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Spectral density analysis of the interface in stratified oil–water flows

A.H. Barral, P. Angeli *

Department of Chemical Engineering, University College London, London, United Kingdom

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ABSTRACT

In this work the wavy interface of stratified oil–water flows was investigated using wire conductance probes. The experiments were carried out in a 38 mm ID acrylic pipe using water and oil (Exxsol D140 oil: $\rho_o = 830\ \mathrm{kg\ m^{-3}}$, $\mu_o = 0.0055\ \mathrm{kg\ m^{-1}\ s^{-1}}$) as test fluids. High-speed imaging revealed that almost two-dimensional interfacial waves develop at the inlet junction for input oil-to-water flow rate ratios different from one. Downstream the inlet section, however, the interface has a complex three dimensional structure with very small amplitude contributions. The structure of such interfaces can be properly investigated from the power spectrum of the conductance probe signal. A rigorous and detailed methodology is presented for estimating the power spectrum of the interface signal that is based on the Wiener–Khinchine theorem and makes extensive use of a Fast Fourier Transform (FFT) algorithm. Interface spectra were studied at two locations, close to the inlet of the test section and at 7 m downstream. The results showed that the waves at the inlet have a unique peak frequency of about 19 Hz and that, at the downstream location, this frequency is still present but has a smaller significance compared to that caused by the mechanical vibrations of the set up. This frequency was independent of the flow rates and could be a characteristic of the pair of the test fluids used rather than of the flow.

1. Introduction and background

The simultaneous flow of two fluids in a pipe (either liquid–liquid or gas–liquid) occurs in a large number of applications in the energy, oil and process industries. Different flow patterns can develop depending on flow parameters such as mixture velocity and input flow rate ratio, properties of the fluids (density, viscosity and surface tension) and the pipe size and inclination. The type of flow pattern determines important parameters of the two-phase flow (such as pressure drop, heat and mass transfer coefficients) and has an effect on the design and operation of multiphase pipelines.

The shape and characteristics of the interface during the stratified flow of oil–water mixtures in horizontal or slightly inclined pipes have been the object of many investigations. In general, it is assumed that the flow would generate interfacial waves which, depending on the conditions, could become unstable and grow in amplitude. From these waves, drops would form and detach. This description was generally drawn from results in gas–liquid systems (see, for example, the five mechanisms of drop formation in gas–liquid flow in Ishii and Grolmes, 1975). The appearance of drops in stratified flows defines the onset of transition towards other flow regimes and, therefore, the study of interfacial structures is important for understanding the mechanism of transition to other patterns. These transitions have been discussed in e.g. Trallero (1995), Al-Wahaibi and Angeli (2007), Al-Wahaibi et al. (2007).

To study wave structures researchers have been using transparent (acrylic or glass) test pipes coupled with high-speed imaging. The benefits of such techniques, however, depend on the existence of visually identifiable waves. Oliemans (1986), Bai (1995), Bannwart (1998), Rodriguez and Bannwart (2006) studied wave characteristics in annular flows of heavy viscous oil and water from images, where defined wavy structures could be followed and investigated. Similarly, Al-Wahaibi and Angeli (2011) investigated the characteristics of oil–water flows from visual inspection and analysis of images using low-viscosity oil. Our previous studies with this oil, however, showed that almost two-dimensional waves appeared only at the inlet of the test section for input oil-to-water flow rate ratios different from 1. In contrast, further downstream the test section and at the inlet for input ratios close to 1 the oil–water interface did not show any easily identifiable waves. Instead the interface appeared to be fluctuating with small three-dimensional perturbations (Barral and Angeli, 2013). Such interface shapes make very difficult the quantitative analysis of wave characteristics via imaging, even when complex mathematical treatments are used. De Castro et al. (2012) investigated stratified

* Corresponding author. Tel.: +44 (0) 20 7679 3832.
E-mail address: p.angeli@ucl.ac.uk (P. Angeli).

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oil–water flows with viscous oil (0.3 Pas). They identified interfacial waves and classified them in three groups according to size using high-speed imaging. They further employed Fourier filters to treat the images and allow for graphical analysis. Although the authors were able to report wave lengths and amplitudes, this procedure required a large simplification, as only the so-called intermediate waves were filtered in for analysis.

