Experimental Investigations of Two-Phase Liquid-Liquid Horizontal Flows Through Orifice Plates

R.G. Morgan, S. Sharaf, I. Zadrazil, G.F. Hewitt and C.N. Markides*

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

* Corresponding author. Email: c.markides@imperial.ac.uk; Tel.: +44 (0)20 759 41601

ABSTRACT

This paper is concerned with two-phase liquid-liquid flows through orifice plates in horizontal pipes, and in particular with a phenomenon known as "phase inversion" that can occur in dispersed flow. Experimental investigations were carried out in which two-phase flows comprising oil and water were pumped via an inlet section into a horizontal pipe of diameter 25.4 mm and length 7 m. In one series of experiments the light phase (oil) was introduced into the inlet section above the heavier one (water), in a "stable" inlet configuration. This was followed by a set of experiments in which the water was introduced above the oil, in an "unstable" inlet configuration. Furthermore, tests were performed with and without the insertion of a static mixer just downstream of the inlet. The orifice plate was placed in two alternate positions with respect to the inlet: one near (1.30 m) the inlet, and one far (5.20 m) downstream, i.e., in both developing and fully developed flows.

The pressure drop across the orifice plate was measured with a differential pressure transducer in a series of independent experimental runs in which the two liquid flow-rates were varied independently in order to span a range of superficial mixture velocities and inlet phase fractions (water-cuts). From the data generated in the present experimental campaign, the pressure drop measured across the orifice plate showed a gradual increase as the mixture velocities were increased, as expected. However, for a given mixture velocity, a decrease in the pressure drop across the orifice plate was observed as the water-cut was varied. This decrease was observed at water-cut values that were close to those for which phase inversion was expected in our flows (~0.2-0.3). It is inferred that the phase inversion point may be associated with this *decrease* in pressure drop. This interesting finding is contrary to the increase in pressure drop demonstrated in previous studies involving two-phase pipe flow and has important implications for the design of pipeline systems that incorporate orifice plates for flow measurement. In addition, the inlet orientation appeared to have little effect on the phase inversion point.

NOMENCLATURE

A	[m^2]	Cross-sectional area of pipe
C	[-]	Discharge coefficient
D	[m]	Pipe diameter
d	[m]	Orifice diameter
d_{vc}	[m]	*Vena contracta*
L	[m]	Length of pipe
$PLIF$		Planar Laser-Induced Fluorescence
ΔP	[Pa]	Pressure across the orifice plate
Q_{oil}	[m^3/s]	Volumetric flow-rate of oil
Q_{tot}	[m^3/s]	Total volumetric flow-rate
Q_{wat}	[m^3/s]	Volumetric flow-rate of water
Re_m	[-]	Reynolds number
U_m	[m/s]	Mixture velocity
φ_{in}	[-]	Inlet phase fraction (water-cut)
β	[-]	Orifice plate dimensionless ratio
μ_m	[kg/m.s]	Mixture dynamic viscosity
ρ_m	[kg/m^3]	Mixture density

INTRODUCTION

Liquid-liquid two-phase flows have been studied extensively over the past fifty years or so. They have many important industrial applications, especially in the oil and gas industry where the two-phase mixtures of oil and water are extracted and pumped over vast distances both offshore and onshore in (mostly) horizontal pipelines. A large number of flow patterns have been reported [1] in these flows, and these have been generally classified as belonging to a smaller number of flow regimes, namely, and referring to Figure 1: stratified flows (S), mixed flows (MO, MW), annular flows (AO, AW), intermittent flows (IO, IW) and dispersed flows (DO, DW).

Of interest to the present study is a phenomenon known as "phase inversion" that occurs in mixed and dispersed flows. Phase inversion is a development whereby the phases of a liquid-liquid dispersion interchange under conditions determined by the system properties, volume ratio and energy

input, such that the dispersed phase spontaneously inverts to become the continuous phase and *vice versa* [2]. Phase inversion is indicated in Figure 1, which is taken from Ref. [3], by the vertical thin region at water-cuts between about 0.2 and 0.3, for superficial mixture velocities above ~0.5 m/s (~1.5 ft/s in the figure) and up to ~2.5 m/s (~8 ft/s).
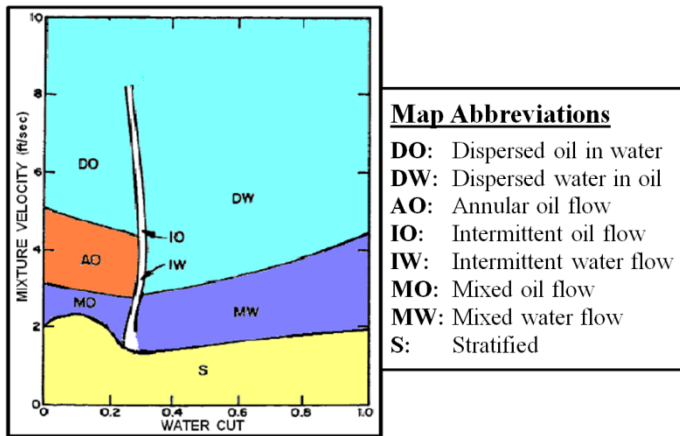
Figure 1. Flow pattern/regime map for liquid-liquid flow; taken from Arirachakaran et al. [3]

The occurrence of phase inversion is a major factor to be considered in the design of oil-water pipelines, due to the fact that it can significantly affect fluid-flow properties such as viscosity, friction (pressure drops), heat transfer and phase distribution, especially near the pipe wall [4]. The phenomenon can have desired, but also in some cases, undesirable effects. In an example of the former, it can be harnessed in the separation process of the two liquid phases. For these reasons, a sound understanding and adequate ability to predict phase inversion is imperative for the reliable design of multiphase systems.

A variety of instruments are used for the examination of multiphase flows, each with its advantages and disadvantages based on intrusiveness, cost, temporal and spatial resolution, etc. For example, in Ref. [5] a Wire-Mesh Sensor was used to study vertical gas-liquid flows, while in Ref. [6] Planar Laser-Induced Fluorescence (PLIF) techniques were used for the visualisation and detailed measurement of horizontal liquid-liquid flows. Similarly, several instruments are available for flow metering and flow-rate measurements. One such instrument is the orifice plate, which is mainly used in single-phase flows. In the present study we consider the pressure drop across an orifice plate with a two-phase liquid-liquid mixture flowing through it. Very few publications report on attempts to employ orifice plates to investigate two-phase flows [7].

