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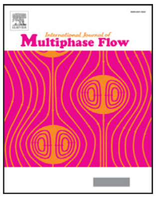

On the role of buoyancy-driven instabilities in horizontal liquid–liquid flow

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ABSTRACT

Horizontal flows of two initially stratified immiscible liquids with matched refractive indices, namely an aliphatic hydrocarbon oil (Exxsol D80) and an aqueous-glycerol solution, are investigated by combining two laser-based optical-diagnostic measurement techniques. Specifically, high-speed Planar Laser-Induced Fluorescence (PLIF) is used to provide spatiotemporally resolved phase information, while high-speed Particle Image and Tracking Velocimetry (PIV/PVT) are used to provide information on the velocity field in both phases. The two techniques are applied simultaneously in a vertical plane through the centreline of the investigated pipe flow, illuminated by a single laser-sheet in a time-resolved manner (at a frequency of 1–2 kHz depending on the flow condition). Optical distortions due to the curvature of the (transparent) circular tube test-section are corrected with the use of a graticule (target). The test section where the optical-diagnostic methods are applied is located 244 pipe-diameters downstream of the inlet section, in order to ensure a significant development length. The experimental campaign is explicitly designed to study the long-length development of immiscible liquid–liquid flows by introducing the heavier (aqueous) phase at the top of the channel and above the lighter (oil) phase that is introduced at the bottom, which corresponds to an unstably-stratified "inverted" inlet orientation in the opposite orientation to that in which the phases would naturally separate. The main focus is to evaluate the role of the subsequent interfacial instabilities on the resulting long-length flow patterns and characteristics, also by direct comparison to an existing liquid–liquid flow dataset generated in previous work, downstream of a "normal" inlet orientation in which the oil phase was introduced over the aqueous phase in a conventional stably-stratified inlet orientation. To the best knowledge of the authors this is the first time that detailed spatiotemporally resolved phase and velocity data have been generated by advanced measurement techniques in such experiments, specifically devoted to the study of long-length liquid–liquid flow development. In particular, the change in the inlet orientation imposes a Rayleigh–Taylor instability at the inlet. The effects of this instability are shown to persist along the tube, increasing the propensity for oil droplets to appear below the interface. Generally, the characteristics of the flows generated with the two inlet orientations are found to be comparable, although only six flow regimes are identified here, as opposed to eight for the original "normal" inlet orientation. The unobserved regimes are: (1) three-layer flow, and (2) aqueous-solution dispersion with an aqueous solution film. Furthermore, similar mean axial-velocity profiles are observed in the current study to those reported for the corresponding "normal" inlet orientation liquid–liquid flows. These findings are important to consider when interpreting published data from experiments performed in laboratory environments and attempting to draw conclusions relating to applications in the field. The generated data promote not only a qualitative, but importantly and uniquely, a quantitate understanding of the role of multiple instabilities on the development of these complex interfacial flows, with detailed insight into how the deviations manifest at distances 244 pipe-diameters downstream of the inlet (from high level information such as regime maps, to detailed flow

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information such as phase and velocity profiles). The data can be used directly for the development and validation of advanced multiphase flow models that require such detailed information.

1. Introduction

The co-current flow of two immiscible liquids is encountered in a range of settings and industrial processes, such as in continuous-flow chemical processes (CFCP) featuring reactions or separations, e.g., on microchips (Toskeshi et al., 2002). At larger scales of application, theses flows are observed in the transportation of immiscible liquids in subsea pipelines from petroleum production facilities, where the motivation for the current research activity originates. The most common pair of immiscible liquids encountered in this case is oil and naturally occurring water from the reservoir (“connate water”). However, these can also arise from operational activities, including: water injection for Enhanced Oil Recovery (EOR), and dead-oil displacement in which hot dead-oil is circulated through the subsea pipelines to mitigate hydrate formation.

The industrial relevance of liquid–liquid flows underpins the necessity to develop a better understanding of the phenomenological mechanisms that govern their global behaviour and to enhance the predictive capability of relevant multiphase flow models. This is exemplified in the offshore oil and gas industry, where the ability to accurately predict intermittent flow behaviour (e.g., slugging) is essential for the development of concept designs and operating philosophies.

