Experimental Investigations of Upward-Inclined Stratified Oil-Water Flows Using Simultaneous Two-Line Planar Laser-Induced Fluorescence and Particle Velocimetry

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Abstract

Experiments are performed in low-inclination ($\leq 5^\circ$) upward stratified oil (Exxsol D140) and water flows. The flows are investigated using a novel two-line laser-based diagnostic measurement technique that combines planar laser-induced fluorescence and particle image/tracking velocimetry to obtain two-dimensional (2-D) space- and time-resolved phase and velocity information. The technique enables direct measurements in the non-refractive-index-matched fluids of interest, as opposed to substitute fluids which are matched optically but whose properties may be less representative of those in real field applications. Flow conditions span *in situ* Reynolds numbers in the range 1300-3630 in the oil phase and 1810-11540 in the water phase, and water cuts from 10% to 20%. Instantaneous velocity vector-fields reveal the presence of complex flow structures in the water phase at low mixture velocities, which become less coherent with increasing pipe inclinations. These structures contribute to the generation of interfacial waves, increase the unsteadiness of the flow and the rate of momentum transfer to the oil phase. Statistical information on the interface heights, mean axial and wall-normal velocity profiles and fluctuations, Reynolds stresses, and mixing lengths is obtained from the analysis of the spatiotemporally resolved phase and velocity data. The normalised mean and rms velocity characteristics (velocity fluctuations and Reynolds stress) are shown to be weakly-dependent on the pipe inclination as the mixture velocity increases. Finally, predictions from a linear mixing-length model agree reasonably well with measurements for the water layer and near-interface regions.

1 Introduction

The flow of oil and water in pipes is encountered in a wide variety of industrial applications, especially in transportation pipelines, which can extend for long distances at low pipe-inclinations (less than $\pm 5^\circ$). The flow regimes observed along the pipe, commonly classified into ‘separated’ (Morgan *et al.*, 2012) and ‘mixed’ (Voulgaropoulos *et al.*, 2019) flows, depend on fluid properties, flow velocities, pipe characteristics, as well as the design of the pipe inlet particularly at short distances from the inlet (Morgan *et al.*, 2017), with further changes imposed by active methods such as the use of crossflow jets (Wright *et al.*, 2018) that can further mix the phases. Separated flows are characterised by two continuous, stratified layers, in which the interface can be smooth or wavy. Mixed flows, on the other hand, are identified by the presence of droplets of one or both phases within the other; these flows encompass ‘dual-continuous’ flows, and dispersions of water-in-oil and oil-in-water (Morgan *et al.* 2012; 2013; Voulgaropoulos *et al.*, 2019).

Most studies of oil-water flows have focused on horizontal pipes (Russell *et al.*, 1959; Oglesby, 1979; Arirachakaran *et al.*, 1989; Nadler and Mewes, 1995; Trallero, 1995; Soleimani, 1999; and Angeli and Hewitt, 2000), and have provided important insight into the observed flow-regime maps, pressure gradients, and *in situ* phase distributions and fractions. However, the inclination of the pipe is known to have a significant effect on the behaviour of the flow. In upwards stratified-flows, the interface becomes more ‘active’, resulting in complex velocity structures, especially at low velocities (*e.g.*, recirculation or backflow). Mukherjee *et al.* (1981) performed one of the first experimental investigations in inclined pipes and developed an empirical correlation for the water holdup as a function of pipe inclination. Other studies of liquid-liquid flows in horizontal and slightly-inclined pipes include those of Vedapuri *et al.* (1997), Alkaya *et al.* (2000), Oddie *et al.* (2003), Rodriguez and Oliemans (2006), Atmaca *et al.* (2009), Voulgaropoulos and Angeli (2017) amongst other, and have been reviewed by Ibarra *et al.* (2014).

Space- and time-resolved information of the *in situ* flow behaviour can be obtained with the implementation of laser-based diagnostic techniques, such as Planar Laser-Induced Fluorescence (PLIF) and Particle Image and/or Tracking Velocimetry (PIV/PTV). PLIF is a two-

dimensional (2-D) planar technique used to extract information on the distribution of the phases and interface profiles, but also in other flows on scalar fields (*e.g.*, Markides *et al.*, 2016), while PIV/PTV can provide information on 2-D velocity vector-fields, conventionally in flow cross-sections, but also over interfaces between immiscible phases (*e.g.*, Charogiannis *et al.*, 2016). In two-phase isothermal flows, PLIF has been used in falling-film flows (Charogiannis *et al.*, 2015; 2017a,b; 2018), in gas-liquid annular vertical flows (Schubring *et al.*, 2010; Zadrazil *et al.*, 2014a,b; Charogiannis *et al.*, 2019; Cherdantsev *et al.*, 2018; 2019), co-current liquid-liquid downward vertical flows (Liu *et al.*, 2006), and co-current liquid-liquid horizontal flows (Morgan *et al.*, 2012; 2013), by employing a thin laser-sheet to illuminate a plane through the flow of interest. The addition of a fluorescence dye in one of the fluid phases enables the spatial identification of the seeded phase. PIV and PTV on the other hand employ seeded particles in the flow that scatter light from the laser light-sheet, which is then captured in successive images for later processing. In PIV, the relative motion of particle groups is analysed based on correlation techniques within defined interrogation windows to obtain displacements (and thereafter) velocity magnitudes and directions. In PTV, correlation algorithms trace individual particle pathlines.

The optical basis of both of the aforementioned techniques requires the refractive index (RI) of the fluid pairing to be matched in order to minimise optical distortions at the liquid-liquid interface. In liquid-liquid systems, Conan *et al.* (2007) and Morgan *et al.* (2013) matched the RIs of the fluids using a water-glycerol solution as the aqueous phase; however, this resulted in a high viscosity aqueous phase. Kumara *et al.* (2010) utilised a non-refractive index matched system (Exxsol D60-water); however, this removed the possibility of obtaining simultaneous information on both phases as only one laser sheet was employed.