The purpose of this study is to perform experimental investigations using modern instrumentation in a horizontal pipe with liquid-liquid flow through an orifice plate, while paying particular attention to the effect of the phase inversion phenomenon. The data provided will be valuable particularly to modellers who wish to study and simulate the mechanism of phase inversion. Although a large number of phase inversion models have already been reported in the literature, these have shown mixed results when compared to experimental data.

BACKGROUND

A large number of flow regime maps are available in the literature for liquid-liquid flows [8]. A common example of a flow map that is often used is shown in Figure 1 [3], which also indicates the existence of phase inversion as described earlier. Nevertheless, despite the number of studies that have reported on the appearance of phase inversion [9-13], this phenomenon remains poorly understood. In addition, since it has been studied more extensively in stirred vessels or closed reactors, there is a gap in the literature particularly with respect to continuous flows, such as the one in the present paper.

Phase inversion can be regarded as a form of instability in the flow system; the stability of the dispersion being a minimum at the point of phase inversion [3]. Assuming two well-mixed and immiscible fluids, one phase is the continuous phase, whilst the other exists in the form of droplets within the continuous phase. An investigation of the inversion process in Ref. [3] showed that under certain conditions a water-in-oil dispersion transitions into an oil-in-water dispersion.

The transition point in this study appeared to be accompanied with a sudden increase in the frictional pressure drop and hence the effective mixture viscosity. This is shown clearly in Figure 2 below. It was concluded that the magnitude of the peak mixture viscosity depended predominantly on the flow regime of the mixture when the inversion appeared. The same tendency was shown with the liquid hold-up. It is therefore of significant industrial importance to predict the phase inversion point at which the extremes in these pressure gradients will occur. The phase inversion behaviour is affected by both the physical properties of the liquids such as the viscosity, density and interfacial tension as well as the pipe section through which they flow.
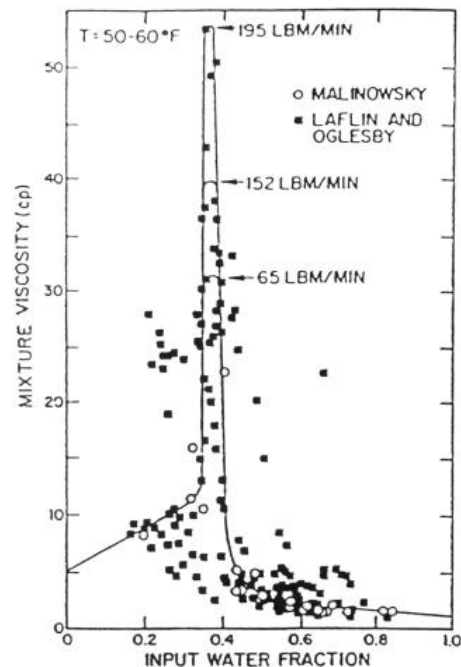
Figure 2. Mixture viscosity against input water fraction for low-viscosity oil; taken from Ref. [3]

Two important parameters that determine the flow patterns in these flows are the superficial mixture velocity U_m (total velocity of both phases flowing together) and the inlet phase fraction, also known as the water-cut φ_{in}. These two independent variables are defined by the expressions:

$$U_m = \frac{Q_{tot}}{A} = \frac{Q_{oil} + Q_{wat}}{A} \tag{1a}$$

$$\varphi_{in} = \frac{Q_{wat}}{Q_{tot}} = \frac{Q_{wat}}{Q_{oil} + Q_{wat}} \tag{1b}$$

respectively, with the total volumetric flow-rate Q_{tot} given by:

$$Q_{tot} = Q_{oil} + Q_{wat} \tag{2}$$

The mixture velocity U_m and water-cut φ_{in} were set by adjusting and measuring the volumetric flow-rates of the oil and water streams supplied to the inlet, Q_{oil} and Q_{wat} respectively.

Results from a closely related study conducted by Soleimani [10] with a similar facility to the one used in the present paper are shown in Figure 3. In this study a differential pressure transducer and two pressure tappings were used to measure the pressure drop along a horizontal liquid-liquid pipe flow. At a given superficial mixture velocity and in the dispersed flow regime, Figure 3 shows an initial fall in the pressure gradient followed by a steeper rise as the water-cut increases. The rise appears at a water-cut around 0.30-0.35, and is caused by phase inversion. These changes become more pronounced at higher mixture velocities. It was found that phase inversion occurred at lower water-cuts for higher mixture velocities. This was explained by the fact that at higher mixture velocities an enhanced degree of mixing in the flow leads to a more homogeneous mixing between the two fluids.
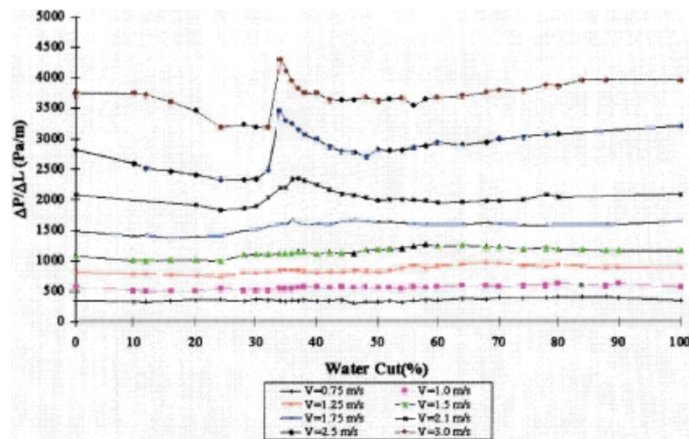

Figure 3. Pressure drop measurements; taken from Ref. [10]

