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An experimental characterization of downwards gas–liquid annular flow by laser-induced fluorescence: Flow regimes and film statistics

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ABSTRACT

Downwards co-current gas–liquid annular flows were studied experimentally and characterized. An advanced optical laser-based measurement technique, namely Planar Laser-Induced Fluorescence (PLIF), was used for the visualization of the annular flow over a range of liquid Reynolds numbers $Re_L = 306–1\,532$ and gas Reynolds numbers $Re_G = 0–84\,600$. Four distinct flow regimes, namely the 'dual-wave', 'thick ripple', 'disturbance wave' and 'regular wave' regimes, have been identified based on qualitative information and a consequent quantitative analysis that provided information on the film thickness, interface and wave statistics, and gas entrainment into the liquid film. The mean film thickness data are generally in good agreement with previous studies. Evidence suggests that the turbulent gas phase affects strongly the shape of the interface, and that the mechanism for gas entrainment into the liquid film is strongly reliant on the existence of large-amplitude waves.

1. Introduction

Two phase gas–liquid flow can exhibit a variety of flow regimes, which are dependent on the flow-rates of the two phases, the choice of fluids (gas and liquid), the sizes of the fluid domains, and also on the orientation of the flow. In the case of a vertically orientated pipe, the two-phase flow can be generally described as bubbly, slug or annular (Barnea et al., 1982; Usui, 1989). In the latter case of *annular* flow, which is observed at higher flow-rates, the gas phase occupies the central core of the pipe cross-section and the liquid phase flows as a film in contact with the inner surface of the pipe, in an annular region between the gas and the pipe wall. In addition, gas bubbles are entrained in the liquid film and liquid droplets are entrained in the gas core. In the special case of *downwards* annular flow, a film flow of liquid on the inner surface of the pipe wall can be formed even at zero gas velocities (the so-called 'falling film' case).

Understanding the behaviour of two-phase interfacial film flows is not only important from a fundamental perspective (e.g., for predicting heat transfer in such flows (Mathie et al., 2012)), but also from a practical point of view. In particular, annular flows are central to a large number of applications, covering a wide range of important industrial processes, systems and plants. Upwards flows are commonly found in the oil-and-gas industry (e.g., raisers, transfer pipelines, gas–liquid oil wells), whereas downwards annular flows are present in important industrial process units, such as condensers and evaporators, distillation towers, and chemical reactors. The industrial relevance of annular flows can be seen, for example, in the work of Nakoryakov et al. (1976), who reported that surface instabilities (i.e., wave activity) can increase mass transfer during the absorption of carbon dioxide by water by up to 170%. An accurate identification of the particular flow regime exhibited in relevant process units, systems, transportation lines or plants is crucial for their correct design and operation. Both upwards and (less so) downwards annular flows have been studied by a number of investigators; in this paper we focus on a vertically downwards co-current gas–liquid annular flow.

The basis of our understanding of downwards co-current annular flows was laid in the 1960s and 1970s (Telles and Dukler, 1970; Chu and Dukler, 1974; Chu and Dukler, 1975; Webb and Hewitt, 1975). In these pioneering early studies, annular flows were characterized based on geometrical or topological features of the gas–liquid flow, by identifying and grouping these features into flow regimes. Specifically, based on topological features, Webb and Hewitt (1975) identified four different flow regimes for downwards annular flow (DAF): (i) the 'ripple' regime, where the interface is occupied by a pattern of ripples, (ii) the 'regular' wave regime in which disturbance waves traverse a film substrate that is covered with ripples, (iii) the 'dual-wave' regime, where two different disturbance wave types coexist, and (iv) the 'thick ripple' regime in which the wave activity decreases with increasing liquid Reynolds number.

In fact, annular flow is often described in terms of the class of interfacial waves that cover the liquid substrate, which is a thin liquid region that is present between the waves. Two main classes

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of waves are typically identified: (i) ‘ripple’ waves, which are short-lived waves that cover the substrate and are associated with small spatial amplitudes that decay quickly after their inception, and (ii) ‘disturbance’ waves, which carry a significant portion of the flowing liquid and have amplitudes many times (typically a factor of $\sim$5) the mean film thickness and high propagation speeds (Chu and Dukler, 1974, 1975). It is important to emphasise, however, that the wave type nomenclature remains unsettled. One can find references in the literature to ‘capillary’ (i.e., ripple) waves and ‘roll’ (i.e., disturbance) waves in various studies (Asali et al., 1985; Yu et al., 2006). Furthermore, the definitions of the two main wave types are not without some ambiguity. As a result, a clear, objective, and generally accepted distinction between the different wave types is still lacking, which, consequently, can lead to discrepancies in the definitions and distinctions between the different flow regimes.

Disturbance waves are considered to be crucial interfacial phenomena in annular flows, not least because they carry a significant fraction of the total liquid flow-rate. These waves are ring-like structures that are circumferentially coherent around the pipe (Zhao et al., 2013), however, the thickness of a given wave need not necessarily be uniform around the circumference. Alekseenko et al. (2012) linked the circumferential non-uniformity to the frequency, amplitude and circumferential size of ripple waves that are formed by the presence of the disturbance waves. The existence of disturbance waves is also important for the entrainment of the liquid phase into the gas core (Azzopardi, 1997). The mechanism of entrainment, as described by Woodmansee and Hanratty (1969), is based on the acceleration of ripples on the crests of disturbance waves. This leads to the lifting and consequent atomization of the liquid into the gas core in the form of droplets, thus determining the liquid fraction that is carried by the gaseous phase. Three additional mechanisms of liquid entrainment were identified by Ishii and Grolmes (1975): (i) undercutting of the liquid film by the gas flow, (ii) bursting of gas bubbles present in the liquid film, and (iii) impingement (direct impact) of the liquid drops entrained in the gas phase on the surface of the liquid film.

