow (3L), defined as continuous layer of oil at the top and water at the bottom with a layer of droplets at the interface; (4)

stratified mixed flow with a water layer (SM/water), described as a continuous layer of water with an oil droplet layer at the top for high water fractions; (5) stratified mixed flow with an oil layer (SM/oil), oil continuous with a water droplet layer at the bottom for low water fractions; and (6) mixed or fully dispersed. Flow pattern maps developed are shown in **Figure 11** for stainless steel and acrylic pipes.

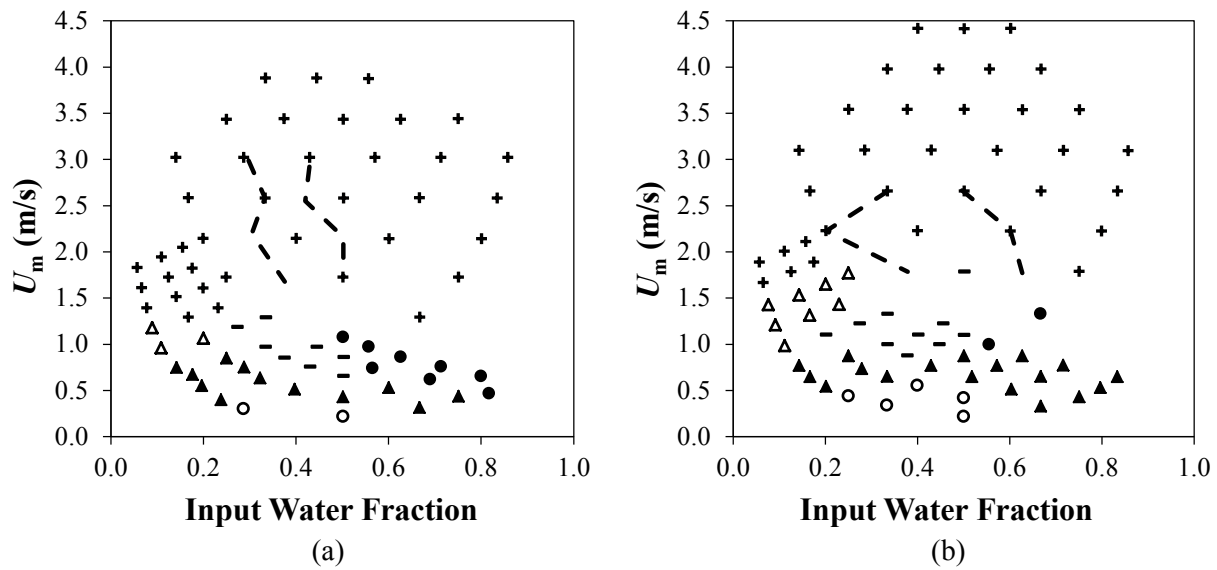


Figure 11: Oil-water flow pattern map for horizontal 1-in. pipe for (a) stainless steel pipe, (b) acrylic pipe. ○, stratified wavy (SW); —, three layers (3L); Δ, stratified mixed/oil (SM/oil); ---, phase continuity boundaries; ▲, stratified wavy drops (SWD); ●, stratified mixed/water (SM/water); +, mixed (M) (adapted from Angeli and Hewitt, 2000).

Angeli and Hewitt (2000) observed some differences in the flow pattern transitions between the steel and the acrylic pipe. The transition from stratified to non-stratified flows occurred at lower velocities for the steel pipe. Angeli and Hewitt (2000) suggested that as increasing the pipe roughness, turbulence increases for the same flow velocity resulting in a transition to dispersed flow patterns. In addition, oil continuous flow patterns were observed for a wider range of conditions for the acrylic pipe. This

phenomenon can be attributed to the wettability of the pipe in which oil tends to wet the acrylic.

Soleimani (1999) acquired data using the same experimental configuration (i.e. test pipe and fluids) by Angeli (1996). A high speed camera was used to observe the flow pattern and a conductivity probe and gamma densitometer were employed to determine in-situ phase fractions. Soleimani (1999) developed a flow pattern map, as shown in **Figure 12**, using the same classification developed by Angeli (1996).

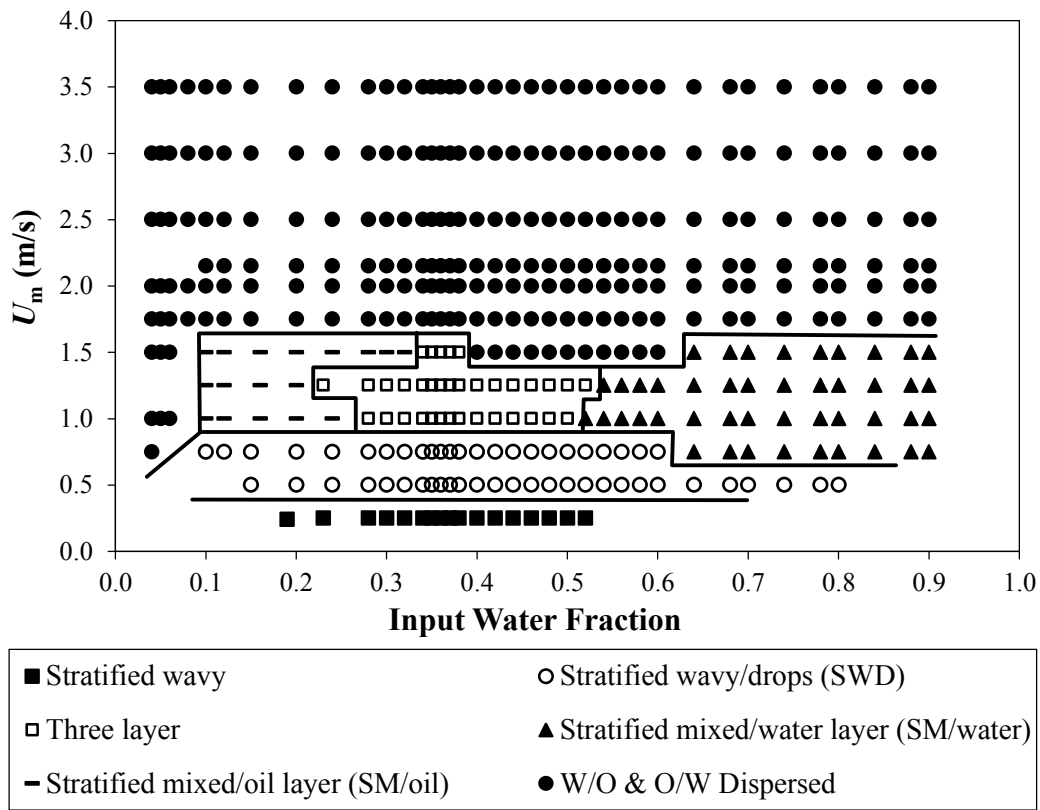


Figure 12: Oil-water flow pattern map for horizontal 1-in. SS pipe (adapted from Soleimani, 1999).