METHODOLOGY

The experimental campaigns were performed in the <u>T</u>wo-Phase <u>O</u>il-<u>W</u>ater <u>E</u>xperimental <u>R</u>ig (TOWER) facility, based at Imperial College London. Extensive details about this facility can be found in Ref. [14]. Briefly, TOWER comprises a main

horizontal test section made from a stainless steel round pipe with a static mixer at the inlet, two pumps for the oil and water, two volumetric flow-meters for each fluid (for low and high flow-rates), a separator, and tanks for the oil and water. Tap water and Exxsol D80 oil were used as the two liquids. A simplified overall schematic of the TOWER facility along with the properties of the oil used can be found in Figure 4.
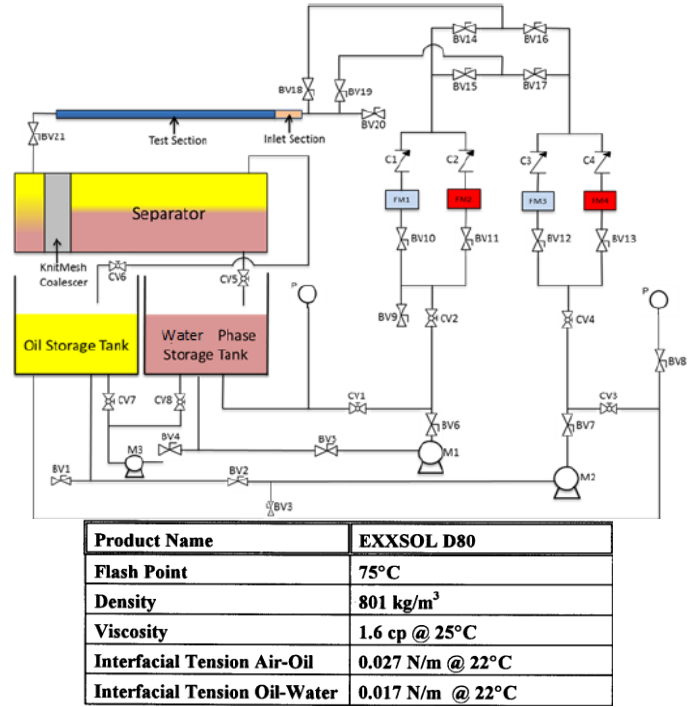

Product Name	EXXSOL D80
Flash Point	75°C
Density	801 kg/m³
Viscosity	1.6 cp @ 25°C
Interfacial Tension Air-Oil	0.027 N/m @ 22°C
Interfacial Tension Oil-Water	0.017 N/m @ 22°C

**Figure 4.** Schematic of the TOWER facility and oil properties

As shown in Figure 4, the oil and water were pumped through the main horizontal pipe of approximate total length 7 m and of inner diameter $D = 25.4$ mm. The volumetric flow-rates (and thus also, mixture superficial velocities) were varied systematically between $Q_{tot} = Q_{oil} + Q_{wat} = 10$ L/min ($U_m = 0.34$ m/s) and $Q_{tot} = 40$ L/min ($U_m = 1.44$ m/s). The pressure drop across the orifice plate was measured with an electronic differential pressure transducer. All the experiments were conducted at atmospheric pressure and room temperature. The two-phase Reynolds number Re_m in the pipe of diameter D is defined based on the mixture velocity U_m:

$$Re_m = \frac{\rho_m U_m D}{\mu_m} \tag{3}$$

where the mixture density ρ_m and viscosity μ_m are linear interpolations with respect to the pure fluid properties, e.g.:

$$\mu_m = (1 - \varphi_{oil})\mu_{oil} + \varphi_{in}\mu_{wat} \tag{4}$$

The Reynolds number Re_m for the mixture varied between 5,000 and 37,000 in our experiments. For a given mixture velocity, Re_m tended to a maximum when the water-cut φ_{in} tended to unity, due to the lower viscosity of the water phase.
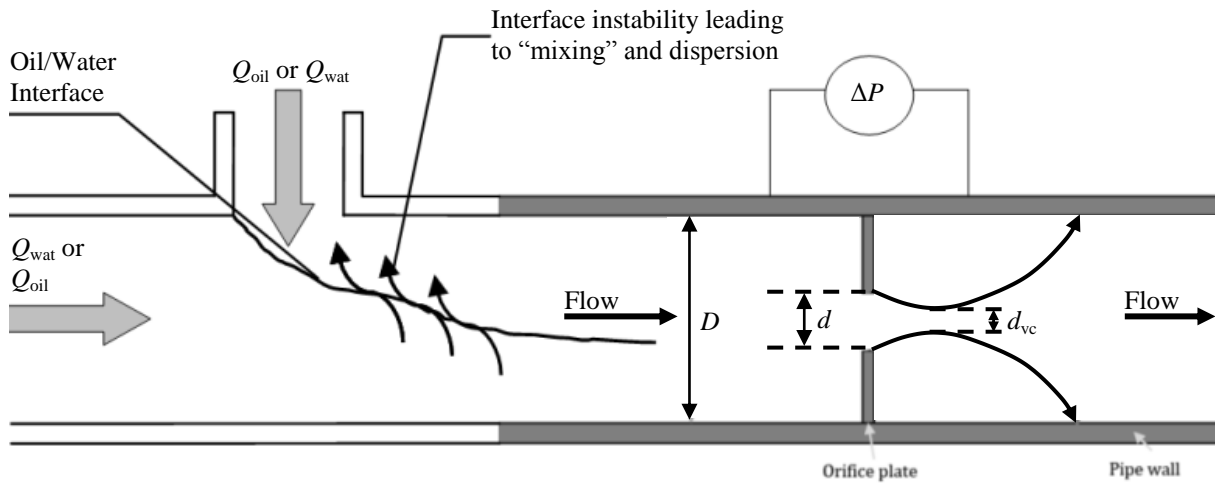
(a) Flow pipe and orifice plate arrangement and geometry, where D is the inner diameter of the pipe, d is the diameter of the orifice and d_{vc} is the diameter of *vena contracta*. In addition, Q_{oil} and Q_{wat} are the volumetric flow-rates of the oil and water flows, respectively, and ΔP is the pressure drop across the orifice plate
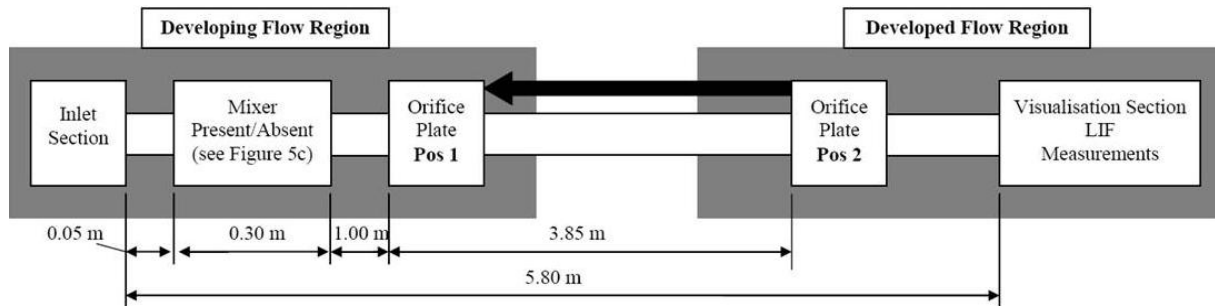
(b) Positioning of the orifice plate, visualisation section and mixer relative to the inlet section

