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Experimental study on interfacial waves in stratified horizontal oil–water flow

Talal Al-Wahaibi [a,*], Panagiota Angeli [b]

[a] Department of Petroleum and Chemical Engineering, Sultan Qaboos University, P.O. Box 33, PC 123, Oman
[b] Department of Chemical Engineering, University College London (UCL), Torrington Place, London, WC1E 7JE, UK

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ABSTRACT

Interfacial wave characteristics were studied experimentally in horizontal oil–water pipe flows during stratified flow and at the transition to dual continuous flow, where drops of one phase appear into the other (onset of entrainment). The experimental investigations were carried out in a stainless steel test section with 38 mm ID with water and oil (density 828 kg/m^{3}and viscosity 5.5 mPas) as test fluids. Wave characteristics were obtained with a high speed video camera and a parallel wires conductivity probe that measured the instantaneous fluctuations of the interface. Experiments were conducted at 2 m and at 6 m from the inlet. Visual observations revealed that no drops are formed when interfacial waves are absent. It was also found that waves have to reach a certain amplitude before drops can detach from their crests. Wave amplitudes are increased as the superficial velocities of both phases increase. In the stratified region, the mean wave amplitude decreases by increasing the oil–water input ratio while mean wavelength increases as the slip velocity between the two-phase decreases. At the onset of entrainment, the mean amplitude and length are found to be a function of the relative velocity between the oil and water layers and of the turbulence in each layer.

Interestingly at 2 m from the inlet no drops were found at the onset conditions observed at 6 m, indicating that along the pipe the relative motion of the two phases causes waves to grow in height until finally drops detach from their crests.

1. Introduction

During the simultaneous flow of two immiscible liquids (e.g. oil and water) in horizontal pipes, several flow patterns can form. At low superficial oil and water velocities the flow is stratified. When the flow rates increase, interfacial waves appear which are initially long compared to the pipe diameter. Such waves will become more disturbed and the wavelengths will decrease as the flow rates increase. Along the waves, water droplets will form in the oil layer and oil droplets will appear in the water layer (onset of entrainment) and the pattern will change to dual continuous, where both phases retain their continuity at the top and the bottom of the pipe respectively but there is dispersion of one phase into the other (Lovick and Angeli, 2004). The amount of droplets in each phase will increase with the superficial velocities of the phases.

The growth and development of wave structures at the liquid–liquid interface during pipe flows is important for understanding the transition from the stratified to the dual continuous pattern and for predicting pressure drop. The characteristics of the waves, such as length, amplitude and frequency, will affect the roughness of the oil water interface; they will also influence the rate of drop entrainment and the amount of drops in each phase which in turn will affect pressure drop in the dual continuous pattern. It is important, therefore, to know wave frequencies, amplitudes and lengths and their development with increasing fluid flowrates.

There are currently no published studies on wave characteristics in liquid–liquid flows for the stratified pattern and at the onset of the dual continuous pattern. The few studies available on waves in liquid–liquid flows concentrate on the core annular pattern of highly viscous oils (Oliemans, 1986; Bai, 1995; Bannwart, 1998; Bai and Joseph, 2000; Rodriguez and Bannwart, 2006a,b). In these cases, all measurements of interfacial waves were obtained via visual observations using high speed video cameras. Bannwart (1998) developed a kinematic wave theory to describe interfacial waves, which was found to describe satisfactorily wave velocity, slip ratio and volumetric fraction of the core. A technique was suggested to determine the core fraction from wave velocity measurements which showed good agreement with direct hold up measurements. Rodriguez and Bannwart (2006a) obtained new experimental data in vertical core annular flow via visual observations on wave speed, length, amplitude and profile and found that the wave amplitude and length decreased as the oil–water input ratio increased. A simple analytical model was developed (Rodriguez and Bannwart, 2006b) to predict wave geometry that showed good agreement with the experimental data.

* Corresponding author.
E-mail addresses: alwahaib@squ.edu.om (T. Al-Wahaibi), p.angeli@ucl.ac.uk (P. Angeli).

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For gas–liquid flows extensive literature exists on the structure of waves at the surface of thin films (Hewitt and Hall-Taylor, 1970; Jurman et al., 1989; Fan et al., 1993; Azzopardi, 1997; Wang et al., 2004; Kadri et al., 2009). Wave properties have been measured either via photography or video recording through transparent pipe walls or with conductivity probes (Azzopardi, 1997). Hewitt and Hall-Taylor (1970) and Azzopardi (1997) described the properties of the waves and their link to drop entrainment. Jurman et al. (1989) used parallel wire conductivity probes to obtain wave characteristics in a rectangular channel that were compared with the predictions of linear theory. Data were predicted well near the point of neutral stability but began to deviate as the gas velocity increased. Fan et al. (1993) employed both photography and conductance probes to investigate slug evolution from wavy stratified flow. According to their observations, wave growth can result to a breaking wave or to a wave that touches the upper wall of the pipe and fills the whole cross section. Using conductivity probes Wang et al. (2004) found that the wave height and relative interfacial roughness increased with increasing gas Reynolds number. Kadri et al. (2009) developed a wave model to predict the transition from stratified to slug flow or to roll waves. The model was able to predict the evolution of waves and their transition for different pipe diameters and different gas and liquid flow rates.