Lovick and Angeli (2004) studied dual continuous flow pattern in a 38 mm internal diameter steel pipe. Water and Exxsol D140 were used as the test fluids ($\mu_o = 6$ mPa.s,

$\rho_o = 828 \text{ kg/m}^3$, interfacial tension 39.6 mN/m). A flow pattern map was constructed (see **Figure 13**) using mixture velocities from 0.8 to 3.0 m/s and input oil fraction from 0.1 to 0.9 . Four flow patterns were identified: (1) stratified wavy (SW), (2) water in oil dispersion (Dw/o), (3) oil in water dispersion (Do/w), and (4) dual continuous (DC). The dual continuous flow pattern was characterised by having two continuous phases along the pipe, such as, water layer at the bottom with water droplets at the top, oil layer at the top with oil droplets at the bottom, and water dispersed on oil at the top with oil dispersed in water at the bottom. Lovick and Angeli (2004) observed that the dual continuous flow pattern occurred between stratified and dispersed flow. The pressure gradient in dual continuous flows was lower than single phase oil. This phenomenon was attributed to a drag reduction and relative oil and water fractions.

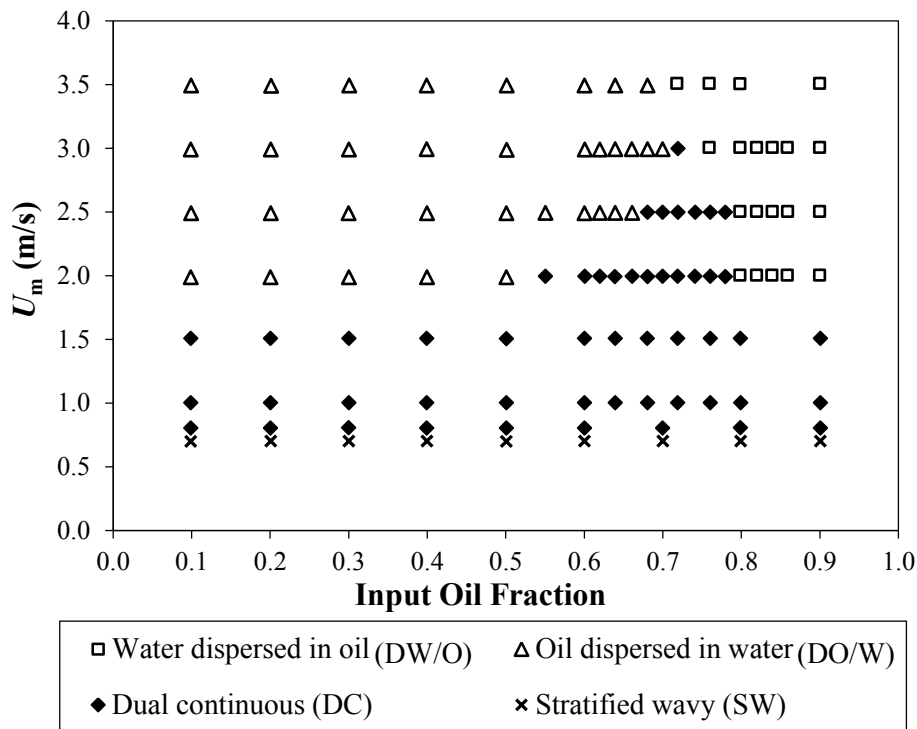


Figure 13: Oil-water flow pattern map for horizontal 1-in. pipe (adapted from Lovick and Angeli, 2004).

Vielma et al. (2007) conducted experimental investigations in two 21.13 m long transparent pipe of 2-in. nominal size. The test fluids were tap water and mineral oil ($\mu_o = 13.5$ mPa.s at 40°C, $\rho_o = 858.8$ kg/m³ at 15.6°C) with superficial velocities between 0.025 to 1.75 m/s. Conductivity probes and high-speed camera were used to determine flow pattern and phase distribution. Vielma et al. (2007) compared the experimental data with Trallero (1995) model for transition boundaries, observing a significant discrepancy at the stratified (ST) and stratified flow with mixing at the interface (ST & MI) region, as shown in **Figure 14**. This discrepancy was attributed to the different temperature of the fluids in both experimental works.

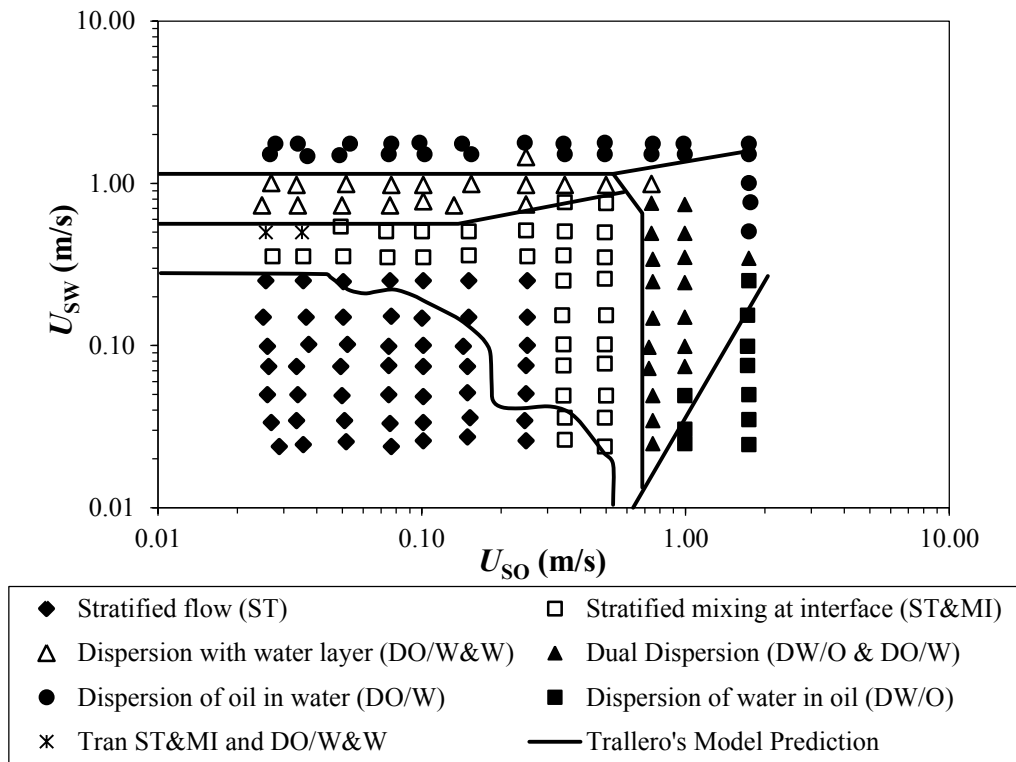


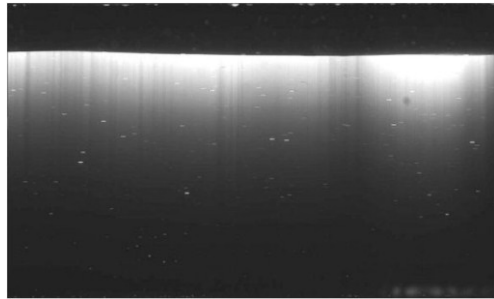
Figure 14: Flow pattern map for oil-water horizontal 2-in. pipe. Comparison with Trallero (1995) transition boundaries model (adapted from Vielma et al., 2007).