(c) Two-element STATIFLO static mixer

Figure 5. Schematics and further details of the TOWER experimental facility

A detailed schematic of the TOWER test section (main pipe, inlet section and orifice plate) is shown in Figure 5(a), with additional detail on the geometrical arrangements used in Figure 5(b). With reference to these figures, experimental campaigns were conducted over a specified range of superficial mixture velocities in each of the following: stable and unstable inlet configurations, and also with and without a passive flow mixer (see photo in Figure 5(c)) upstream of the orifice plate:

   (a) Stable inlet orientation without the static mixer;

   (b) Unstable inlet orientation without the static mixer;

   (c) Stable inlet orientation with the static mixer; and,

   (d) Unstable inlet orientation with the static mixer.

Recall that a "stable" inlet signifies the less dense liquid (i.e., oil) being pumped over the denser liquid (i.e., water), whereas an "unstable" inlet signifies the reverse.

Refs. [15] and [16] previously used a similar arrangement and liquids, though they did not include an orifice plate in the pipe. The orifice plate was designed in accordance to EN ISO 5167 (formerly BS 1042). The pressure drop in the orifice plate can be calculated for any incompressible single-phase fluid using the following equation, taken from the ISO specification:

$$\Delta P = \frac{8(1-\beta^4)\rho Q^2}{(C\beta^2 \pi D^2)^2} \tag{5}$$

The dimensionless geometric ratio $\beta = d/D$ for the orifice plate used in the present work is equal to 0.62, while $C = 0.62\text{-}0.64$ which is known as the discharge coefficient was evaluated directly from the Reader-Harris/Gallagher equation as suggested in the EN ISO 5167 standard documentation.

The orifice plate was placed in two positions with respect to the inlet. The first position was at a distance of 5.20 m in the developed flow region far downstream of the mixing section (> 200 D). In a follow-up experimental campaign the orifice plate was positioned closer to the mixer at a distance of 1.30 m from the inlet (50 D), and the experiments were repeated.
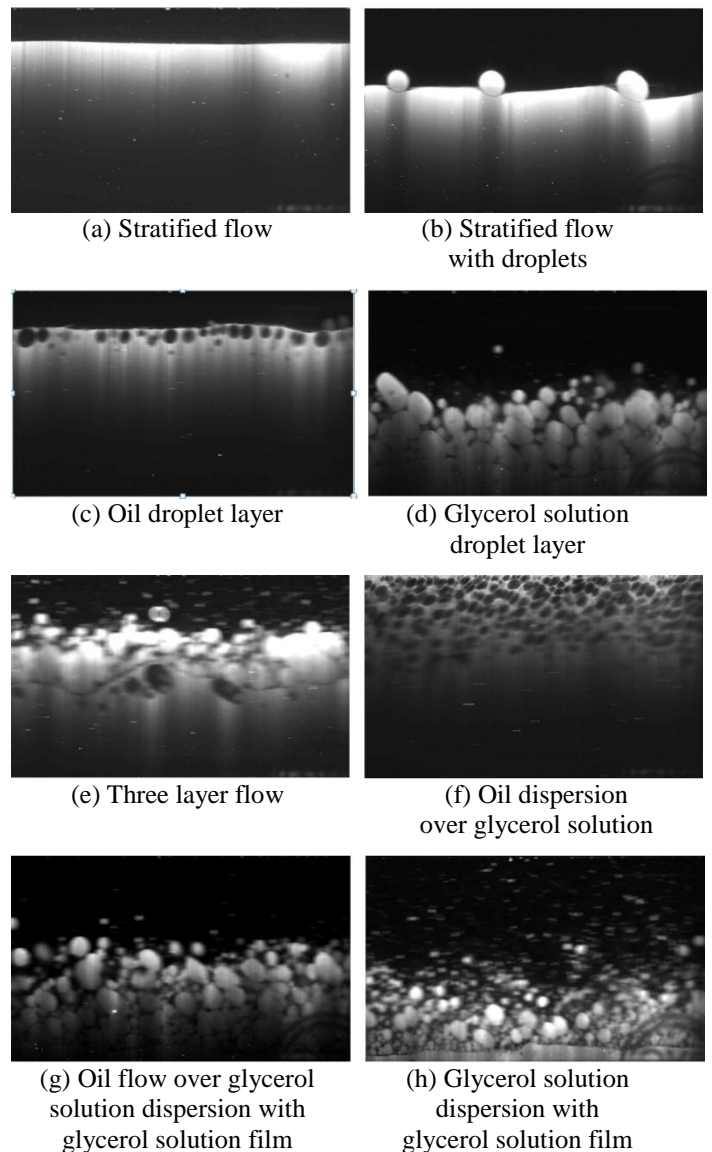
Finally, in order to visually inspect the various flow regimes established upstream of the orifice plate in these initially stratified liquid-liquid horizontal flows, an independent set of experiments were performed with a state of the art PLIF technique. The PLIF technique offers several advantages over other visualisation methodologies, such as high-speed camera imaging, by capturing the flow in high spatial detail within a known plane without the problems of line-of-sight averaging, which allows for a more reliable assessment of the flow. Certainly, the two-phase mixture through the orifice plate will be greatly affected by the sudden contraction. Unfortunately, although useful, it was not possible to perform direct visualisation of the flow through the orifice plate with PLIF. Thus, the PLIF visualization was intended to provide some knowledge, by extension, of the (unperturbed) flow that would be expected to occur upstream to the orifice plate.