In this work, the interfacial wave characteristics are studied during horizontal oil–water pipe flow in the stratified region and at the onset of entrainment, at 6 m from the inlet, using a high speed video camera and a parallel wires conductivity probe. Parameters such as the distribution of wave amplitudes and lengths were obtained at different oil and water velocities. Measurements were also carried out at 2 m from the inlet to study the development of the waves along the pipe.

2. Experimental set-up

Experiments were carried out in the flow facility shown schematically in Fig. 1. Oil and water were used as test fluids with properties given in Table 1. The fluids are stored, pumped and their flowrates are measured separately before they join at the inlet of the test section through a *Y*-junction in a stratified manner. For both fluids variable area flowmeters (ABB Instrumentation) are used to measure flowrates which are connected to a computer for data logging. For each fluid two flowmeters were used. The large flowmeters have 0–240 l/min range both for oil and water, with an accuracy of 1% full scale. The small flowmeters have a 2% full scale accuracy and a range of 0–20 l/min for oil and 0–6.5 l/min for water. All flowmeters were calibrated for the corresponding fluid. The test pipe, with 38 mm ID, consists of two 8 m long sections joined by a U-bend. Experiments were carried out at the first section. After the test pipe the oil–water mixture is led to a separator that has a Knitmesh™ coalescer which aids drop coalescence and enhances separation. From the separator the two fluids return to their respective storage tanks. The system can run continuously as a closed loop.

A 54 cm long transparent acrylic tube that was placed either at 2 m or 6 m from the test section inlet allowed visual observations

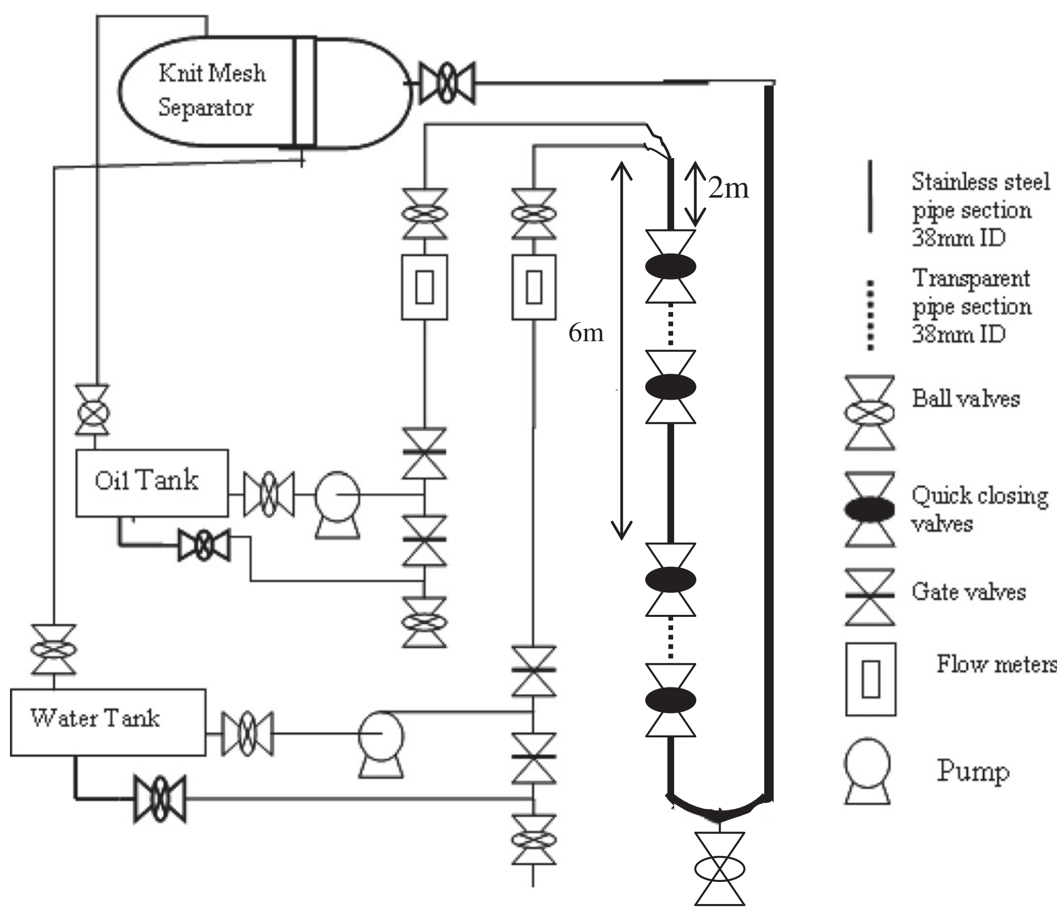

Fig. 1. Schematic diagram of the oil–water experimental flow facility.