Recently, Morgan et al. (2013) performed experiments in a 1-in. horizontal steel pipe of 7.3 m long. Two visualisation sections were used: (i) square channel and (ii) circular

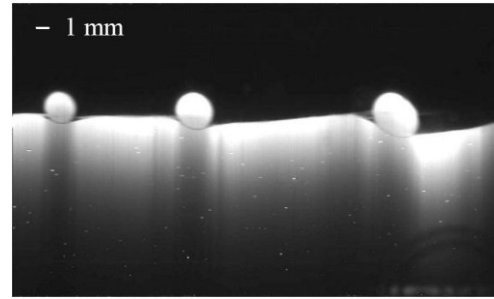
section. The test fluids were Exxsol D80 ($\mu_o = 1.9$ mPa.s, $\rho_o = 802.7$ kg/m³) and an 81.7wt% glycerol solution ($\mu_{gs} = 82.3$ mPa.s, $\rho_{gs} = 1213.3$ kg/m³). Fluids were selected to match refractive indices and allow the implementation of advanced optical visualisation techniques, namely, Planar Laser Induced Fluorescence (PLIF), Particle Image Velocimetry (PIV), and Particle Tracking Velocimetry (PTV). A pulsed laser, coupled with a high-speed camera, was used to obtain high accuracy images. These images were processed to obtain information on phase distribution, in-situ phase fraction, interfacial level and droplet size distribution. PIV and PTV were used to obtain velocity profiles. Morgan (2013) identified eight flow patterns, presented in **Figure 15**, grouped into four general flow pattern categories as shown in **Table 2**. In addition, Morgan et al. (2013) constructed a flow pattern map (see **Figure 16**) for mixture velocities from 0.11 to 0.84 m/s and input oil fraction between 0.1 and 0.9.

Table 2: Flow pattern category (Morgan et al., 2013).

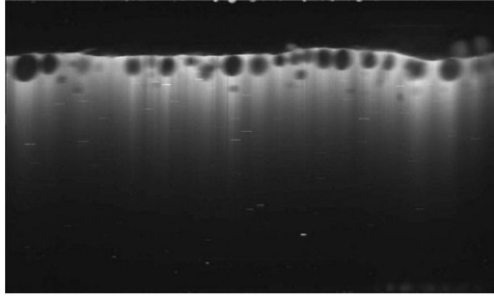
Category	Flow Pattern
Stratified flow	A- Stratified flow
	B- Stratified flow with droplets
Mixed flow	C- Oil droplet layer
	D- Glycerol solution droplet layer
	E- Three-layer flow
Two-layer, dispersed over/under continuous flow	F- Oil dispersion over glycerol solution flow
Dispersed flow	G- Oil flow over glycerol solution dispersion with glycerol solution film
	H- Glycerol solution dispersion with glycerol solution film



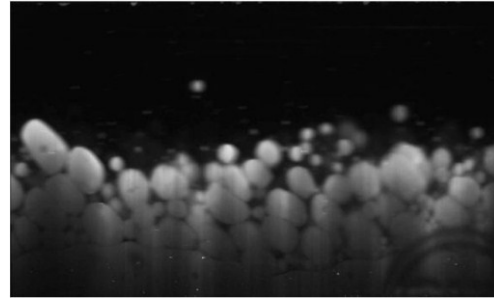
(a) Stratified flow



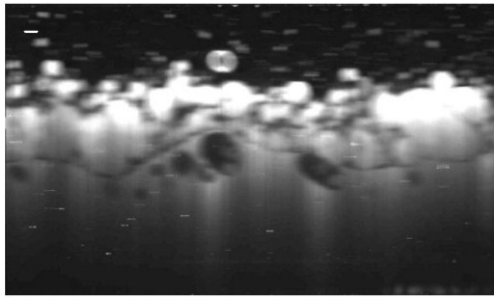
(b) Stratified flow with droplets



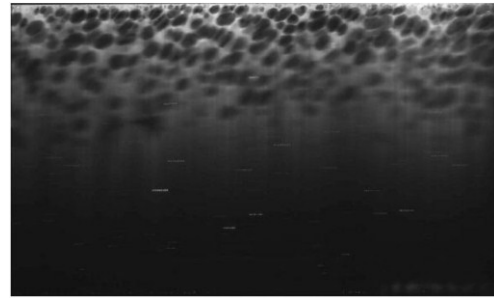
(c) Oil droplet layer



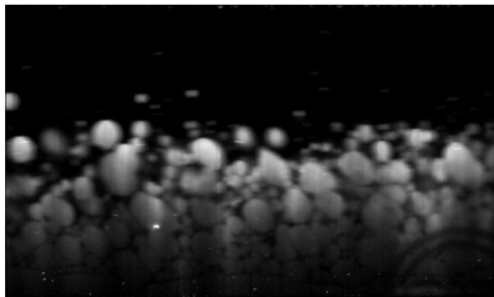
(d) Glycerol solution droplet layer



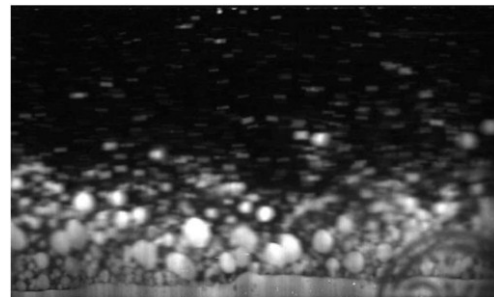
(e) Three layer flow



(f) Oil dispersion over glycerol solution



(g) Oil flow over glycerol solution dispersion with glycerol solution film



(h) Glycerol solution dispersion with glycerol solution film

Figure 15: Flow patterns observed from instantaneous PLIF images for a circular test section (from Morgan et al., 2013).

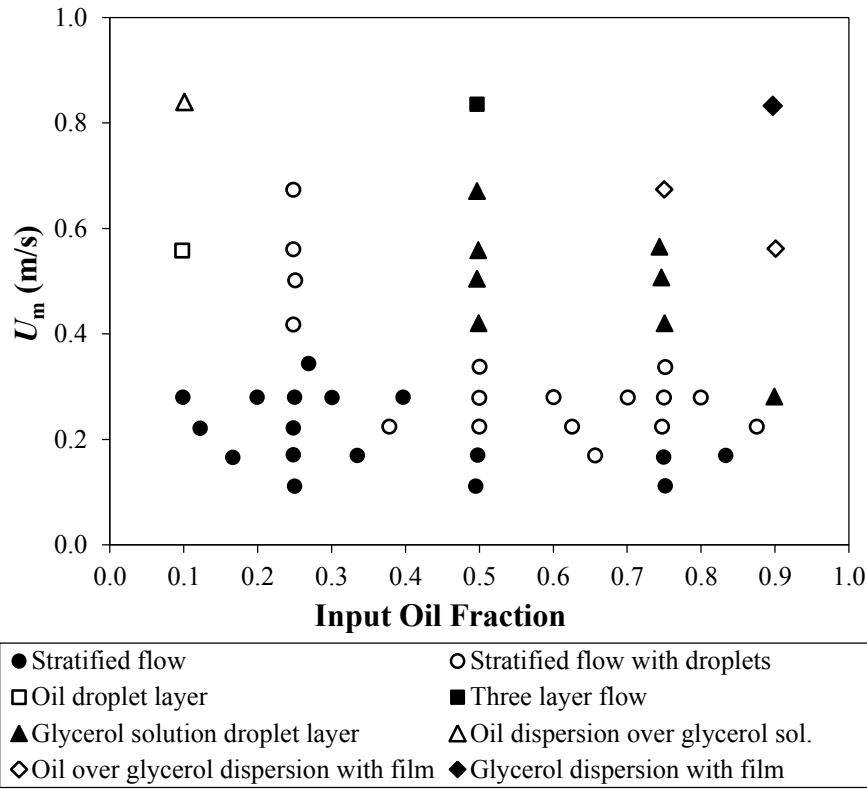


Figure 16: Flow pattern map for horizontal 1-in. steel pipe for a circular test section (adapted from Morgan et al., 2013).

