On disturbance and ripple waves in downwards annular flow: Observations by simultaneous PLIF and PIV/PTV

I. Zadrazil1,2, C.N. Markides1

1: Department of Chemical Engineering, Imperial College London, London SW7 2AZ, UK
* Correspondent author: i.zadrazil06@ic.ac.uk

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An interfacial flow of a gas and a liquid where the liquid occupies the area around the circumference of a pipe and the gas is located in the pipe core is referred to as annular flow. This two-phase flow regime presents a challenge due to its complexity and multi-scale character, and remains not fully understood even after decades of research (Webb and Hewitt, 1975; Alekseenko et al., 2012). A comprehensive characterization, classification and understanding of this flow is not only important from a fundamental but also from an industrial point of view, since these flows are highly important in many practical areas, such as, in oil-and-gas industry (distillation columns, raisers and transport pipelines), and the chemical and pharmaceutical industries (reactors and evaporators).

The nomenclature describing the different classes of waves that appear in annular flows was established in the 1970s, based on observations and evidence provided by direct photography, and local liquid film thickness and pressure drop measurements. Thus, downwards annular flows have been generally described in terms of small amplitude ripple waves, and large amplitude, high-speed disturbance waves. Both of these wave types are said to cover the liquid substrate, i.e. a thin liquid region that is located between the waves (Chu and Dukler, 1975). Yet, it should be noted that a clear, unambiguous and generally accepted definition of the different wave classes is still lacking. The experimental work presented in the present paper is aimed at the application of a combination of detailed measurement techniques, specifically, simultaneous Planar Laser Induced Fluorescence (PLIF) and Particle Image/Tracking Velocimetry (PIV/PTV) measurements, to identify and characterise wave behaviour in downward annular flows, also with information on the velocity in the liquid film underneath the waves.

Methodology

The measurements were performed on the Downwards Annular Flow Laser Observation Facility. This facility consists of 3 m long, 32.4 mm nominal bore fluorinated ethylene propylene (FEP) pipe, where the annular flow is introduced at the top of the pipe using a specially designed injector, which forms circumferentially uniform liquid films. The investigated liquid and gas Reynolds numbers were in the range of $Re_c = 306–1,530$ and $Re_f = 0–84,600$, respectively. The laser-based measurements were performed 2.35 m downstream of the injector (i.e. 72 D). The visualisation section was enclosed in an optical correction box in order to minimize any distortions that would arise from the round FEP test section.

In this work, the gas-liquid downwards annular flows were measured by laser-based optical characterisation techniques, i.e. simultaneous utilization of PLIF and PIV/PTV. A double-pulsed frequency-doubled 532 nm Nd:YAG laser equipped with a sheet optics was used for the flow illumination in a 2-D plane. Rhodamine-B dye and Rhodamine-B particles (10 µm mean diameter) were used for the PLIF and PIV/PTV measurements, respectively. The fluorescent light was recorded by a CMOS camera which was positioned at a right angle with respect to the laser sheet. Additional details of the flow facility and laser system used can be found in Zadrazil et al. (2013).

The raw-image pairs were evaluated using an in-house MATLAB interface tracking algorithm (PLIF) and the DaVis software package (PIV/PTV). The information derived from the processed images, i.e. film thickness, film roughness, interfacial velocity, instantaneous and time-averaged velocity profiles, and rms profiles were used for a detailed characterisation of both disturbance and ripple waves.

Results

Figure 1 shows instantaneous velocity profiles underneath waves that were observed for falling films (with $Re_c = 0$) at $Re_f = 306$. The gas-liquid interface and instantaneous velocity profiles were constructed by using the PLIF and PIV measurements, respectively. The following observations can be made: (i) the disturbance waves travel at higher velocities than the substrate; (ii) ripples can be found on both the substrate and the disturbance waves; (iii) some ripples located near the top of disturbance waves have larger velocities than the disturbance waves themselves; and (iv) some ripples located on the substrate (both upstream and downstream of a disturbance wave) have velocities lower than the substrate.

The information derived from Figure 1 together with a statistical analysis of the gas-liquid interfacial topology indicate that ripples populating the main body of disturbance waves are a crucial component of the mechanism for liquid entrainment.

Conclusions

PLIF and PIV/PTV techniques were successfully employed to track the gas-liquid interface and to obtain velocity information in the liquid film underneath the waves in gas-liquid co-current downwards annular flows. The results obtained from the subsequent analysis of the resulting data (e.g. local film thickness, interfacial velocity and velocity profiles relating to individual ripples and disturbance waves) can be used to classify the various interfacial phenomena (i.e. waves) observed in these flows. Alekseenko, S., Cherdantsev, A., Cherdantsev, M., Isaenko, S., Kharlamov, S. and Markovich, D., 2012. Application of high-speed laser-induced fluorescence technique for studying the three-dimensional structure of annular gas-liquid flow. Exp. Fluids 53, 77-89.