In a recent study by the present authors (Ibarra *et al.*, 2018), a novel simultaneous two-line (two-colour) technique combining planar laser-induced fluorescence with particle image/tracking velocimetry was implemented in horizontal stratified and stratified-wavy oil-water flows (non-RI-matched fluids). The present work is extended to low-inclination upward flows in order to provide detailed space- and time-resolved phase and velocity information at low water-cuts to

study the effect of pipe inclination on the flow hydrodynamics. The data generated can be used to improve our fundamental understanding of liquid-liquid flows, and to develop and validate closure relations and advanced computational multiphase flow models.

The rest of this paper is organised as follows. Section 2 describes the flow facility and the laser-based diagnostic technique approach. The experimental results and analysis are presented and discussed in Section 3. Finally, Section 4 contains the main conclusions of the study.

2 Experimental methods

2.1 Flow facility and test fluids

The experimental investigations were performed in the flow facility known as TOWER (Two-phase Oil-Water Experimental Rig) located at Imperial College London, which is illustrated in Figure 1. The experimental facility allows investigation of co-current flows of two immiscible liquids in horizontal and low-inclination pipes. The test fluids utilised in the experimental investigations were water and Exxsol D140 (oil phase). The physical properties of the two liquid phases are shown in Table 1. The same facility and test fluids were used in our earlier study focused on horizontal flows (Ibarra *et al.*, 2018).

Figure 1: Schematic of the TOWER flow facility (FT: turbine flowmeter, TT: temperature transducer, DPT: differential pressure transducer, PT: pressure transducer).

Table 1: Physical properties of the test liquids.

	Oil Exxsol D140	Water
Density, ρ , at 25 °C (kg/m ³)	824	998
Interfacial tension, γ , at 22 °C (mN/m)	35.1	
Refractive index	1.456	1.333
Viscosity, μ , at 25 °C (mPa·s)	5.4	0.9

TOWER consists of a liquid-liquid separator (total capacity of 450 L), two storage tanks (one per liquid phase, each with a maximum capacity of 680 L), two vertical pumps (each with a nominal capacity of 160 L/min) that deliver the liquid phases separately to the test section inlet, and an inclinable test section. The volumetric flow rates of each liquid phase were measured with a combination of two turbine flowmeters with a capacity of 2-20 L/min and 14-140 L/min and an accuracy of $\pm 0.5\%$ of full scale. Low water flow rates were measured using a Coriolis mass-flow controller with a capacity of 5-300 kg/hr (0.08-5 L/min based on the water density) and an accuracy of $\pm 0.2\%$ of the measured value. Flowmeters with different measuring ranges were employed to reduce the flow rate measurement uncertainty over the full range of investigated flow conditions.

Both phases were introduced into the test section through a specially-designed inlet section equipped with an inline splitter or baffle plate (installed horizontally in the azimuthal direction), located at 10 mm from the bottom of the pipe, in order to separate both phases from mixing at the inlet section and to promote initially stratified flows. The oil phase was introduced from the top and the water from the bottom into this inlet section, which was also equipped with a series of flow conditioners for the purpose of promoting uniformity, reducing large-scale turbulent structures and secondary flows. Details of the inlet section can be found in Ibarra *et al.* (2018).

The main pipe test section has an internal diameter of $D = 32$ mm and a total length of 8.5 m, and consists of 5 acrylic and fused quartz-glass pipe sections connected with acrylic flanges. The first three sections are made of acrylic pipe with lengths of 1, 2 and 2 m, while the fourth and final sections comprise a 2-m long quartz pipe and a 1.5-m long acrylic pipe, respectively. For the purpose of reducing optical distortions, the optical measurement region was

located in the quartz pipe section, $L/D = 209$ with L the distance from the inlet, since quartz matches the RI of the oil phase (Wright *et al.*, 2017).

Commonly, the optical measurement section consists of a short transparent pipe made of a different material than the rest of the test section, *e.g.*, Morgan *et al.* (2013) used a borosilicate glass optical section in a longer, stainless-steel pipe test section. The contact angle between the liquids and the pipe wall can differ between these sections and can locally affect the behaviour of the flow. In this work, the oil-water-acrylic and oil-water-quartz contact angles, α , on an oil pre-wetted substrate are $\alpha = 108.7 \pm 2.9^\circ$ and $\alpha = 59.2 \pm 2.3^\circ$, respectively. For this reason, a long quartz pipe was selected as the measurement section and the optical measurements were performed at the farthest point from the acrylic/quartz transition (*i.e.*, at a length of $53D$). By visual observations supported by processed high-speed images over a range of conditions, it was confirmed that minor changes to the oil-water contact line decayed within a transition length of $15\text{--}20D$ as the flow travelled from the acrylic to the quartz pipe sections. However, the precise effect of wettability effects must be further analysed for experiments conducted using similar configurations, especially if flow regimes and flow conditions differ from those studied in this work.

Pressure drop measurements from transducers DPT1 and DPT2, as shown in Figure 1, were analysed to study the development of the flow along the test section. These transducers measured pressure drops over distances of $136D$ and $66D$, with an entry length of $L/D = 92$ and 155 . The difference in the mean measured values between the two pressure transducers was less than $\pm 5\%$, which indicates that the flow was fully developed at the measurement section (*i.e.*, $L/D = 209$).

The outlet of the test section is connected to a horizontal liquid-liquid separator, equipped with a coalescing mesh, to collect and separate both liquids, which are then transferred to their respective storage tanks, from where they are pumped again into the test pipe.

2.2 Flow conditions and experimental procedure

Experiments were performed over a range of inlet water-cuts, WC , mixture velocities, U_m , and pipe inclinations, θ , of 1° , 3° , and 5° from the horizontal. The water cut is defined as the ratio

between the water and total volumetric flow rates introduced at the inlet section which were measured by dedicated flow meters, $WC = Q_w/Q_T$ where $Q_T = Q_w + Q_o$, while the (bulk) mixture velocity cut is defined as the area-averaged total volumetric flow rate, $U_m = Q_T/A$ with A being the total flow cross-sectional area of the pipe, $A = \pi D^2/4$.