2.2 Inclined Experimental Studies

Currently, limited data are available for slightly inclined liquid-liquid flows. Vedapuri et al. (1997) studied oil-water flows in slightly inclined pipes ($\pm 2^\circ$). Semi-segregated and semi-mixed flows occurred for a wide range of conditions, i.e., oil layer at the top, water layer at the bottom and a mixed layer at the interface. Alkaya et al. (2000) performed experiments at inclination angles of $\pm 0.5^\circ$, $\pm 1^\circ$, $\pm 2^\circ$ and $\pm 5^\circ$ using oil and water. Alkaya et al. (2000) identified the same flow pattern as Trallero (1995). However, an additional flow pattern was observed only for inclined flow, i.e., dispersion of water in oil and oil layer (Dw/o & o).

Oddie, et al. (2003) studied liquid-liquid flows in inclined pipes for large diameters. The test section consisted of a transparent 15 cm internal diameter pipe of 11 m long. The fluids used were tap water and kerosene ($\mu_o = 1.5$ mPa.s and $\rho_o = 810$ kg/m³). A gamma densitometer and ten conductivity probes were employed to determine the in-situ water fraction at inclination angles of -2° , 0° , $+2^\circ$, $+10^\circ$, $+20^\circ$, $+45^\circ$, $+85^\circ$ and $+90^\circ$. Oddie, et al. (2003) identified six flow patterns: (1) segregated, when both liquids flow in separate layers; (2) semi-segregated, which consisted of stratified layers with mixing at the interface; (3) semi-mixed, defined as three layer flow with a dispersion in the middle, pure oil and water at the top and the bottom of the pipe, respectively; (4) mixed, in which the oil-water dispersion occupies more than half of the pipe; (5) dispersed, when oil and water mixtures occupies the total pipe cross section, and (6) homogeneous, in which no distinction was observed between both liquids (i.e. for high mixture velocities). Oddie et al. (2003) observed stratified flow for a wide range of flow conditions at an inclination of -2° . For slightly inclined pipes (i.e. $+2^\circ$, $+10^\circ$), all six flow patterns were observed. With increasing inclination angle (i.e. $\theta > +45^\circ$), only dispersed and homogeneous flow were identified. Oddie et al. (2003) observed that dispersed flow appears in upward inclined flows at lower velocities than in horizontal flow.

Lum et al. (2006) studied the effect of pipe inclination (-5° , $+5^\circ$, $+10^\circ$) on oil-water flows in a 38 mm internal diameter stainless steel pipe. The test fluids used were tap water and Exxsol D140 ($\mu_o = 5.5$ mPa.s and $\rho_o = 828$ kg/m³). Mixture velocities were varied from 0.7 to 2.5 m/s and phase fractions from 0.1 to 0.9. Lum et al. (2006) observed five flow patterns in upward inclined flow (see **Figure 17**): (1) stratified wavy (SW); (2) plug flow (PG); (3) dual continuous (DC); (4) oil in water dispersion (Do/w); and (5) water in oil

dispersion (Dw/o). Lum et al. (2006) observed that the flow pattern transitions are not affected by the inclination angle at high mixture velocities. With increasing inclination angle, plug flow (i.e. large oil droplets at the top of the pipe) and oil in water dispersions were observed for a wider range of conditions.

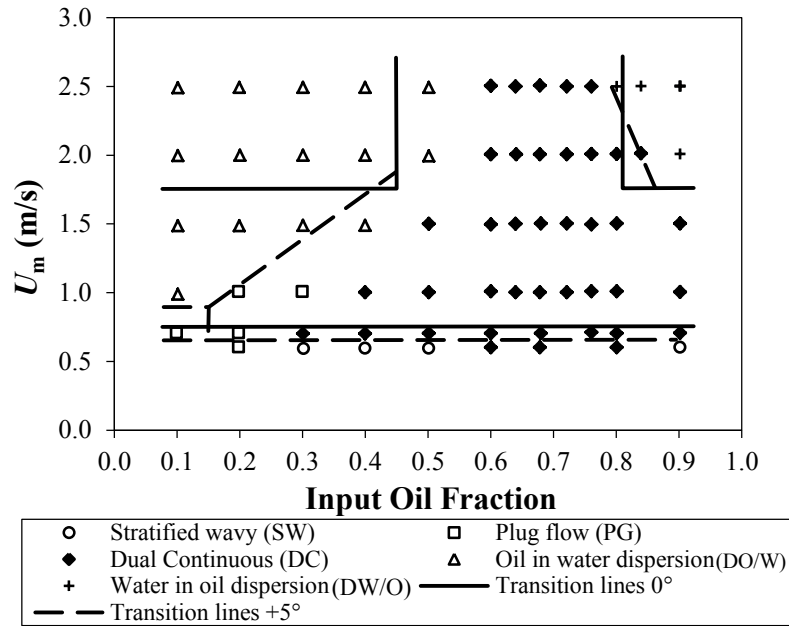


Figure 17: Oil-water flow pattern map at +10° inclination for a 38 mm ID pipe and comparison with transition boundaries at 0° and +5° (adapted from Lum et al., 2006).

At downward flow (-5°), mixing is dominant over the entire flow pattern map (see **Figure 18**). Stratified wavy and plug flow were not observed. This was attributed to the higher velocity of the water layer which enhances dispersions of oil in water.

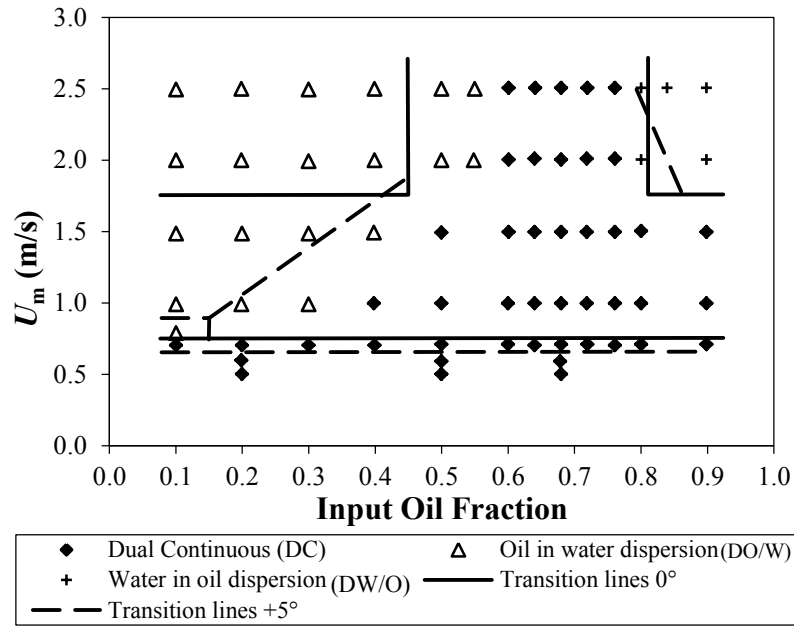


Figure 18: Oil-water flow pattern map at -5° inclination for a 38 mm ID pipe and comparison with transition boundaries at 0° and $+5^\circ$ (adapted from Lum et al., 2006).