Extensive statistical analyses of the dynamics of DAF have shown that the liquid film thickness fluctuates in a stochastic way. The first comprehensive statistical examination of DAF was presented by Chu and Dukler (1974, 1975). Webb and Hewitt (1975) reported further that a critical gas flow-rate exists, and hence also a gas superficial velocity (defined as the volumetric flow-rate of the gas divided by the full internal cross-sectional area of the empty pipe) and gas Reynolds number (Re_G), below which the frequency of appearance of disturbance waves is independent of the gas flow-rate. An increase in the gas superficial velocity above this critical value leads to an increase in the wave frequency. Increasing the liquid superficial velocity (liquid volumetric flow-rate divided by the full internal cross-sectional area of the pipe) was also found to increase the wave frequency. The excellent study by Karapantsios et al. (1989) focused on falling films (i.e., with zero gas velocity) and described them in terms of various statistical moments of a film thickness (i.e., mean, RMS, skewness and kurtosis), probability density functions (PDF) and autocorrelation functions (ACF) of the interfacial film shape (thickness variation). Additionally, the waves were characterized via the evaluation of the power spectral density (PSD) and PDF of the wave peaks. The main findings of this effort were that: (i) the mean thickness data deviate from the Nusselt relation for a liquid Reynolds number of about $Re_L \geqslant 400$; (ii) for $Re_L \leqslant 1\,250$ the disturbance waves dominate the flow and they increase in amplitude, but not frequency of appearance, with increasing Re_L; and (iii) for $Re_L \geqslant 1\,250$ the amplitude and frequency of appearance of the disturbance waves is constant, however, the substrate thickens gradually with increasing Re_L. It should be noted that the liquid Reynolds numbers are based on the bulk-mean film velocity and the mean film thickness. More recently, similar observations to those of Webb and Hewitt (1975), concerning the effect of the liquid superficial velocity on the frequency wave frequency, were reported by Karimi and Kawaji (2000).

In addition to the aforementioned previous work on wave characterization, other experimental studies focused mainly on the global (or integral) characterization of these flows (Koskie et al., 1989; Azzopardi, 1997), for example by measuring pressure gradients or phase fraction/hold-up (e.g., with pinch valves), or employed intrusive or point measurement methods such as hot wire probes, fibre-optics or wire-meshes (e.g., Zhao et al., 2013). Yet, annular flows comprise highly localized, small-amplitude and high-speed flow disturbances. Therefore, these flows present a major challenge from the point of view of experimental design for the provision of accurate, detailed data for understanding and characterisation, and by extension model development and validation. Although invaluable in providing insight into these flows, these techniques are intrusive, and introduce a degree of uncertainly into the final measurement. Non-intrusive measurement techniques, such as flush-mounted conductance probes or acoustic methods, have also been used, but these can only provide temporal measurements at one point (Clark, 2002). These methods are also associated with complications, such as a reduced spatial resolution due to their finite size, and an increasingly insensitive signal response at large thicknesses due to signal nonlinearity in the case of the conductance probes, leading to an inability to capture accurately short-wavelength and/or large-amplitude (including the all-important disturbance) waves.

Typically, conductivity probes have been used extensively to measure a liquid film thickness in annular flows (Wolf et al., 2001; Belt et al., 2010). Recently, non-intrusive visualization techniques, such as Laser-Induce Fluorescence (LIF), are gradually being introduced into the efforts to measure and characterize multiphase flows (Liu et al., 2006; Schubring et al., 2010; Morgan et al., 2013). These techniques can allow both the detailed qualitative investigation of these flows (i.e., imaging), and the reliable and simultaneous evaluation of quantitative flow parameters, such as film thickness and bubble size. The present study applies a detailed, spatiotemporally resolved, non-intrusive optical technique, specifically two-dimensional (2-D) planar LIF (PLIF), to the measurement of downwards co-current gas–liquid annular flows (DAFs). The measurements using these methods provide qualitative and quantitative data based on which the downwards annular flows can be accurately characterized and mapped, and based on which existing models can be verified and on which new models can be proposed. Attention is focused on the development of the various regimes that accompany this flow. The distinction between these regimes is determined based on a quantitative analysis of the waves in terms of the film thickness, interface and wave statistics, and gas entrainment into the liquid film. Our results indicate that the interfacial shape is dependent upon the level of turbulence in the gas phase, and that the presence of large-amplitude waves exerts a strong influence on the rate of gas entrainment.

2. Experimental methods

This section presents the experimental flow facility used (Fig. 1), the investigated experimental conditions, measurement procedures and post-processing analysis methods. Specifically, Section 2.1 contains a description of the experimental flow facility and outlines the flow conditions investigated, Section 2.2 contains details of the design of the visualization test section and describes the equipment used for the optical flow measurements, and finally, Section 2.3 contains a description of the processing methods performed on the raw PLIF images and details on the consequent data extraction analysis.