Experiments were conducted at steady-state conditions at nearly atmospheric pressure keeping the water cut and mixture velocities constant during each run. The temperature of the fluids was kept at 25 ± 2 °C for all experiments and measured with K-type thermocouples installed upstream of the inlet section (TT as shown in Figure 1). The pressure drop was measured with two pressure transducers with an accuracy of $\pm 0.15\%$ of the full span (*i.e.*, 3 kPa). The system was operated using a LabVIEW® control panel built for this experimental campaign.

The full set of investigated flow conditions covered in the present experiment campaign is given in Table 2 as a function of the mixture velocity, water cut, and *in situ* Reynolds number (at the optical measurement location) defined for phase i as $Re_i = \rho_i U_i D_{hi}/\mu_i$. This definition is based on the bulk *in situ* fluid velocity (see Table A1 in Appendix A) $U_i = Q_i/A_i$ where A_i is the cross-sectional area occupied by the respective phase, and the hydraulic diameter D_{hi} of each fluid calculated from the liquid/pipe wetted perimeters, S_i , based on the mean water layer height, $\langle h_w \rangle$, and assuming a flat interface in the azimuthal direction from the expression $D_{hi} = 4A_i/S_i$, thereby neglecting the error related to the curvature of the interface as it meets the wall at the contact-line, similar to (Ibarra *et al.*, 2018). We note here that all our results are based on measurements in the vertical plane that passes through the centreline of the pipe (where the laser sheet is located), and that the interface height and the curvature of the interface outside of this plane, including where the interface contacts the pipe wall, cannot in general be inferred from these measurements. Nevertheless, for the flow conditions studied in our work, it was observed visually during our experiments that the cross-sectional interface profile (in the azimuthal direction) showed only a slight curvature. This observation confirms an expectation raised by considering the work of Ng *et al.* (2001) and Ng (2002), who developed a model to predict the interface curvature in laminar-laminar stratified flows accounting for the effects of buoyancy, interfacial forces and contact

angle. This model predicts, for the test fluids, pipe material and flow conditions in our study, an azimuthal interface profile that is nearly flat, with a local water holdup in the range 10-35%.

Our experimental investigations revealed that the azimuthal interface curvature shape, which was also a function of the flow rates (mixture velocities), showed minor deviations with the profiles predicted by the Ng model. These deviations can be understood in terms of the interfacial (waves) and flow unsteadiness that is not accounted for in the Ng model.

Table 2: Inlet mixture velocities, water cuts, and corresponding *in situ* Reynolds numbers (see text for all definitions) for the experimental condition envelope investigated in this work.

U_m (m/s)	WC (%)	$\theta = 1^\circ$		$\theta = 3^\circ$		$\theta = 5^\circ$	
		Re_o	Re_w	Re_o	Re_w	Re_o	Re_w
0.2	20	1310	3570	1540	3330	1600	3260
	10	1300	2270	1550	1930	1560	1810
0.3	20	1790	5850	1900	5330	2110	5380
	10	1770	3500	1930	3310	2210	3100
0.4	20	2470	7540	2510	7030	2610	7350
	10	2180	4870	2380	4590	2690	4710
0.5	20	3010	9070	3210	9110	3240	9270
0.6	20	3470	10800	3490	10950	3630	11540

2.3 Optical diagnostic techniques

The study of two-phase flows in pipes using any optical diagnostic technique must take into consideration the refraction of light as it passes through all fluid-pipe (*i.e.*, both on the inside and outside of the pipe) and fluid-fluid interfaces. Ideally, a fully RI-matched system is desired to avoid such optical distortions (Wright *et al.*, 2017). However, this is a challenging task to accomplish for liquids with properties comparable to those encountered in actual practical applications and pipe materials suited for laboratory analysis using laser-based techniques (*e.g.*, rigid with optical transparency). In the present study, the test pipe had a similar RI (*i.e.*, 1.456) to

the oil phase, resulting in minimal optical distortions at the oil-pipe wall interface; however, the refractive indices between both fluids are not matched.

The difference in the refractive indices of the test fluids selected for this campaign implies that light is refracted as it passes through the liquid-liquid interface increasing the uncertainty of the acquired information in the second liquid layer. This can be overcome by employing two laser sheets in order to obtain accurate simultaneous information on both phases. The laser-based system employed in this work consisted of a copper-vapour laser which emits two narrow-band laser beams at 510.6 nm (green light) and 578.2 nm (yellow light) at a nominal output power of 20 W, frequency of 10 kHz, pulse-duration of 2 ns, and pulse energy of 2 mJ. Each beam/colour was delivered to a separate sheet generator (see Figure 2), using a fibre optic cable, one located at the top (green) and one at the bottom (yellow) of a correction box. The correction box, made of acrylic and filled with the oil phase, was used to reduce optical distortion due to the difference in the refractive index (water-pipe) and the relative position of the cameras (geometric distortion). The green and yellow light illuminated the test section from the top and bottom of the pipe, respectively, in the vertical axial plane through the centre of the pipe. The same laser arrangement and image processing techniques were used in our earlier study (Ibarra *et al.*, 2018). Note that the implementation of two laser sheets, one per liquid phase, allows the extraction of simultaneous information simultaneously in both phases when the refractive indices are not matched. When only time-averaged information is needed in the two liquid phases with different refractive indices and having only one laser sheet, the experimental procedure can be performed in two steps: firstly, the flow can be illuminated with the laser sheet from top to bottom to obtain information in the oil phase; secondly, the laser sheet can be moved and introduced from the bottom of the pipe to obtain information in the water phase (*i.e.*, interrogating each phase separately) or *vice versa*. However, this means that the laser-sheet generator must be re-positioned and re-aligned, and also it is not possible to obtain simultaneous, time-resolved information in both phases.

Figure 2: Laser sheet arrangement at the measurement section.