Rodriguez and Oliemans (2006) conducted experiments in a 82.8 mm internal diameter steel pipe at inclination of -5° , -2° , -1.5° , 0° , 1° , 2° and 5° using mineral oil and brine ($\rho_o = 830 \text{ kg/m}^3$, $\rho_w = 1070 \text{ kg/m}^3$ and $\mu_w = 0.8 \text{ mPa}\cdot\text{s}$). Rodriguez and Oliemans (2006) used the same flow pattern classification developed by Trallero (1995) with the addition of stratified wavy (SW) flow with no mixing to the interface for downward and upward inclinations. Rodriguez and Oliemans (2006) constructed a flow pattern map for different pipe inclinations, as shown in **Figure 19**. Rodriguez and Oliemans (2006) observed that stratified smooth (ST) flow was replaced by stratified wavy (SW) at downward and upward inclinations. For upward pipe inclinations and low superficial water velocity, caterpillar waves and water back flow with recirculation were observed for 2° and 5° , respectively (Figure 19 (c) and (d)).

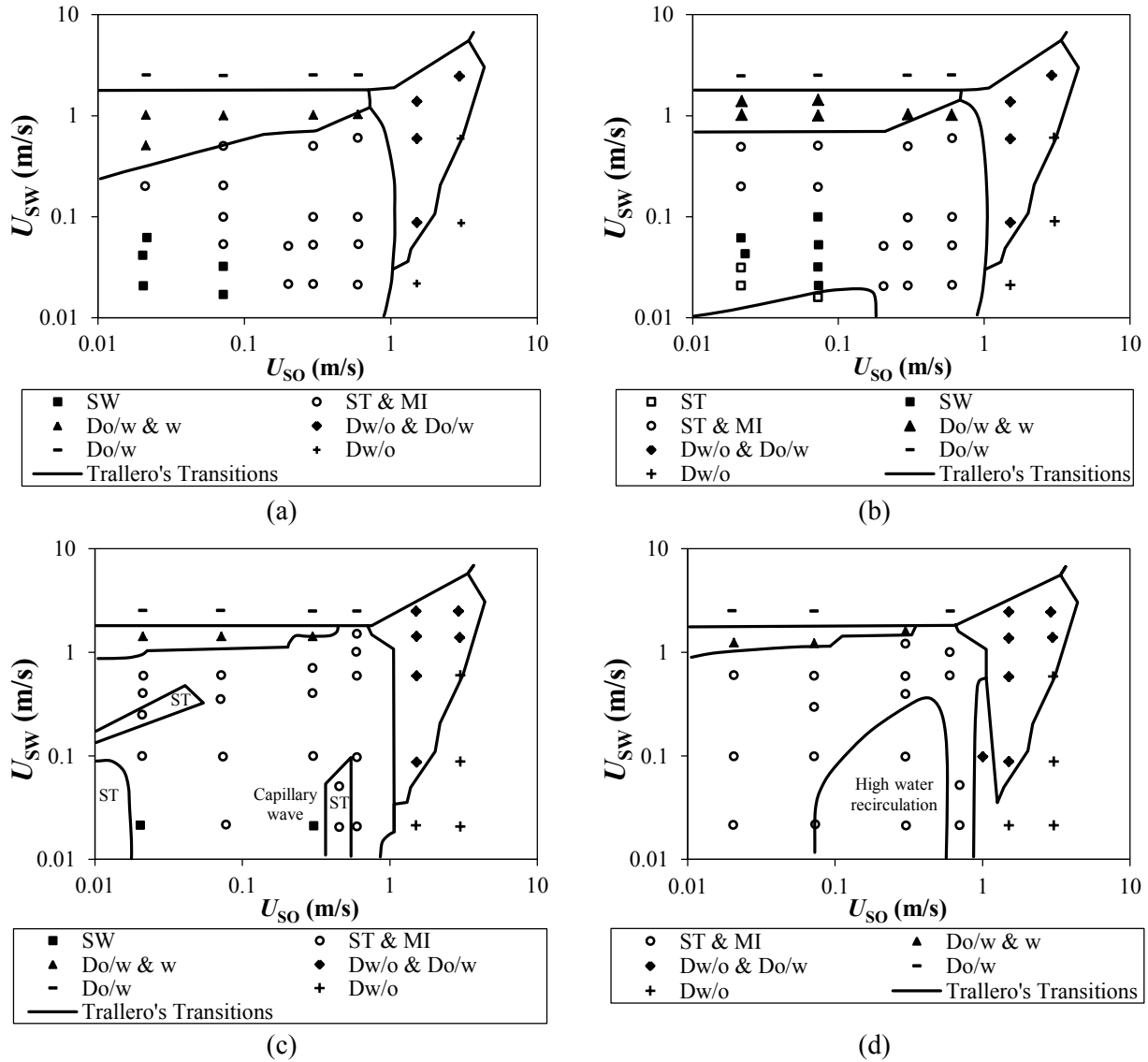


Figure 19: Oil-water flow pattern map for a 82.1 mm ID pipe at inclinations of: (a) -5° ($\mu_o = 6.86$ mPa.s), (b) -2° ($\mu_o = 7.28$ mPa.s), (c) 2° ($\mu_o = 7.02$ mPa.s), and (d) 5° ($\mu_o = 7.42$ mPa.s), as function of superficial water (U_{sw}) and superficial oil velocity (U_{so}) (adapted from Rodriguez and Oliemans, 2006).

Atmaca et al. (2009) studied oil-water flows at inclinations of 0° , $\pm 1^\circ$, $\pm 2^\circ$ and -5° . The test pipe consisted of a 50.8 mm internal diameter of 21.1 m long. Tap water and mineral oil ($\mu_o = 13.5$ mPa.s and $\rho_o = 858.8$ kg/m³) were used as test fluids. Flow patterns were identified using a high-speed camera. Atamaca et al. (2009) identified the

same flow patterns as Trallero (1995). Atamaca et al. (2009) observed that the stratified region slightly decreases for downward flow. Transitions to dispersed flow were found at the same flow conditions for upward and downward flow.

Kumara et al. (2009) presented flow pattern maps (see **Figure 20**) for inclinations of $\pm 1^\circ$ and $\pm 5^\circ$ in a 56 mm internal diameter steel pipe using water and Exxsol D60. Eight different flow patterns (see **Table 3**) were identified in accordance with Trallero (1995), Lum et al. (2006), Rodriguez and Oliemans (2006) and Atmaca et al. (2009).

Table 3: Flow pattern category (Kumara et al., 2009).

Category	Flow Pattern
Segregated flow	A) Stratified smooth (ST)
	B) Stratified wavy (SW)
	C) Stratified with mixing at the interface (ST&MI)
Dispersed flow	Water dominated:
	D) Oil in water dispersion and water layer (Do/w & w)
	E) Oil in water dispersion (Do/w)
	Oil dominated:
	F) Oil in water and water in oil dispersion (Do/w & w/o)
	G) Water in oil dispersion (Dw/o)
	H) Plug flow (PF)

Kuamara et al. (2009) observed plug flow and stratified wavy flow at an inclination of 5° for low mixture velocities and high input water fractions (i.e. $\phi_{in,w} > 0.925$). At inclined pipes, dispersed flow patterns occurred at lower mixtures velocities than horizontal pipes.