A different approach for the study of the fluctuating three dimensional structure of the interface was presented in a previous work by Barral and Angeli (2013) via the use of a double wire conductance probe. The use of conductance probes (including double-wire ones) has been extensive for over 50 years in both gas–liquid and liquid–liquid flows and in a variety of applications (Jurman et al., 1989; Tsochatzidis et al., 1992; Andritsos 1992; Azzopardi 1997; Fossa 1998; Wu and Ishii 1999; Kim et al. 2000; Wang et al., 2004; Chakrabarti et al., 2006; Panagiotopoulos et al., 2007; Alamu and Azzopardi 2011; Xu et al., 2012; Zhai et al., 2012; to name just a few). More recently, several investigators have attempted to identify flow patterns in oil–water flows by analyzing conductance probe signals, for example Hernández et al. (2006), Jin et al. (2003), Sun et al. (2011), Du et al. (2012). Given the complexity of such flows, including many non-stratified patterns, the authors needed to use complex mathematical techniques in order to deal, in many cases, with non-stationary data.

It has been found previously that the records of the interface height over time collected with a double wire conductance probe in horizontal stratified oil–water flows are stationary and follow a Gaussian distribution (Barral and Angeli, 2013). These properties allowed the estimation of the time-average interface height and related time average flow parameters (such as in-situ water fraction and actual velocities of the two phases) with confidence intervals. Under these conditions the power spectrum of the interface signal could be estimated via the Wiener–Khinchine theorem and some results were presented from the direct computation of the auto-correlation function. In this present work, the calculation of the power spectrum of the probe signal is thoroughly investigated; improvements based on windowing and truncation and corrections related to the circular convolution problem are introduced. A complete methodology widely applicable to stratified flows is presented to perform the spectral analysis of the oil–water interface signal, based on the extensive use of the Fast Fourier Transform (FFT). Following this procedure, the contributing frequencies in the wavy interface are identified close to the inlet of the test section and further downstream the inlet for different oil and water flow rates.

2. Experimental set-up and data acquisition

Experiments were performed in the oil–water flow facility located in the Department of Chemical Engineering, UCL. The rig consists of a 38 mm ID acrylic test pipe, which allows the visual inspection of the flow. The test fluids used are tap water (ρ = 1000 kg m^{-3} and μ = 0.001 kg m^{-1} s^{-1}) and ExxsolD140 oil (ρ = 830 kg m^{-3} and μ = 0.0055 kg m^{-1} s^{-1}), where ρ and μ are density and viscosity, respectively. The two fluids are stored and pumped separately using centrifugal pumps. Their flow rates are regulated via gate valves and measured separately with variable area flow meters (ABB Instrumentation Ltd.) with a range from 20 L min^{-1} to 250 L min^{-1} and 1% FS accuracy. The flow rate values are logged in a computer at a high sampling frequency (i.e. 256 Hz).

Oil and water are joined at a Y-shaped inlet section, with the top duct (oil) inclined 10° downwards and the bottom one (water) kept horizontal. Both ducts are 38 mm ID and made of acrylic (Fig. 1). This junction allows the two fluids to enter the test pipe in layers according to their density, minimizing mixing. There is no additional split plate. The test pipe consists of two horizontal sections, each 8 m long, joined with two 90° elbows. After the test section, the mixture of the two fluids flows into a separator vessel equipped with a KnitMesh™ coalescer. Oil and water are then returned from the top and the bottom of the separator respectively into their storage tanks. A high speed video camera (Phantom Miro 4) was used to record the flow patterns and to inspect the oil–water interface along the pipe.

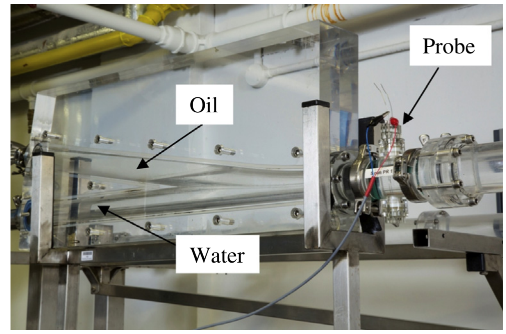

Fig. 1. Photograph of the *Y*-inlet section and one of the probes installed at Position 1.

2.1. Double wire conductance probe

Two double wire conductance probes were used in the present work for the investigations of the oil–water interface structure. The probes consist of two parallel stainless steel wires, 0.5 mm in diameter, located either 2 mm apart (probe 1) or 5 mm apart (probe 2), and stretched along the vertical pipe diameter. Fig. 2 shows a photograph of the 2 mm probe; the 5 mm probe is identical, apart from the distance between the wires.

The probes were located either immediately after the inlet section or further downstream the pipe at about 7 m from the inlet (~180 *D*) where the flow is assumed to be fully developed. In the experiments one probe was used (either the 2 mm or the 5 mm) but some experiments were also carried out with both probes installed at the different locations. In the latter case, the 5 mm probe was placed close to the inlet and the 2 mm one in the

Fig. 2. Photograph of the 2-mm double-wire, conductance probe.