The generated laser sheets had a width of approximately 1 mm and were expanded in the streamwise direction using a set of plano-convex and concave cylindrical lenses. Two high-speed cameras were used to capture instantaneous images of the flow. Camera 1, an Olympus iSpeed 3 with a maximum resolution of 1280×1024 pixels at a maximum frame-rate of 2 kHz, equipped with a Nikon 60 mm lens, was installed in a horizontal arrangement perpendicular to the correction box, as per Figure 3. This camera was used to capture the fluorescent emission from a dye added to the water phase (excited by the green light) and the scatter light from the seeded particles in the water phase. The camera was also equipped with a bandpass filter (Edmund Optics, part number 65-222), with a centre wavelength at 580 nm and a width of $\pm 10 \text{ nm}$, used to only allow the fluorescence from the dye emission (in the water phase) and the scatter light from the seeded particles at 578.2 nm. It was found that using the fluorescent dye Eosin Y (Sigma-Aldrich) at a concentration of 0.075 mL of a 5% wt. per L of water, along with the bandpass filter, an optimum balance between the scatter light intensity from the seeded particles and the background intensity from the fluorescent emission of the dye was achieved. Camera 2, an Olympus iSpeed 2 with a maximum resolution of 800×600 pixels at a maximum frame rate of 1 kHz, equipped with

a Nikon 50 mm lens, was installed at approximately 20° from the horizontal. This camera captured the scattered light from the particles in the oil phase and the fluorescent emission from the dye in the water phase, which was later removed using masked images from the PLIF processing.

Figure 3: PLIF and particle velocimetry high-speed camera arrangement at the measurement section.

The selection of the seeded particles considered the intensity of the light scattered and the ability to follow the flow. Large particles scatter more light, however, the response to the flow direction and velocity is reduced. Different particles sizes and materials have been used in liquid-liquid flow experiments, for example, Kumara *et al.* (2010) used polyamide particles with a mean particle diameter, d_p , of $20 \mu\text{m}$ and a density of 1.03 g/cm^3 , and Pouplin *et al.* (2015) used fluorescent PMMA particles with Rhodamine B of $d_p = 10 \mu\text{m}$ and a density of 1.18 g/cm^3 . In this work, the water phase was seeded with hollow glass spheres (LaVision 110P8) of $d_p = 10 \mu\text{m}$ and a density of 1.1 g/cm^3 , and the oil phase with silver coated glass spheres (HART AGSF-20) of $d_p = 50 \mu\text{m}$ and a density of 0.8 g/cm^3 . The Stokes number of the seeded particles, defined here as $St = \rho_p d_p^2 U_c / (18 \mu_c D)$ where ρ_p is the density of the particles, and U_c and μ_c are the velocity and viscosity of the continuous phase, respectively, can be used to determine if the particles response time is fast enough to follow the fluid velocity and direction. The Stokes numbers based on a fluid velocity twice the maximum mixture velocity studied are less than 10^{-3} for both the oil and water phases, so the particles can be assumed to follow the flow reliably in the current flow system.

Images were recorded continuously over 3 s at a sampling frequency of either 500 Hz or 1 kHz, with up to two 3-s recordings made per condition, depending on the flow. The laser-based diagnostic technique presented in this work is applicable only to separated rather than dispersed flows, with a single continuous interface (*i.e.*, stratified-smooth, or wavy) as the refractive indices of both fluids are not matched. The presence of droplets acts to distort the incident laser light and the scattered and fluorescence signals, reducing the accuracy of the information obtained.

2.4 Image processing

Firstly, the raw instantaneous images from both cameras were corrected for optical distortions. In this step, images of a graticule calibration target inserted into the test section at the measurement section and in the same plane as the laser sheets (with the pipe filled with each liquid for the corresponding phase correction) were recorded by both cameras before the actual experiments. The target consisted of crosses of known size and separation, which were used in an existing post-processing step devoted to such optical distortion corrections to raw images, which exists within the DaVis 8.3 software environment (LaVision GmgH). For details on the employment of this correction procedure in liquid-liquid pipe flows see, *e.g.*, Morgan *et al.* (2013).

Corrected images from Camera 1 (see Figure 4a) were first analysed to extract the interface profile (PLIF processing from an in-house MATLAB code) and then to construct binary black-white images (see Figure 4b). This was based on the higher intensity of the water layer due to the fluorescent dye emission as compared with the oil layer. Regions of high reflections above the interface were corrected using a moving local intensity threshold in order to obtain an accurate detection of the liquid-liquid interface. Note that azimuthal curvature of the interface in our flows was observed to be, as expected (Ng *et al.*, 2001; Ng, 2002), either flat or concave (*i.e.*, the water phase wets the quartz pipe), such that the contact line at the glass pipe does not affect the liquid-liquid interface detection at the pipe centreline plane from Camera 1 (see illustration in Figure 3).

The binary black-white images from Camera 1 were then scaled in the x - y plane in order to correspond to the scale and size of the images from Camera 2 (oil phase). This was performed

using the relative position of the field-of-view of both images taken from the graticule calibration target. The final PLIF-image pixel resolution was 56 μm .

Figure 4: Example of the 2-D instantaneous velocity vector-fields from the PIV processing for $U_m = 0.3$ m/s, $WC = 20\%$, $\theta = 3^\circ$, and a 1-kHz image acquisition frequency: (a) raw PLIF image corrected for optical distortion; (b) corresponding binary image after correction for interface reflections; (c) PIV velocity vector-field in the water phase; and (d) PIV velocity vector-field in the oil phase (for visualisation purposes not all vectors in the PIV grid are shown).

Binary images from both cameras were used to mask the corresponding images in order to remove information above and below the interface for the water and oil particle velocimetry analysis, respectively. PIV and PTV algorithms in Davis 8.3 were independently performed for each phase using similar parameters in a multi-pass approach. The first two passes were performed using an interrogation window of 64×64 pixels with 50% overlap, which was reduced to 32×32 pixels with 50% overlap for the third and final passes. Instantaneous velocity vector-fields were post-processed (in the intermediate and final PIV passes) in order to delete vectors based on a cross-correlation peak intensity filter, groups with < 5 vectors, and vector velocity ranges in the axial and wall-normal components based on pre-defined thresholds. The final PIV vector-to-vector spatial resolutions were 0.88 mm in the water phase and 1.27 mm in oil phase.