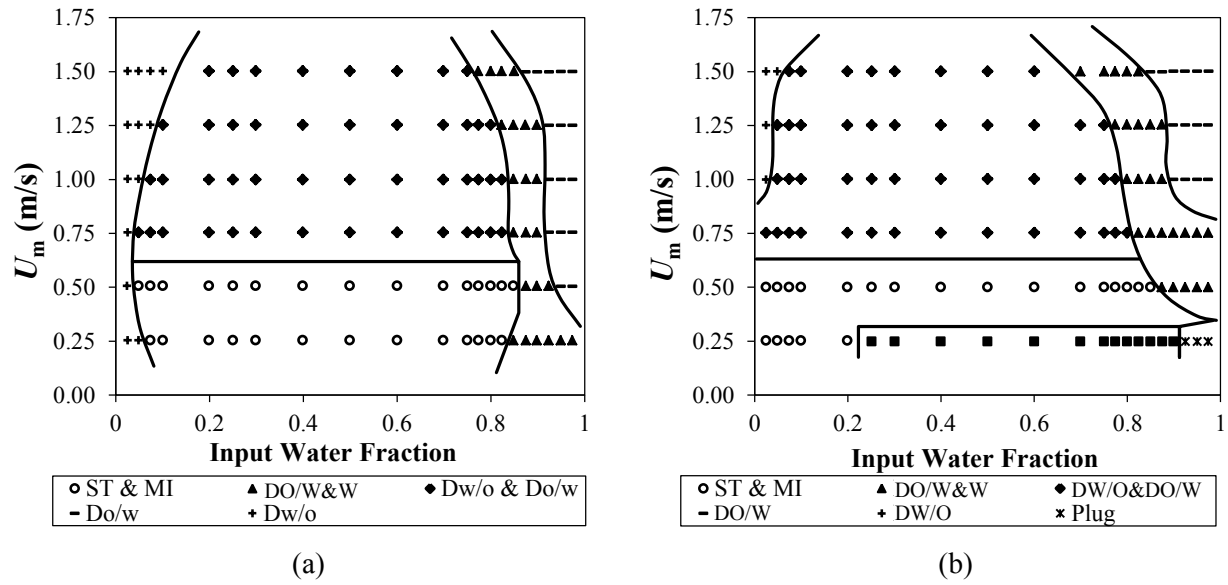


Figure 20: Oil-water flow pattern map for a 56 mm ID pipe at inclinations of: (a) -5° and (b) 5° (adapted from Kumara et al., 2009).

3. Unified Liquid-Liquid Flow Pattern Classification

Liquid-liquid flows is characterised for having an inconsistent flow pattern distribution for different flow conditions, fluid properties and pipe characteristics. The flow pattern identification is an arbitrary process which is defined by the researcher criterion. This is in contrast with gas-liquid flows in which flow patterns are consistent for different conditions and identification is straight forward. A unified liquid-liquid flow pattern classification would enable the researcher to identify the flow pattern according to a establish classification. The following unified classification is based on previous studies for the purpose of allowing easy identification and comparison with existing flow patterns maps.

- **Stratified flow (ST):** the two liquids flow in separate layers. The heavier liquid flows at the bottom of the pipe while the lighter at the top. The interface can be flat or wavy as increasing the flow velocity.
- **Stratified wavy with droplets at the interface (SWD):** when flow velocities increase, droplets are formed and flow only at the interface between both liquids.
- **Dispersion of oil in water with water layer (DO/W & W):** droplets of oil are encountered at the upper part of the pipe with a pure water layer at the bottom. In this pattern, water is the only continuous phase.
- **Dispersion of water in oil with oil layer (DW/O & O):** droplets of water are encountered at the lower part of the pipe with a pure oil layer at the top.
- **Dual continuous (DC):** this flow pattern is encountered at intermediate mixtures velocities above the separated flow regimes, for which flow velocities are not sufficient enough to create a full dispersion. Instead, both liquid are the continuous phase for a define cross-section of the pipe with dispersed droplets of

one phase into the other. This flow pattern presents a variety of combinations depending on the entrainment level, leading to extended classifications, such as three layer flow, dispersion of oil and water with and oil layer, and dispersion of water in oil with a water layer.

- **Dispersion of oil in water (DO/W):** this flow pattern is characterised by having only one continuous phase (i.e. water) and one dispersed phase (i.e. oil). The dispersion profile across the cross-section of the pipe varies with the flow velocity. Homogenous dispersions are encountered for very high velocities.
- **Dispersion of water in oil (DW/O):** water is dispersed in the oil phase.
- **Intermittent flow (IT):** slugs of one liquid into the other travel long the pipe. These slugs consist of a continuous phase or an accumulation of droplets.
- **Annular flow (AN):** in this pattern one liquid flows at the centre of the pipe (core) and the other at the annulus between the core and the pipe wall. Annular flow can be observed for mixtures with significant viscosity ratio.