Early research into liquid–liquid flows was premised on improving the pumping requirements when transporting viscous, heavy oils by injection of water into oil lines (Russell and Charles, 1959). However, these early studies concentrated on the measurement of global flow parameters such as pressure gradient and phase fractions (Arirachakaran et al., 1989; Trallero, 1997; Angeli and Hewitt, 1998). Subsequently, laser-based optical diagnostic techniques have proved to be one of the most powerful tools for the detailed diagnostic inspection of multiphase flows, when utilizing refractive index matching and the addition of particles and/or fluorescent dyes (e.g., Hewitt and Nicholls, 1969; Liu et al., 2006). More recent investigations have accelerated the rate at which data is made available for the development of closures in modern multiphase flow models. Contributions have focused on the measurement of the interfacial characteristics of various flows, including phase distributions using Planar Laser-Induced Fluorescence (PLIF) (Zadrazil et al., 2014; Charogiannis et al., 2015), and instantaneous velocity profiles using Particle Image/Tracking Velocimetry (PIV/PTV) (see Zadrazil and Markides, 2014).

A number of complex geometrical flow configurations can be encountered in oil–water flows for a given pipe material, inlet design, pipe inclination, fluid properties and flow rates. The resulting flow patterns range from separated flows (e.g., stratified smooth, stratified wavy and stratified with droplets at the interface) to fully dispersed flows (e.g., dispersion of oil in water). For an intermediate range of velocities, dual continuous flows can be observed (Lovick and Angeli, 2004). These types of flow patterns, identified by having two continuous phases with dispersions in one or both layers, are commonly encountered in a wide variety of configurations (e.g., three-layer flow, dispersions of oil in water with an oil layer). In addition to the aforementioned flow patterns, intermittent and annular flows can be also observed in liquid–liquid systems; however, only a few researchers have reported observing these configurations, e.g., oil slugs in water were observed by Charles et al. (1961) and Oglesby (1979) for intermediate viscous systems in horizontal pipes, and by Lum et al. (2006) and Kumara et al. (2009) for slightly inclined upward flow. These previous studies have been carried out with different inlet configurations, i.e., ‘T’-, ‘Y’- and ‘Y’-junctions with a separation plate along the pipe centreline.

The development of the flow from an (initially) stratified state to the more complex flow regimes (e.g., dual continuous and dispersed flows) can arise due to increased flow complexity and enhanced mixing that is associated with turbulence. Turbulence arises at higher flow velocities (i.e., higher liquid flow rates), from nonlinear inertial effects (described by the Reynolds number) that cannot get damped out (or, dissipated) by viscosity. It is no surprise that the regime maps published in previous studies showed stratified flows at lower superficial mixture velocities, and increasing phenomenological flow complexity at higher velocities (Trallero et al., 1997; Soleimani, 1999; Angeli and Hewitt, 2000; Morgan et al., 2012, 2013).

The flow complexity can also be augmented by additional instability mechanisms, which are mentioned briefly (along with turbulence) in the listing below.

Inertia – In a pipe flow the macroscale Reynolds number (Re) is defined as:

$$Re = \frac{\rho U D}{\mu}, \tag{1}$$

where ρ is the density and μ the dynamic viscosity of the fluid, U the bulk flow velocity, and D the inside diameter of the pipe, and represents a ratio of inertial to viscous forces in the flow. At low Re, when the viscous forces dominate, instabilities are damped leading to laminar, stratified flow. At high Re, when the inertial forces dominate, the flow becomes turbulent leading to instabilities, spatiotemporal complexity and higher dimensionality that manifests as multiscale unsteadiness, eddies/vortices in the bulk of the flow, and waves at the interface.

Yih instability – This instability mechanism is relevant to flows of immiscible liquids with a non-unity viscosity ratio, i.e., for sharp interfaces between immiscible fluids of different viscosity. In early work on this mechanism, Yih (1967) demonstrated the existence of an unstable mode associated with this interfacial discontinuity in viscosity (viscous stratification), which is present at all Re (although in the limit of $Re = 0$ the growth rates are asymptotically small).

The Yih mode arises from instabilities that “nucleate” initially in the single-phase fluid regions (“matching regions”) that surround the viscous boundary layer. Theofanous et al. (2007) postulated that the viscosity changes which initiate this instability arise from a diffusion (heat or mass) process and that instability character of the Yih case can be approached continuously and monotonically by letting $\delta \to 0$ (thickness of diffuse layer) and $Sc \to \infty$, where the Schmidt number (Sc) is the ratio of momentum diffusivity (viscosity) to mass diffusivity,

$$\mathrm{Sc} = \frac{\upsilon}{D}, \tag{2}$$

where υ denotes the kinematic viscosity and D is the mass diffusivity. Sahu et al. (2007) studied the linear stability of pressure-driven two-layer flow on a channel (i.e., Newtonian fluid layer above a non-Newtonian fluid. Their analytical and numerical analysis showed that instabilities are enhanced as increasing the yield stress and the power-law behaviour of the non-Newtonian fluid. A