An example of the PIV velocity vector-fields for the water and oil phase is shown in **Error! Reference source not found.c** and **Error! Reference source not found.d**, respectively, plotted against the wall-normal distance from the bottom to the top of the pipe, which corresponds to the plane of illumination of the laser sheet. A final PTV processing was performed to capture large velocity gradients in the flow. An interrogation window of 8×8 pixels was selected to track individual particles. The pixel-vector resolution of the PTV processing was of $56 \mu\text{m}/\text{pixel}$ and $82 \mu\text{m}/\text{pixel}$ for the water and oil phase, respectively.

Instantaneous PIV and PTV velocity vector-fields were post-processed to remove velocity vectors that deviate significantly from the direction and magnitude of their surrounding vectors (*i.e.*, spurious vectors) by using an allowable vector range threshold. The instantaneous PIV and PTV vector-fields were then time-averaged over the total set of recordings (images) for each flow condition. The time-mean axial and radial (wall-normal) velocity components are defined as:

$$\langle u \rangle = \frac{1}{n} \sum_{i=1}^n u_i, \quad (1)$$

$$\langle v \rangle = \frac{1}{n} \sum_{i=1}^n v_i, \quad (2)$$

where n is the number of instantaneous velocity data points (images) used in the averaging, and u_i and v_i are the instantaneous and local axial and vertical velocity components, respectively.

Equation (1) and (2) were then spatially-averaged in the axial direction in order to construct mean velocity profiles in the wall-normal direction and, thereby, to capture the large velocity gradients near the wall and interface region. These profiles were then post-processed by applying a moving average function in MATLAB (*rloess*), which is based on locally-weighted polynomial regression that assigns a lower weighting to outliers.

The PIV vector-fields were also employed for the construction of velocity fluctuation profiles, and were post-processed by: (1) imposing a zero value at the wall, and (2) using a shape-preserving piecewise cubic interpolation to connect values between those obtained from the PIV grid, while keeping the original values unchanged.

Similarly, the standard deviation of the local velocity components, or root-mean-square (rms) velocity fluctuations, u_{rms} and v_{rms} , and Reynolds stress $\langle u'v' \rangle$ are respectively given by:

$$u_{\text{rms}} = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (u_i - \langle u \rangle)^2}, \quad (3)$$

$$v_{\text{rms}} = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (v_i - \langle v \rangle)^2}, \quad (4)$$

$$\langle u'v' \rangle = \frac{1}{n-1} \sum_{i=1}^n (u_i - \langle u \rangle)(v_i - \langle v \rangle). \quad (5)$$

3 Results and discussion

Results are focused on the effect of pipe inclination on the flow hydrodynamics from the application of the two-line PLIF-PIV/PTV technique to stratified oil-water pipe flows. This includes measurement data on *in situ* interface levels, mean and rms velocity profiles, and Reynolds stresses, along with the construction of mixing-length profiles.

3.1 *In situ* interface level

Instantaneous, *in situ* (local) water-layer height values, h_w , were extracted from the PLIF images. Time-averaged (mean) and fluctuation rms water-layer height values over the entire set of images in each flow condition are presented in Figure 5. The rms of the water-layer height is given by:

$$h_{w \text{ rms}} = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (h_{wi} - \langle h_w \rangle)^2}. \quad (6)$$

For a given mixture velocity, it is observed from the results in this figure that both the mean water-layer height, $\langle h_w \rangle$, and fluctuation amplitude rms increase with pipe inclination; these variations are amplified at low mixture velocities. This is expected as the effect of gravity is enhanced with increasing pipe inclination thus reducing the velocity of the heavier fluid and increasing the *in situ* volume fraction. As the velocity of the flow increases, inertial forces become more important and the difference in the water-layer height values for different pipe inclinations decreases.

Figure 5: (a, b) Time-averaged water-layer height (interface level), $\langle h_w \rangle$; and (c, d) rms interface height fluctuation, both normalised by the pipe diameter, D , as a function of the mixture velocity, U_m , for WC of: (a, c) 10%, and (b, d) 20%.

Interface level fluctuations for $WC = 10\%$ (see Figure 5c) seem to have a converging trend as the mixture velocity increases, *i.e.*, for $\theta < 5^\circ$, $h_{w \text{ rms}}$ increases with U_m , while the opposite behaviour is observed for $\theta = 5^\circ$. Conversely for $WC = 20\%$ and $\theta = 1^\circ$ (see Figure 5d), the interface level fluctuations reach a plateau at $U_m > 0.3$ m/s. For the other pipe inclinations, the interface level fluctuations are fairly constant with the mixture velocity with a slight reduction for $\theta = 5^\circ$. These findings are in line with the expected flow behaviour as function of the pipe inclination, *i.e.*, gravitational effects are more noticeable for larger amounts of water (the heavier fluid) as the pipe inclination increases, which in turn increase the amplitude of interfacial waves. The velocity of the heavier fluid is reduced as the pipe inclination increases leading to complex flow structures such as local recirculation regions which appear at low flow velocities creating

high amplitude waves. Then, as the velocity increases, inertial forces become more dominant thus wave amplitude decreases. This will be discussed further in the section below.

3.2 Flow structures

Instantaneous velocity fields provide a description of structures encountered in the flow of interest. Figure 6 shows examples of such fields for different pipe inclinations at the lowest mixture velocity studied in order to elucidate any gravitational effects on the flow dynamics. At the lowest inclination studied, $\theta = 1^\circ$, the oil and water phases exhibit near-parallel streamlines, corresponding to a smooth interface (see Figure 6a). At higher pipe inclinations, the mean axial velocity of the oil (water) phase increases (decreases), with larger velocity gradients observed across the interfacial region, as shown in Figure 6b, generated for a pipe inclination of 3° . These gradients lead to the development of interfacial waves of larger amplitude. As shown in Figure 6c, at the highest inclination of 5° , the axial velocity becomes negative (indicating flow reversal) most often in the near-wall region underneath wave troughs in parallel rise in the amplitude of the interfacial waves, consistent with Charogiannis *et al.*, (2017a,b; 2018), and the magnitude of the velocity gradients in the interfacial region increases.

Furthermore, complex flow structures can be observed clearly in the water phase at this pipe inclination angle, which are connected to the presence of interfacial waves, as well as the flow unsteadiness that will be discussed in Section 3.4. The results presented in Figure 6 indicate that the flow behaviour is strongly dependent on the pipe inclination at low mixture velocities.