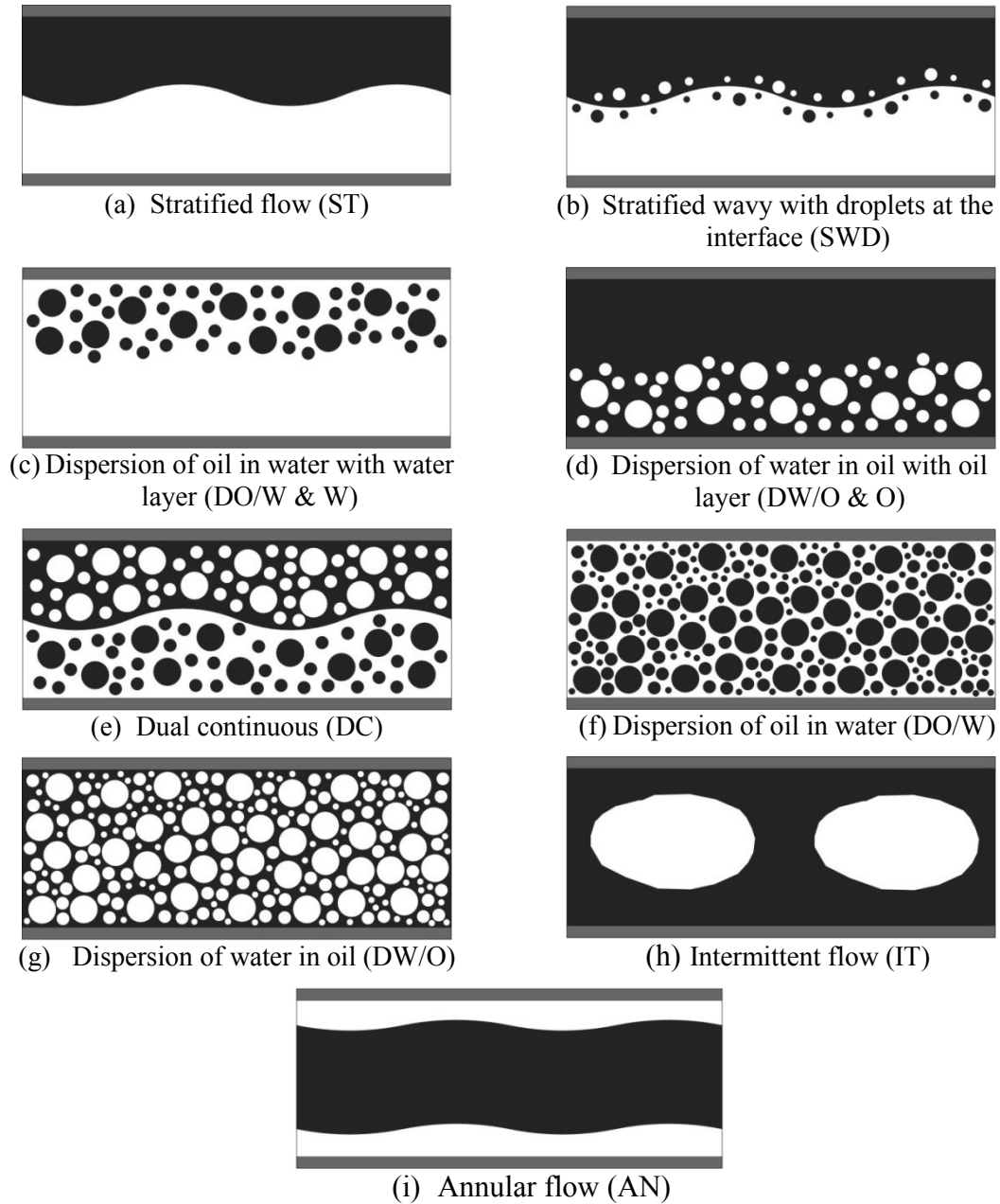


Figure 21: Unified liquid-liquid flow pattern classification.

4. Conclusions

The analysis of co-current liquid-liquid flow in pipes requires extensive study in order to reach an accurate understanding of the complex hydrodynamics. The construction of flow pattern maps would enable the development of predictive models applicable at different conditions, i.e., flow velocities, fluid properties, and pipe characteristics. Furthermore, the implementation of a unified liquid-liquid flow pattern classification

allows a direct flow patterns maps comparison for further analysis. This eliminates the ambiguity in the flow pattern identification process in which unnecessary classifications could arise.

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Appendix A. Summary of experimental studies on liquid-liquid flows in pipes

Table A1: Liquid-liquid flow studies in horizontal pipes.

Authors	Pipe ID (mm) L_F/D Pipe Material	Type of Inlet/Mixer	U_m (m/s)	$\phi_{in,o}$	ρ_w ρ_o (kg/m ³)	μ_w μ_o (mPa.s)	γ_{ow} (mN/m)	Investigated parameters. System conditions.
Russell et al. (1959)	25.4 315 Smooth clear	-	$U_{sw}=0.01-$ 1.00 $U_{so}=0.04-$ 1.08	-	998 835	1 18	-	Pressure drop, flow patterns, holdup
Charles et al. (1961)	25.4 346 Smooth clear	-	0.05 - 2.09	0.09 - 0.91	998 998	1 6.29; 16.8;65	-	Pressure drop, flow patterns, holdup
Hasson et al. (1970)	12.6 214 Glass	Initially concentric nozzle (water core)	-	-	1020 1020	0.8 1.0	-	Flow patterns, wetting properties (hydrophobic and hydrophilic pipes)
Oglesby (1979)	41 - -	-	$U_{sw}=0.03-$ 3.19 $U_{so}=0.07-$ 2.71	-	998 851;861 ;868	1.0 32;61; 167	-	Pressure drop, flow patterns
Arirachakaran et al. (1989)	41 275 Steel	-	0.46 - 3.66	0.10 - 0.95	998 867	1.06 4.7;58; 84;115	29 - 31	Pressure drop, flow patterns T=10 to 36.7°C
Nädler and Mewes (1995)	59 225 Acrylic	Cone-shaped nozzle separated by baffle plates	0.09 - 1.64	0.01 - 0.95	998 841	1.0 31.0	-	Pressure drop, flow patterns
Trallero (1995)	50.1 257, 281 Acrylic	“Y” Junction at 30°	0.25 - 3.00	0 – 1	1037 884	0.97 28.80	36	Pressure drop, flow patterns, holdup
Angeli (1996) / Angeli and Hewitt (2000)	24.3 / 24.0 370 / 375 SS / Acrylic	“T” Junction and static mixer	0.2 - 3.9	0.14 - 0.94	998 801	1.0 1.6	17	Pressure drop, flow patterns, holdup
Soleimani (1999)	24.3 246 SS	“T” Junction	0.24 - 3.50	0.10 - 0.96	997 801	0.9 1.6	17	Pressure drop, flow patterns, holdup
Lovick and Angeli (2004)	38 210 SS	“T” Junction (oil inline - water beneath oil phase)	0.8 - 3.0	0.1 - 0.9	997 828	0.9 6.0	39.6	Pressure drop, flow patterns, holdup T=25°C. P=1 bar

Authors	Pipe ID (mm) L_E/D Pipe Material	Type of Inlet/Mixer	U_m (m/s)	$\phi_{in,o}$	ρ_w ρ_o (kg/m ³)	μ_w μ_o (mPa.s)	γ_{ow} (mN/m)	Investigated parameters. System conditions.
Vielma et al. (2007)	49.3 272 Clear pipe	“Y” Junction	0.05 - 3.50	0.02 - 0.99	997 850	0.9 15.0	16.38	Pressure drop, flow patterns, holdup, phase distribution, droplet size T=29.4 to 40.6°C
Morgan et al. (2013)	24.3 244 SS	“T” Junction with static mixer (water inline - oil above water phase)	0.11 - 0.84	0.1 - 0.9	1213 802	82.3 1.9	25	Flow patterns, holdup, phase distribution, interface level, droplet size, velocity profiles T=21°C. P=1 bar

Table A2: Liquid-liquid flow studies in slightly inclined pipes.

Authors	Pipe ID (mm) L_E/D Pipe Material Inclination	Type of Inlet/Mixer	U_m (m/s)	$\phi_{in,o}$	ρ_w ρ_o (kg/m ³)	μ_w μ_o (mPa.s)	γ_{ow} (mN/m)	Investigated parameters. System conditions.
Vedapuri et al. (1997)	101.6 - Plexiglas 0°, ±2°	-	0.2 - 2.0	0.2 - 0.8	sea water -	sea water 2	-	Pressure drop, flow patterns, holdup, phase distribution, velocity profiles T=40°C P=1.3 bar
Alkaya et al. (2000)	50.8 299 Acrylic 0°, ±0.5°, ±1°, ±2°, ±5°	-	0.025 - 1.75	0 - 1	994 848	0.72 12.9	16.7	Pressure drop, flow patterns, holdup, phase distribution T=35°C P=1.4 bar
Oddie et al. (2003)	152 71 Plexiglass 0°, ±2°, +10°, +20°, +45°, +85°	Inlet plenum chamber	0.06 - 2.14	0 - 1	998 810	1.0 1.5	-	Flow patterns, holdup