A visualisation section was positioned 5.80 m (~230 D) from the inlet and PLIF measurements were made with oil and a glycerol/water mixture as the liquid-liquid flow. The liquids were chosen to ensure refractive index matching, which allowed the PLIF technique to be correctly performed. A laser sheet was sent through the pipe axis in the visualisation section. Since the refractive index of the two fluids was matched, the laser sheet passed through the section without distortion at the liquid-liquid interface. Any distortion in the image due to the pipe curvature was solved by using a graticule and a geometrical correction algorithm. Adding a fluorescent dye to the aqueous phase allowed the visualisation of that phase and the determination of the liquid-liquid interface within the illuminated plane. Although they involved a glycerol/water mixture in place of pure water, the planar PLIF experiments are of interest here since they otherwise resemble the exact set-up used for the main experimental campaign with water-oil, and therefore we expect to qualitatively capture the flow behaviour. Further details can be found in Ref. [14].

RESULTS

The flow regimes that were observed by using the PLIF technique on the TOWER test section with oil-glycerol/water flows can be seen in Figure 6, where typical examples (a selection of representative instantaneous images) of each of the various flow types are presented. The observed flows can be grouped into four more general flow regimes, namely:

(1) Stratified flows;

(2) Mixed flows, characterised by two distinct continuous phase regions with droplets in each;

(3) Two-layer flows, comprised of a dispersed region and a continuous, unmixed region; and,

(4) Dispersed flows.

(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 6. Images of the 8 distinct flow types observed in the experimental campaign with oil-glycerol/water flows. These were recorded for mixture velocities ranging from $U_m = 0$ m/s to 1 m/s and water-cuts φ_{in} from zero to unity

We expect that the flow regimes visualised for oil-glycerol/water flows can provide useful *qualitative* insight into the regimes that appear in the oil-water flows upstream of the orifice plate, however, we also expect that quantitatively there will be differences, for example in the exact position in the parameter space of any boundaries between the various flow regimes. Thus, images such as those in Figure 6 allow us to gain an understanding of the flow processes *upstream* of the orifice plate in the fully developed flow region.

In the limit of low flow-rates, the more dense liquid tends to occupy or stratify in the bottom half of the pipe as the flow develops. At higher flow-rates the flow becomes more unsteady and eventually turbulent, leading to interfacial instabilities, distortions, droplet break-up and separation, and eventually re-coalescence, giving rise to phase inversion.

(1a)   (1b)

(2a)   (2b)

(3a)   (3b)

(4a)   (4b)
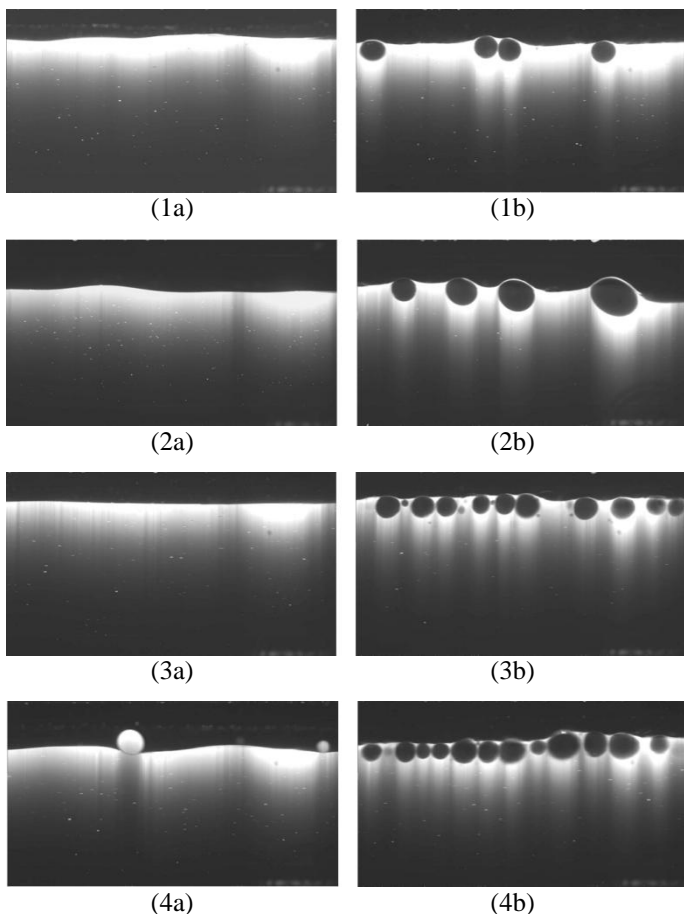
Figure 7. Instantaneous flow images for: (1) $U_\mathrm{m} = 0.17$ m/s for $\varphi_\mathrm{in} = 0.17$; (2); $U_\mathrm{m} = 0.22$ m/s for $\varphi_\mathrm{in\,(oil)} = 0.12$; (3) $U_\mathrm{m} = 0.28$ m/s for $\varphi_\mathrm{in\,(oil)} = 0.25$, and; (4) $U_\mathrm{m} = 0.33$ m/s for $\varphi_\mathrm{in\,(oil)} = 0.25$; "a" refers to the "stable" inlet configuration and "b" to the "unstable" inlet configuration[*]

Going beyond Figure 6, Figure 7 features a comparison between instantaneous images that were generated with the stable inlet configuration (on the left-hand side, i.e., those denoted by "a") and corresponding images generated with the unstable inlet configuration (right-hand side, i.e., those denoted by "b"). It can be concluded that the inlet configuration does have an effect on the flow regime at the distance far downstream of the inlet ($\sim$230 D) at which the PLIF measurements were made, in particular at the lower end of mixture velocities ($U_\mathrm{m} < 0.4$ m/s). Note that, as is often stated (e.g., [17]), developed flow occurs approximately 100 pipe diameters D from the inlet, and here, the orifice plate and the visualisation section were placed well beyond this length.

We proceed now to the main results from the present investigation, concerning the pressure drop across the orifice plate measured in the various two-phase flows as described earlier (i.e., developing and fully developed, with a stable and unstable inlet configuration, with and without a static mixer,

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[*] Note that these values of φ_in are defined according to Equation (1), but with the volumetric flow-rate of the glycerol/water phase replacing the flow-rate of water.

and over a range of superficial mixture velocities and water-cuts). These are shown in Figures 8 to 12.