Figure 6: Instantaneous velocity vector-fields and axial velocity magnitude from PIV (indicated by the background colour) for $U_m = 0.2$ m/s, $WC = 20\%$ and pipe inclinations of: (a) 1° ; (b) 3° ; and (c) 5° . The interface profile is shown as a thick black solid line and streamlines as thin lines.

Our experimental measurements have revealed the existence of three different flow structures in the water phase for $\theta \geq 3^\circ$ and $WC = 20\%$, as shown in Figure 6, and for $\theta = 5^\circ$ and $WC = 10\%$, as shown in Figure 7. There are regions of high axial velocity local to the crests of interfacial waves, and recirculation regions with clockwise-rotating vortices (in particular, see Figure 7). There are also regions where the flow is primarily in the wall-normal direction, with a negligible axial component, either towards the bottom of the pipe, or from the bottom of the pipe to the oil-water interface; these were observed at the onset of the generation of large vortices. These flow structures are characteristic of low-velocity flows. At higher flow rates, velocity fields exhibit similar profiles for a given mixture velocity and water cut, at different pipe inclinations.

Figure 7: (a) Instantaneous axial velocity vector; and (b) wall-normal velocity from PIV in both cases indicated by the background colour, showing regions of high recirculation (vortices) for $U_m = 0.2$ m/s, $WC = 10\%$ and a pipe inclination of $\theta = 5^\circ$. The interface profile is shown as a thick black solid line and streamlines as thin lines.

3.3 Velocity profiles

Figure 8 shows time-averaged axial, $\langle u \rangle$, and wall-normal, $\langle v \rangle$, velocity profiles normalised by the corresponding mixture velocity, U_m , for $WC = 20\%$ at different pipe inclinations.

Figure 8: Mean axial (top) and wall-normal (bottom) velocity profiles normalised by the corresponding mixture velocity, U_m , at $WC = 20\%$ and different pipe inclinations, θ . See Table 2 for the oil and water Reynolds numbers at each mixture velocity flow condition.

In general, the time-averaged axial velocity component in the water phase shows flatter profiles and lower velocities at higher inclinations for a given mixture velocity. This behaviour becomes more pronounced at low mixture velocities (*i.e.*, $U_m = 0.2$ m/s). Conversely, the mean axial velocity component in the oil phase shows a transition from parabolic to flatter profiles as the mixture velocity and, hence, the Reynolds number increase. Similar results can be observed for the set of results generated in equivalent runs with lower water-cuts of $WC = 10\%$ (see Appendix B).

At $U_m = 0.2$ m/s, in particular, the parabolicity of the axial velocity component profiles is accentuated with increasing pipe inclination, for both sets of flows (*i.e.*, $WC = 10$ and 20%) with a parallel rise in the maximal $\langle u \rangle$ value; this is the result of the reduction in the oil cross-sectional area, since $\langle h_w \rangle$ increases with pipe inclination, as shown in Section 3.1. The Reynolds number in the oil phase at $U_m = 0.2$ m/s increases slightly with pipe inclination though it is still considered

to be in the laminar regime based on single-phase pipe flow criteria. At higher mixture velocities, the Reynolds numbers in the oil phase fall within the transitional regime (based on the single-phase pipe flow criterion) for which the mean oil axial velocity profiles collapse to a generic trend for $U_m = 0.6$ m/s ($Re_o > 3000$). Note that such a single-phase pipe flow criterion is insufficient to characterise the flow regime in stratified flow conditions and is only used here as reference. However, the velocity profiles obtained from this study can be used to shed light into the flow regime (*i.e.*, laminar-transitional-turbulent) of each phase for liquid-liquid stratified flows.

In general, the normalised mean axial and wall-normal velocity profiles seem to be weakly dependent on the pipe inclination as the flow rate increases. Large axial gradients are observed at the interfacial region and strong wall-normal components in both the oil and water phases, especially at low mixture velocities and higher inclinations. This is attributed to the significant influence of gravitational forces at low flow rates increasing the transfer of momentum from high amplitude interfacial waves to the oil phase (promoting flow instabilities) and increasing the velocity fluctuation of the flow. Wall-normal velocity profiles also show that, for most of the flow conditions, the liquid flows towards the bottom of the pipe in both the water and oil layers. As these measurements correspond to the vertical plane at the centreline of the pipe, it is hypothesised that flow on the opposite direction (*i.e.*, to the top of the pipe) must be present near/at the wall. This indicates the presence of secondary flows, which will be discussed in the next section.

3.4 Flow unsteadiness

The flow unsteadiness can be characterised via the quantification of the velocity fluctuation in the axial and wall-normal components. Figure 9 shows the axial and wall-normal local velocity fluctuation rms normalised by the local time-averaged axial velocity, $\langle u \rangle$, for $WC = 20\%$ at different pipe inclinations. It is seen that u_{rms} and v_{rms} decrease in magnitude, and their profiles become weakly-dependent on U_m with increasing mixture velocity for all studied pipe inclinations.

Figure 9: Profiles of local axial (top) and wall-normal (bottom) velocity fluctuation rms normalised by local mean axial velocity, $\langle u \rangle$, at $WC = 20\%$ and different pipe inclinations, θ .

Focusing on the flows with $U_m = 0.2$ m/s, it is interesting to observe that the normalised u_{rms} and v_{rms} increase significantly with pipe inclination as a result of the occurrence of complex flow structures in the water phase and the momentum transfer from the interfacial waves to the oil layer. This is not observed at higher velocities where the profiles exhibit collapse indicating that inertial forces overcome the gravitational effects on the flow.