Authors	Pipe ID (mm) L_F/D Pipe Material Inclination	Type of Inlet/Mixer	U_m (m/s)	$\phi_{in,o}$	ρ_w ρ_o (kg/m ³)	μ_w μ_o (mPa.s)	γ_{ow} (mN/m)	Investigated parameters. System conditions.
Lum et al. (2006)	38 184 SS $\pm 5^\circ, +10^\circ$	“T” Junction	0.7 - 2.5	0.1 - 0.9	998 828	0.9 5.5	40	Pressure drop, flow patterns, holdup, phase distribution
Rodriguez and Oliemans (2006)	82.8 250 SS $-1.5^\circ, 0^\circ, +1^\circ,$ $\pm 2^\circ, \pm 5^\circ$	“T” Junction (oil inline)	0.04 - 5.55	0 - 1	1060 830	0.8 7.5	20.4	Pressure drop, flow patterns, holdup, phase distribution
Atmaca et al. (2009)	50.8 272 Clear pipe $0^\circ, \pm 1^\circ, \pm 2^\circ, -5^\circ$	“T” Junction	$U_{sw}=0.025$ -1.75 $U_{so}=0.025$ -1.75	-	997 858	0.9 13.5	16.38	Pressure drop, flow patterns, holdup
Kumara et al. (2009)	56 268 Steel $\pm 1^\circ, \pm 5^\circ$	“Y” Junction with a separation plate	0.25 - 1.50	0 - 1	996 790	1.00 1.64	43	Pressure drop, flow patterns, holdup T=25°C P=1 bar (outlet)

References

- Alkaya, B.; Jayawardena, S. S. and Brill, J. P., 2000. Oil-water flow patterns in slightly inclined pipes. Proceedings of ETCE/OMAE2000 Joint Conference, New Orleans, LA.
- Arirachakaran, S., 1983. An experimental study of two-phase oil-water flow in horizontal pipes. M.S. thesis. The University of Tulsa.
- Arirachakaran, S., Oglesby, K. D., Malinowsky, M. S., Shoham, O. and Brill, J. P., 1989. An analysis of oil/water phenomena in horizontal pipes. SPE Paper 18836, SPE Prod. Oper. Symp., Oklahoma City, March 13-14, pp. 155-167.
- Angeli, P., 1996. Liquid-liquid dispersed flows in horizontal pipes. Ph.D. thesis, Imperial College London, London.
- Angeli, P. and Hewitt, G. F., 2000. Flow structure in horizontal oil-water flow. *Int. J. Multiphase. Flow* **26** (7), 1117-1140.
- Atmaca, S., Sarica, C., Zhang, H.Q. and Al-Sarkhi, A.S., 2009. Characterization of oil/water flows in inclined pipes. SPE Projects, Facilities & Construction, June 2009, pp. 41-46.
- Barnea, D., 1987. Unified model for predicting flow-pattern transitions for the whole range of pipe inclinations. *Int. J. Multiphase Flow* **11**, 1-12.
- Beggs, H.D. and Brill, J.P., 1973. A study of two-phase flow in inclined pipes. *JPT* 607.
- Charles, M. E., Govier, G. W. and Hodgson, G. W., 1961. The horizontal pipeline flow of equal density oil-water mixtures. *Can. J. Chem. Eng.* **39** (1), 27-36.

- Guzhov, A. I., Grishin, A. D., Medredev, V. F. and Medredeva, O. P., 1973. Emulsion formation during the flow of two liquids in a pipe. *Neft. Khoz.* 8, 58-61 (in Russian).
- Hagedorn, A.R. and Brown, K.E., 1965. Experimental study of pressure gradients occurring during continuous two phase flow in small diameter vertical conduits. *J. Pet. Tech.*, 475-484.
- Hasson, D., Mann, U. and Nir, A., 1970. Annular flow of two immiscible liquids. *Canadian J. Chem. Eng* **48**, 514-520.
- Joseph, D.D., Nguyen, K. and Beavers, G.S., 1984. Non-uniqueness and stability of the configuration of flow of immiscible fluids with different viscosities. *J. Fluid Mech.* **141**, 319-345.
- Kumara, W.A.S., Halvorsen, B.M. and Melaaen, M.C., 2009. Pressure drop, flow pattern and local water volume fraction measurements of oil-water flow in pipes. *Mesurement Science and Technology* **20**.
- Lovick, J., 2004. Horizontal, Oil-Water Flows in the Dual Continuous Flow Regime. Ph.D. thesis. University College London, London.
- Lovick, J. and Angeli, P., 2004. Experimental studies on the dual continuous flow pattern in oil-water flows. *Int. J. Multiphase Flow* **30**, 139-157.
- Lum, J.Y.-L., Al-Wahaibi, T. and Angeli, P., 2006. Upward and downward inclination oil-water flows. *Int. J. Multiphase Flow* **32**, 413-435.
- Morgan, R.G., Markides, C.N., Hale, C.P. and Hewitt, G.F., 2012. Horizontal liquid-liquid flow characteristics at low superficial velocities using laser-induced fluorescence. *Int. J. Multiphase Flow* **43**, 101-117.

- Morgan, R.G., Markides, C.N., Zadrazil, I. and Hewitt, G.F., 2013. Characteristics of horizontal liquid-liquid flows in a circular pipe using simultaneous high-speed laser-induced fluorescence and particle velocimetry. *Int. J. Multiphase Flow* **49**, 99-118.
- Nädler, M. and Mewes, D., 1995. The effect of gas injection on the flow of immiscible liquids in horizontal pipes. *Chem. Eng. Tech.* **18**, 156-165.
- Oddie, G., Shi, H., Durlofsky, I.J., Aziz, K., Pfeffer, B. and Holmes, J.A., 2003. Experimental study of two and three phase flows in large diameter inclined pipes. *Int. J. Multiphase Flow* **29**, 527-558.
- Oglesby, K.D., 1979. An Experimental Study on the Effects of Oil Viscosity Mixture Velocity, and Water Fraction on Horizontal Oil-Water Flow. M.S. thesis. The University of Tulsa.
- Rodriguez, O.M.H. and Oliemans, R.V.A., 2006. Experimental study on oil-water flow in horizontal and slightly inclined pipes. *Int. J. Multiphase Flow* **32**, 323-343.
- Russell, T. W. F., Hodgson, G. W. and Govier, G. W., 1959. Horizontal pipeline flow of mixtures of oil and water. *Can. J. Chem. Eng.* **37** (1), 9-17.
- Soleimani, A., 1999. Phase Distribution and Associated Phenomena in Oil-Water Flows in Horizontal Tubes. Ph.D. thesis. Imperial College London, London.
- Taitel, Y. and Dukler, A. E., 1976. A model for predicting flow regime transitions in horizontal and near horizontal gas-liquid flow. *AIChE Journal* **22** (1): 47-55.
- Torres-Monzón, C.F., 2006. Modeling of Oil-Water Flow in Horizontal and near Horizontal Pipes. Ph.D. thesis. The University of Tulsa.
- Trallero, J.L., 1995. Oil-Water Flow Pattern in Horizontal Pipes. Ph.D. thesis. The University of Tulsa.

Valle, A., 2000. Three Phase Gas-Oil-Water Pipe Flow. Ph.D. thesis. Imperial College London.

Vedapuri, D., Bessette, D. and Jepson, W. P., 1997. A segregated flow model to predict water layer thickness in oil-water flows in horizontal and slightly inclined pipelines. BHR Group Multiphase.

Vielma, M., Atmaca, S., Sarica, C., and Zhang, H.Q., 2007. Characterization of oil/water flows in horizontal pipes. SPE Annual Technical Conference and Exhibition in Anaheim, November 2007.