Figure 8(a) shows the results from a series of experiments with a stable inlet orientation, while Figure 8(b) shows the results from a similar series of experiments but with an unstable inlet orientation. In both cases the measured were made far downstream of the inlet, in fully developed flow conditions, and without a static mixer after the inlet. The pressure drop ΔP across the orifice plate increases with the superficial mixture velocity and also with the water-cut.
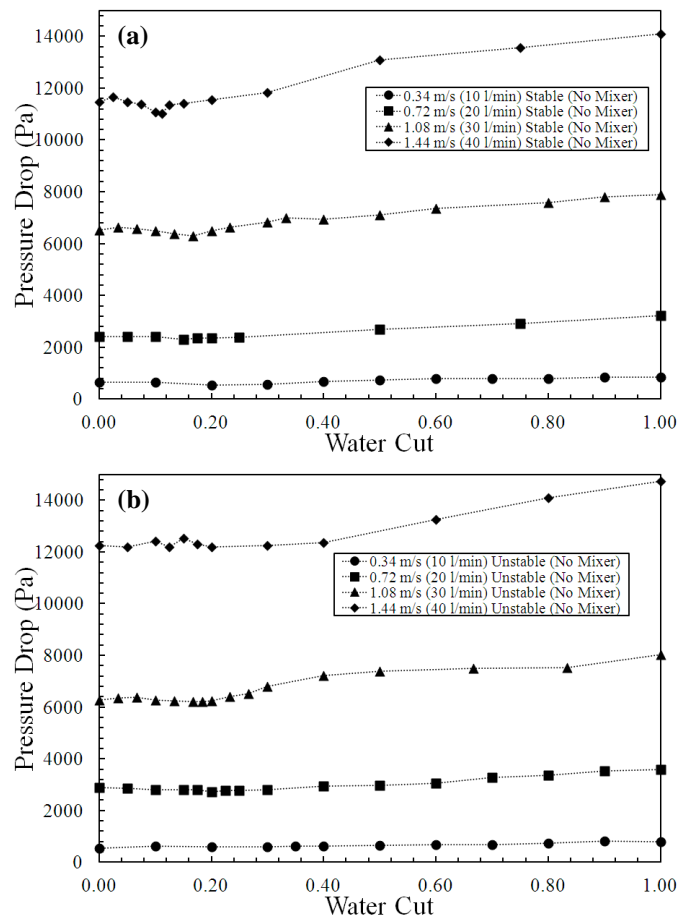
Figure 8. Pressure drop across the orifice plate ΔP against water-cut φ_in for fully developed oil-water flows at different superficial mixture velocities U_m without a static mixer, for: (a) a stable inlet configuration; and (b) an unstable inlet configuration
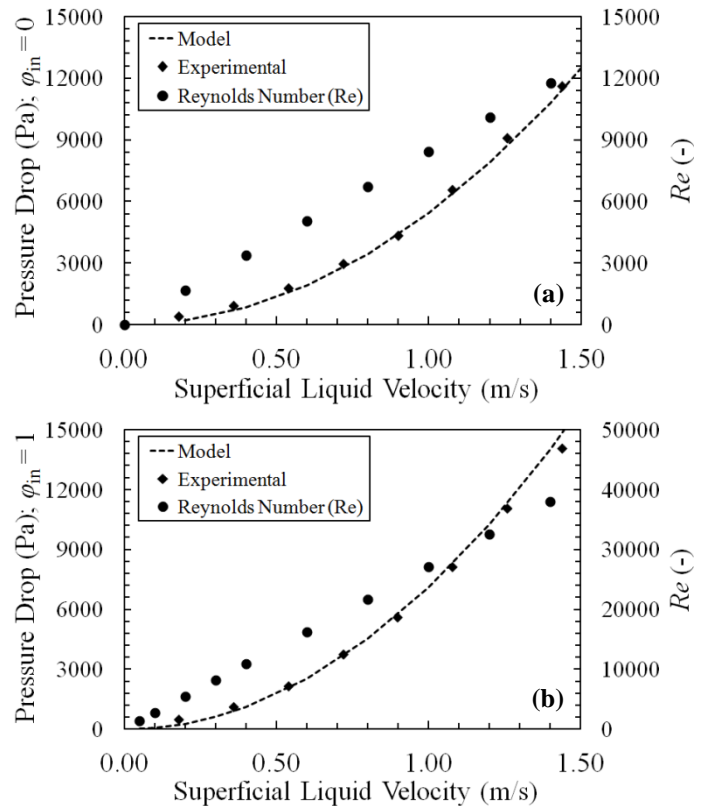
A slight decrease in ΔP can be seen at lower water-cut values between $\varphi_\mathrm{in} = 0.1$ and $\varphi_\mathrm{in} = 0.3$, however, this trend is not entirely clear in this figure since the range of spanned values of ΔP is large. The dip in ΔP is best seen in Figure 9, which contains the same data as Figure 8, but normalised by their respective values at zero water cut ($\varphi_\mathrm{in} = 0$) at the same superficial mixture velocity U_m, i.e., $\Delta P/\Delta P(\varphi_\mathrm{in}=0)$.
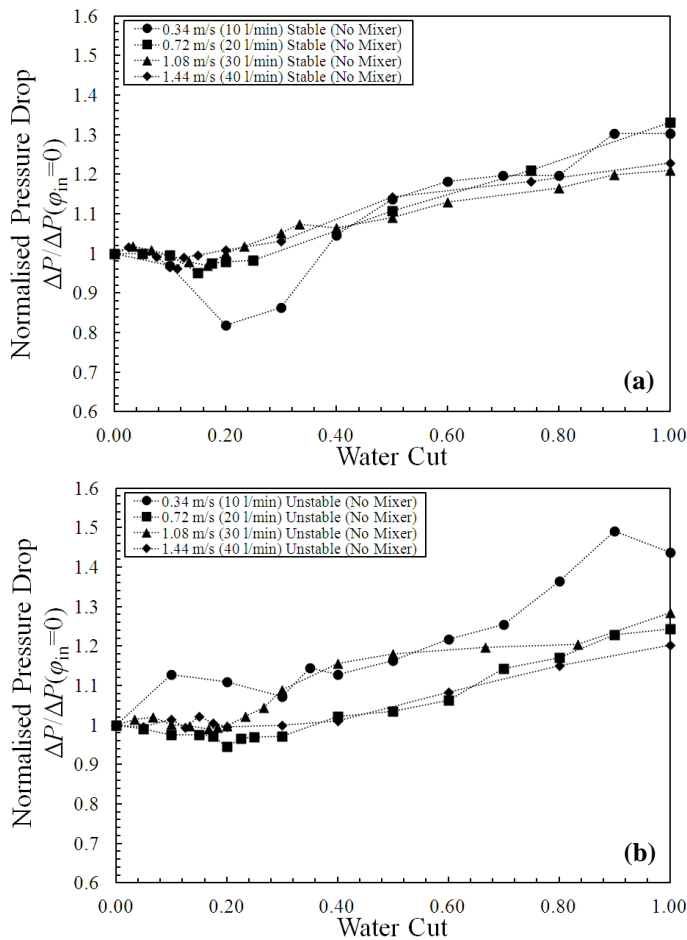
Figure 9. Normalised pressure drop across the orifice plate $\Delta P/\Delta P(\varphi_{in}=0)$ against water-cut φ_{in} for fully developed oil-water flows without a static mixer, for: (a) a stable inlet configuration; and (b) an unstable inlet configuration