The velocity fluctuation rms, *i.e.*, u_{rms} and v_{rms} profiles show peaks in the regions of high shear, *i.e.*, close to the pipe wall and at the liquid-liquid interface, and minima in the bulk of each phase in line with observations for horizontal flows. However, velocity fluctuations in the water phase at low mixture velocities ($U_m = 0.2$ m/s) show an irregular trend with no clear concave profile confirming that the appearance of complex flow structures increase the unsteadiness in the flow. An additional region of high shear in the wall-normal component for high mixture velocities is observed

in the bulk of the oil layer as presented in Figure 10 which shows v_{rms} profiles normalised by the maximum mean axial velocity, U_{max} , for $U_m = 0.6$ m/s. This additional peak may be linked to the presence of secondary flows (Ibarra *et al.*, 2018). It is hypothesised that this peak is the result of the presence of counter-rotating vortices in the flow identified by a change in the direction of the wall-normal velocity from negative to positive values as moving from the top of the pipe toward the interface. This can be further observed in the instantaneous velocity vector-fields, presented in Figure 11, where negative wall-normal velocities indicate flow towards the pipe bottom, whereas, positive wall-normal velocities indicate flow towards the top of the pipe. This can lead to possible secondary flows from single-vortex to more complex counter-rotating vortices assuming symmetry along the vertical plane that passes through the pipe centreline. This hypothesis could be confirmed with the extraction/analysis of velocity profiles (axial and wall-normal) at different planes.

Figure 10: Local wall-normal velocity fluctuation rms profiles normalised by the corresponding maximum mean axial velocity, U_{max} , at different pipe inclinations, θ , for $U_m = 0.6$ m/s and $WC = 20\%$. The additional peak in the oil layer is located at $y/D = 0.7\text{--}0.8$.

Figure 11: Instantaneous axial velocity vector-fields and wall-normal velocity magnitude from PIV (indicated by background colour) for $U_m = 0.6$ m/s, $WC = 20\%$ and pipe inclinations of: (a) 1° ; (b) 3° ; and (c) 5° . The interface profile is shown as a thick black solid line and streamlines as thin lines.

The axial and wall-normal velocity fluctuation rms, *i.e.*, u_{rms} and v_{rms} , profiles for flows with $WC = 10\%$ shown in **Error! Reference source not found.** Appendix B follow the same behaviour as that observed for $WC = 20\%$; however, the water phase shows a higher level of unsteadiness for a given pipe inclination as compared with the $WC = 20\%$ cases even though the Reynolds number is considerable lower, *e.g.*, for $U_m = 0.2$ m/s and $\theta = 5^\circ$, $Re_w = 1810$ and 3260 for $WC = 10\%$ and 20% , respectively.

The Reynolds stress, $\langle u'v' \rangle$, has also been studied and presented in Figure 12 for $WC = 20\%$ at different pipe inclinations. In single-phase flows, the Reynolds stress profiles show peaks at similar distances from the bottom of the pipe (negative) and top of the pipe (positive), and decrease to zero towards the centre of the pipe, with a symmetric profile with respect to the pipe axial centreline. As the Reynolds number increases, these peaks are located closer to the pipe wall. In stratified two-phase flows, the location of the peaks is also affected by the pipe inclination. From our experimental data at low mixture velocities ($U_m = 0.2$ m/s), the negative peak, in the water phase, is shifted along the wall-normal component towards the interface as the pipe inclination increases. This means that significant shear is generated at the interfacial region which overcomes the shear at the bottom pipe wall. This behaviour was also observed by Kumara *et al.* (2010) and Amundsen (2011) for pipe inclinations of 5° and 10° . Interestingly, a peak in the Reynolds stress profile at the top region of the pipe, which corresponds to the oil phase, appears at a pipe inclination of 5° for which $Re_o = 1600$. Based on the single-phase pipe criterion, the flow regime at this Reynolds number should be laminar. However, the Reynolds stress profile (at $\theta = 5^\circ$) indicates transitional flow (*i.e.*, peak close to the top of the pipe), which shows that this criterion is insufficient to characterise accurately the flow regime in each layer in stratified flows. This is as expected since these flows are accompanied by instabilities related to the presence of the interface, so-called ‘interfacial modes’, in addition to others of the ‘shear mode’ type.

Figure 12: Local Reynolds stress $\langle u'v' \rangle$ profiles normalised by the square of the corresponding mixture velocity, U_m^2 , at $WC = 20\%$ and different pipe inclinations, θ .

At higher mixture velocities ($U_m = 0.6$ m/s), the Reynolds stress profiles collapse, indicating that the influence of the gravitational forces on the level of unsteadiness decreases (*i.e.*, weakly dependent on the pipe inclination). The Reynolds stress maximum in the water layer is located close to the bottom of the pipe while in the oil layer the maximum is located at $y/D \approx 0.9$ for which Reynolds numbers are within the transitional/turbulent region ($Re_o = 3400$ - 3700).

In our earlier study that focussed on oil-water horizontal flows (Ibarra *et al.*, 2018), we presented a simple mixing length model for the water phase and near-interface region. The mixing length concept, proposed by Prandtl (1925), relates the Reynolds stresses to the mean velocity gradient through a proportionality parameter (mixing length, l_m) as follows:

$$-\langle u'v' \rangle = l_m^2 \left| \frac{\partial \langle u \rangle}{\partial y} \right| \frac{\partial \langle u \rangle}{\partial y}. \quad (7)$$

Prandtl (1925) assumed that the mixing length varies linearly with the distance from the wall, $l_m = ky$, where k is the von Karman constant ($k = 0.41$). In stratified two-phase flows, the shear at the liquid-liquid interface and the shape of the axial velocity profile in the water phase (for low water cuts) modify the mixing length profile in the near-interface region.

Our proposed model estimates the mixing length using a modified version of the standard expression of the mixing length (*i.e.*, $l_m = ky$) in three different regions: (1) at the bottom of the pipe the mixing length linearly increases from the pipe bottom until the wall-normal distance which corresponds to the inflection point in the mean axial velocity profile in the water phase; (2)

in the region above the inflection point and below the interface the mixing length decreases as y increases; and (3) above the interface, the mixing length shows the same trend as that at the pipe bottom. Therefore, the mixing length model has the form:

$$l_m = nk(y - y_0), \quad (8)$$

where coefficients n and y_0 are given in Table 3, as functions of the mean water-layer height, $\langle h_w \rangle$.

Table 3: Coefficients for the mixing length model.

Region	n	y_0
Bottom pipe wall	1	0
Below interface	-1	$\langle h_w \rangle$
Above interface	1	$\langle h_w \rangle + 0.07D$

Figure 13 shows measured mixing length profiles from Eq. (7) for three flows, all with $U_m = 0.2$ m/s and $WC = 20\%$, but at different pipe inclinations (as indicated), along with predictions from the proposed model. Model predictions in the water layer show good agreement with measurements, for which Re_w is between 3200 and 3600, with the exception of the pipe bottom region at $\theta = 5^\circ$. For this inclination, the mean axial velocity in the water phase at the bottom region of the pipe (see Figure 8) shows a nearly flat profile. The resulting velocity gradient is close to zero, thus significantly increasing the mixing length values. Above the interface, mixing length values are higher than zero for $Re_o > 1500$ (for $\theta \geq 3^\circ$) and approximate to the model approach only in the region $y_0 < y < y_0 + 0.014D$.

Figure 13: Mixing length profiles at different pipe inclinations, θ , and predictions based on the von Karman constant ($k = 0.41$) shown as the black solid lines for $U_m = 0.2$ m/s and $WC = 20\%$.

For higher mixture velocities, mixing length profiles in the three regions described above show similar trends for the different pipe inclinations as presented in Figure 14 for $U_m = 0.6$ m/s and $WC = 20\%$. The model predictions capture the overall trend of the mixing length for which $Re_w > 10800$ and $Re_o < 3700$. From our experimental observations in oil-water flows at low water-cuts, it appears that the mixing length profiles for the pipe bottom and near-interface regions are predicted reasonably well by using the simple linear mixing length approach for laminar, transitional and turbulent regimes (*i.e.*, $Re_w = 3200$ - 11600 and $Re_o = 1300$ - 3700).

Note that the results presented in this study correspond to the vertical plane that passes through the centreline of the pipe. Thus, the proposed mixing length model and its suitability as suggested by the present results are only valid within this vertical plane and for the range of conditions studied in this work. Extensions of this model can be performed with measurements at different planes such that the complex behaviour of stratified flows can be described fully.

Figure 14: Mixing length profiles at different pipe inclinations, θ , and predictions based on the von Karman constant ($k = 0.41$) shown as the black solid lines for $U_m = 0.6$ m/s and $WC = 20\%$.

4 Conclusions

A novel technique combining two-line planar laser induced fluorescence and particle velocimetry, which was developed and applied elsewhere to horizontal stratified-wavy oil-water flows (Ibarra *et al.*, 2018), was implemented here in order to obtain simultaneous spatiotemporally resolved phase and velocity information in stratified-wavy oil-water flows at shallow pipe inclinations

($\leq 5^\circ$). This technique removes the requirement of having refractive-index-matched test fluids, thereby enabling the study of liquids with similar properties to those encountered in real applications of interest, however, is intended for separated rather than dispersed flows.

Instantaneous velocity vector-fields reveal interesting flow structures in the water and oil phases, which are enhanced with the pipe inclination. These structures, which show complex flow paths at low velocities, contribute to the generation of local interfacial waves which in turn affect the unsteadiness of the flow, especially at the near-interface region and also the near-wall region where flow reversal can be observed often underneath wave troughs. Furthermore, the transfer of momentum to the oil phase, from the significant interface activity, modifies the wall-normal velocity components. Normalised mean and rms (velocity fluctuations and Reynolds stresses) velocity profiles are shown to be weakly dependent on the pipe inclination at high mixture velocities, *i.e.*, gravitational effects are overcome by inertial forces. At low mixture velocities and a pipe inclination of 5° , the Reynolds stress profile in the oil layer indicates transitional flow even though the Reynolds number is 1600 (*i.e.*, laminar flow based on the single-phase pipe criterion). This shows that the single-phase transition criterion for flow regime is insufficient to fully characterise the flow regime in stratified liquid-liquid flows, as expected. Complex phenomena (*e.g.*, interfacial instabilities) affect the laminar-transitional-turbulent flow boundary.

The simple linear mixing length model, based on the von Karman constant and the mean water-layer height, show reasonable predictions with measurements for the water layer and the near-interface region for flows in the laminar, transitional and turbulent regime at different pipe inclinations. However, this approach is only valid within the vertical plane through the centreline of the pipe where measurements were made, and for the flow conditions studied in this work. Measurements at different planes can be used to further expand the suitability of model.

The information presented in this work can assist ongoing efforts to improve our understanding of liquid-liquid stratified flows at different pipe inclinations, by providing experimental data that can be used to validate closure relations and computational models. While the generated 2-D velocity information has offered valuable insight into these flows, the extraction of the third velocity component can further assist with the analysis of complex structures such as secondary flows which are attributed to affect the unsteadiness in the flow.

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Appendix A. *In situ* velocities**Table A1:** Inlet mixture velocities, water cuts, and corresponding *in situ* oil and water velocities (in m/s) for the experimental condition envelope investigated in this work.

U_m (m/s)	WC (%)	$\theta = 1^\circ$		$\theta = 3^\circ$		$\theta = 5^\circ$	
		U_o	U_w	U_o	U_w	U_o	U_w
0.2	20	0.238	0.121	0.293	0.089	0.297	0.085
	10	0.220	0.109	0.266	0.062	0.270	0.059
0.3	20	0.325	0.229	0.348	0.189	0.364	0.173
	10	0.317	0.203	0.333	0.160	0.361	0.120
0.4	20	0.424	0.305	0.450	0.264	0.452	0.272
	10	0.406	0.336	0.421	0.271	0.429	0.245
0.5	20	0.510	0.408	0.542	0.370	0.547	0.361
0.6	20	0.640	0.480	0.622	0.505	0.629	0.501

Appendix B. Complementary results for $WC = 10\%$

Figure B1: Profiles of mean axial (top) and wall-normal (bottom) velocity normalised by the corresponding mixture velocity, U_m , at $WC = 10\%$ and different pipe inclinations, θ .

Figure B215: Profiles of local axial (top) and wall-normal (bottom) velocity fluctuation rms normalised by local mean axial velocity, $\langle u \rangle$, at $WC = 10\%$ and different pipe inclinations, θ .

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