Figure 10. Pressure drop across the orifice plate ΔP against superficial liquid velocity U_m for: (a) single-phase oil (i.e., $\varphi_{in} = 0$); and (b) single-phase water (i.e., $\varphi_{in} = 1$). Also, showing predicted values from Equation (5) and the mixture Reynolds numbers Re_m over which the experiments were carried out

In Figure 9(a) a decrease in ΔP is evident in the range of water-cuts $\varphi_{in} = 0.1$-0.3 for both inlet configurations. The decrease in normalised ΔP is up to 20% for the stable inlet and 10% for the unstable one. This *decrease* is of the order of (though perhaps slightly lower than) the 15-25% *increase* observed in simple two-phase pipe flows (e.g., see Figure 3), and appears over water-cut values φ_{in} that are closely associated with those where the appearance of phase inversion is expected (that is, between 0.2 and 0.3). The dip in the normalised pressure drop ΔP appears highest for the lower mixture velocities U_m (and hence also, Reynolds numbers Re_m). At higher velocities the normalised pressure drop lines seems to collapse, at least for low water-cut values φ_{in}. Overall, the stable and unstable inlet configuration results appear similar.

The data for the single-phase liquid flows, also extracted from Figure 8, are shown in Figure 10(a) for oil and Figure 10(b) for water, respectively. The experimental data show very good agreement with the predictions from the pressure drop equation (Equation (5)). The two plots also show the range of Re_m numbers that were spanned in this study, as a function of U_m.

Figure 11(a) shows results for a superficial mixture velocity of $U_m = 0.34$ m/s generated with both the stable and unstable inlet configuration, and with and without the introduction of the static flow mixer at the exit of the inlet, well upstream of the orifice plate. For the stable inlet and no mixer a minimum in the pressure drop ΔP is observed at a water-cut φ_{in} of approximately 0.2. Introducing the mixer shifts the entire range of measured ΔPs to higher values, and the position of the minimum to a higher water-cut φ_{in} of around 0.3. Similarly, inverting the inlet to an unstable arrangement (while continuing to operate without a mixer) also leads to a shift in the minimum to a higher water-cut of $\varphi_{in} \sim 0.3$.
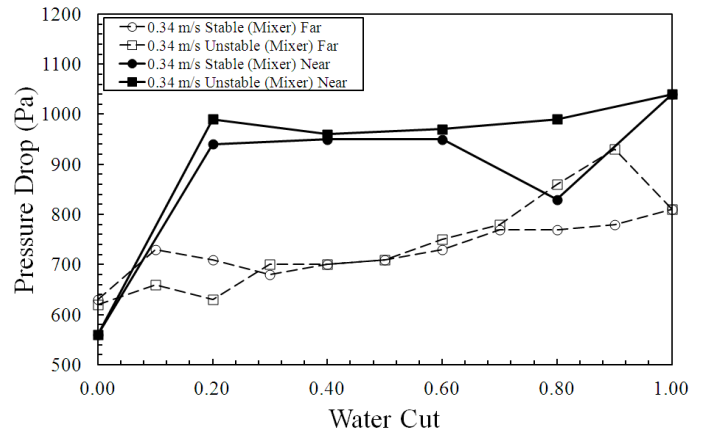
Figure 11(b) is similar to Figure 11(a), but shows data with a higher superficial mixture velocity of $U_m = 1.08$ m/s. In this case, there is much less scatter in the data and the resulting trend-lines appeared collapsed over the range of small water-cut values up to $\varphi_{in} \sim 0.35$. A noticeable decrease in the pressure drop ΔP is observed at a water-cut of approximately $\varphi_{in} \sim 0.15$ before increasing again. These water-cut values φ_{in} are, once again, close to those predicted by Ref. [3], and shown in Figure 1, as being representative of phase inversion. Together, the results presented in Figures 8 to 10, provide indirect evidence that suggests that the dip in the pressure drop that appears in the investigated flows may be linked to phase inversion.
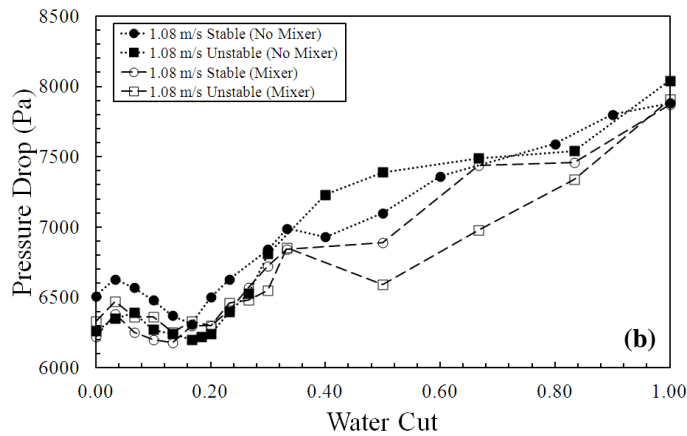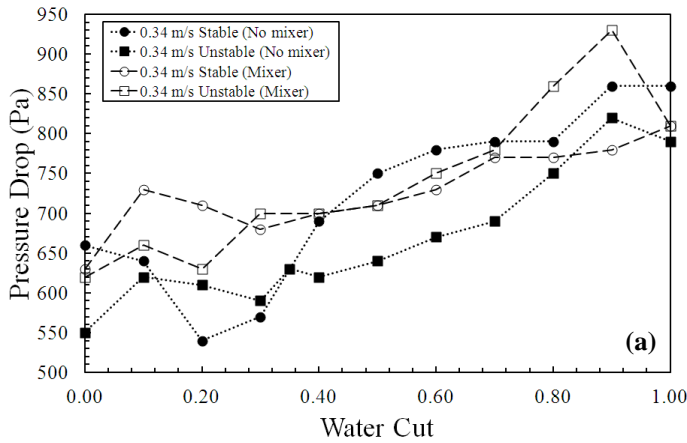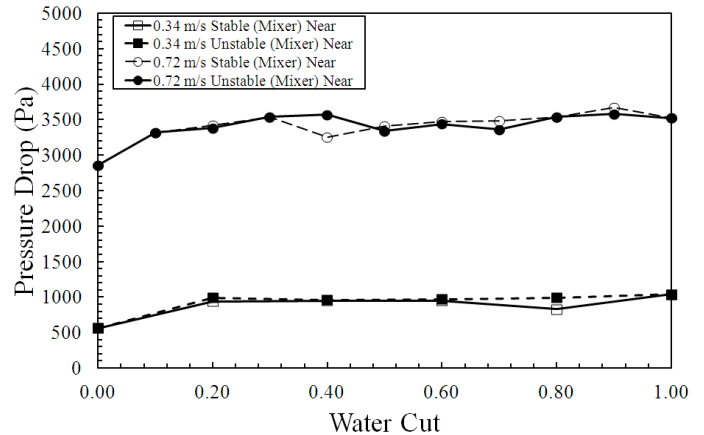
Figure 11. Pressure drop ΔP across the orifice plate against water-cut φ_{in} for liquid-liquid horizontal flows at: (a) a superficial mixture velocity of $U_m = 0.34$ m/s; and (b) a superficial mixture velocity $U_m = 1.08$ m/s. In both cases, results are shown for both the stable and unstable inlet configurations, and with and without an upstream static mixer

Figure 12. Pressure drop ΔP across the orifice plate against water-cut φ_{in} at a superficial mixture velocity of $U_m = 0.34$ m/s, in the stable and unstable inlet configurations. Results shown with the static mixer and with the orifice plate placed close to the mixer and further away

Figure 13. Pressure drop ΔP across the orifice plate against water-cut φ_{in} at superficial mixture velocities of $U_m = 0.34$ m/s and $U_m = 0.72$ m/s, in the stable and unstable inlet configurations. Results generated with the orifice plate placed close to the mixer

In Figure 12 we examine specifically the role of the degree of development of the flow on the observed orifice plate pressure drops. It is evident that significantly higher pressure readings were recorded with the orifice plate close to the mixer than further away, especially at lower water-cuts φ_{in}. A possible explanation for this must consider the more intense mixing and higher turbulence levels that would be expected when measurements were made at shorter distances from the mixer. Interestingly, the minimum observed in the pressure drop across the orifice plate at $\varphi_{in} \sim 0.2\text{-}0.3$ when the orifice plate was positioned far away from the mixer is not observed at all when the plate is positioned close to the mixer.

Finally, Figure 13 shows additional results with the orifice plate placed close to the inlet and the mixer (which is only 0.05 m downstream; see Figure 5(b)). Data are shown at two superficial mixture velocities, $U_m = 0.34$ m/s and $U_m = 0.72$ m/s, and also in the stable and unstable inlet configurations. As before, the decrease in the pressure drop at lower water-cuts in the range $\varphi_{in} = 0.1\text{-}0.3$ is absent when the orifice plate is positioned close to the mixer, while inverting the liquids appears to have had little effect on this observation.

FURTHER DISCUSSION AND CONCLUSIONS

The pressure drop across an orifice plate placed in a horizontal pipe was investigated experimentally over a range of two-phase oil-water flows. When the orifice plate was placed close to a static flow mixer, which in turn was positioned close to the flow inlet section that introduced the initially stratified flow into the main pipe section, the pressure drop across the orifice plate showed a gradual increase as the water-cut was varied from pure oil to pure water, for the same superficial mixture velocity. Higher mixture flow velocities led to higher pressure drops across the orifice plate, with the single-phase results following closely the expected predictions from the orifice plate correlation standard in EN ISO 5167.

With the mixer in place but far downstream (> 200 pipe diameters) of the inlet where the flow is expected to be fully developed, and also in the absence of the mixer (irrespective of

the measurement position), a minimum in the pressure drop across the orifice plate was observed as the water-cut was varied, for a given superficial mixture velocity. The magnitude of this decrease in the pressure drop was between 10% and 20% depending on the flow condition, while the minimum pressure drop appeared at water-cut values between 0.1 and 0.3.

These water-cut values are close to those for which phase inversion is expected in the oil-water flows under investigation (e.g. from previous studies such as Ref. [3]), and so it is possible that this phenomenon is related to our observations. Interestingly, the change in the pressure drop that is possibly related to phase inversion appears as a *minimum* over the range of water-cuts tested, as opposed to a *maximum* shown in previous studies involving two-phase pipe flow.

The pressure drop (drag) in fluid flow can be either due to viscosity (e.g., laminar flow in a pipe), or due to the flow separation (e.g., separated flow through an orifice plate). The former is termed "skin friction drag" or "viscous drag" and the latter is called "pressure drag" or "form drag". Measurements of skin friction drag in a two-phase pipe flow leads to an *increase* in pressure at the phase inversion point (shown in previous work); this is associated with an *increase* in the effective viscosity of the flow. The present results suggest that in the context of the form drag arising from flow through an orifice plate, the pressure drop *decreases* at the phase inversion point, in direct contradiction to the earlier results concerning simple pipe flow. This has important implications for the design of pipeline systems that incorporate orifice plates for flow measurement; operation near or at the phase inversion point is expected to lead to a smaller pressure drop than for other flow mixtures. The generated data can also be used to gain an understanding of these complex two-phase flows, and to validate advanced numerical models for two-phase flow.

Finally, evidence from an independent set of PLIF experiments that we have performed in order to visualise the investigated flows suggests that the inlet orientation of the two liquid phases (i.e., whether the lighter phase is introduced into the pipe above or below the heavier phase, in a "stable" or "unstable" configuration respectively) does appear to impact the flow and the phase distribution in the approaching flow *upstream of the orifice plate*, in particular at lower superficial mixture velocities. This observation reflected well the effect of the inlet configuration on the orifice plate pressure drop, which was mostly evident at lower flow velocities. It is noted that the PLIF experiments were done in the absence of the orifice plate, and with the water phase replaced with a glycerol/water mix for the purpose of matching refractive indexes, but otherwise in the same apparatus as the rest of our measurements.

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