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A PIV investigation of stratified gas–liquid flow in a horizontal pipe

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ABSTRACT

Simultaneous Particle Image Velocimetry (PIV) measurements of stratified turbulent air/water flow in a horizontal pipe have been performed using small water droplets, $\overline{d_p} = 6$ µm, as tracer particles in the gas-phase. This seeding technique ensures that the surface tension of the water layer remains unaffected upon contact with the tracer particles in the gas-phase and thus allows small scale interfacial structures, such as capillary waves to occur and evolve naturally. Experiments have been conducted in a 31 m long, 100 mm in diameter PVC pipe using air and water at atmospheric pressure as test fluids. For the purpose of validation of the experimental set-up and the suggested seeding technique, gas single-phase measurements were performed at $Re_D = 45{,}000$ and compared to existing DNS results from the literature with similar Re-number, showing very good agreement. Two stratified flow cases, i.e. smooth and wavy, are extensively discussed with emphasis on the effect of the interface pattern on the gas streamwise turbulence profile u'_g. A simple analysis using the u'_g-profiles of 17 stratified flows suggests the presence of a correlation between the turbulence structure of the gas-phase and global flow conditions such as the pressure drop and the bulk velocity.

1. Introduction

Stratified two-phase flow is a flow regime that occurs when the velocity of each phase is relatively low. In such flows the inertia forces are not large enough to generate large waves that may lead to the onset of intermittent flow regimes such as slug flow or dispersed flow, which are considered as more complicated and problematic in industrial contexts. Sanchis et al. (2011) reported on how stratified flow can develop into hydrodynamic slugging through wave interaction. Furthermore, despite its relative simplicity, stratified flow is still far from completely understood due to its complex underlying physics. For instance, one may intuitively think of the two-way interaction between the flow dynamics, or more specifically, the dynamics of turbulent structures of each phase and the local interface morphology, as one of such physical phenomena. In a co-current gas/liquid flow, where the gas moves faster than the liquid-layer beneath it, the waves that were initially induced upstream by interfacial shear forces will be perceived, by the gas-phase, as a slowly moving deformed surface locally. This will in turn influence the flow conditions of the gas and consequently change the interfacial shear downstream.

Also, stratified gas/liquid flow is frequently encountered in industrial applications within the petroleum, nuclear or process industries, to mention a few. In the natural gas industry, gas/liquid flow is the dominating two-phase combination inside transportation pipelines and is mainly present as a gas/condensate or gas/water mixture. The condensation of natural gas is an inevitable process that occurs due to the temperature and pressure changes that are imposed on the pipes by the natural surroundings. In off-shore gas fields, the raw production is often transported in multiphase pipelines before it reaches a processing unit. These lines lie at the bottom of the sea in horizontal and near-horizontal positions. Hence, a better understanding of the flow characteristics of stratified gas/liquid flow in horizontal pipes is needed for proper design and operation of pipelines that are subjected to not only stratified flows, but also slug flows, see e.g. Mokhatab et al. (2006) for more information about the natural gas industry.

The key pipeline design parameters are the pressure drop, average hold-ups and velocities. Their prediction has traditionally been based on greatly simplified representation of the flow where both phases are treated as one-dimensional bulk flows, also called the two-fluid 1D model, see Ullmann and Brauner (2006), Schulkes (2010) and Johnson (2005) for details about the two-fluid model. However, the application of this model in a stratified flow relies on the availability of closure relations for the wall and interface shear stress. These closure relations should depend on both system parameters (e.g. fluid properties, pipe characteristics, etc.) and flow related parameters in both phases. In the most common approaches, empirical correlations for the interfacial friction factors

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are obtained from experimental data, highlighting the importance of the experimental aspect within this field. Among others, the models proposed by Andreussi and Persen (1986), Andritsos and Hanratty (1987), and Biberg (2007) are based on this method. It should be worth mentioning that the latter model is incorporated in the flow assurance simulator, OLGA (HD module), Bendiksen et al. (1991).

Most of the existing experimental work consists mainly of superficial velocity, pressure-drop and liquid hold-up measurements, e.g. Lockhart and Martinelli (1949) and Andritsos and Hanratty (1987). Some more complicated studies also involve measurements of the wave fields using conducting probes, Strand (1993) and Espedal (1998), or other techniques such as Laser Doppler Velocimetry (LDV), see Fernandino and Ytrehus (2006). By analyzing the spectral cross correlation output, they established that the stratified flow regime consists of a range of well defined sub-regimes determined by the interfacial wave kinematics. Espedal (1998) divided them into the following five regions:

1. Smooth flow: No waves were observed.
2. Small amplitude waves I: Amplitudes below 2 mm and wave lengths between 2 and 6 cm. The power spectrum showed no peak at all or one peak.
3. Small amplitude 2D waves II: Similar to the waves above, but the power spectrum showed two peaks.
4. Large amplitude 2D waves: Amplitudes above 2 mm, and the waves are less regular. The power spectrum has a one, two or no marked peaks.
5. Large amplitude 3D waves: Amplitudes above 2 mm, and the waves do not have a two dimensional shape.

Furthermore, it is of common knowledge that interfacial turbulence structures are responsible for not only the scalar mixing (mass, momentum, temperature, energy, etc.) between phases, but also for the pressure drop along the pipe as they enhance the overall shear friction of the flow. Therefore, a better understanding of the relation between the different stratified flow patterns and their belonging turbulence dynamics might be the key to more accurate mathematical modeling. However, details about the turbulent structures near the gas–liquid interface are difficult to access using conventional instrumentation such as hot-wire or hot-film anemometery, as the probes can interfere with the free surface. Fabre et al. (1987) presented one of few successful LDA measurements of turbulence parameters close to the interface of wavy stratified flow.

The use of more recent non-intrusive measuring techniques such as Particle Image Velocimetry (PIV) can offer both qualitative and quantitative measurements of both global and local flow conditions, e.g. liquid hold-up, velocity field, etc. More importantly, this technique can provide information about either the instantaneous or time-averaged turbulence structure of both phases. Hence, PIV not only helps to obtain fundamental understanding of the physics of the flow, but can also provide important empirical parameters that can be implemented into existing numerical models, such as Biberg (2007).

The basic principle of this method is to determine a two-dimensional fluid velocity field in a thin light sheet from the motion of small tracer particles that are added to the fluid. Images of the tracer particles are recorded with the help of a high resolution camera and a high power double-pulsed laser. The recordings are then subsequently analyzed on a point-by-point basis in small interrogation areas by means of a correlation method. Raffel et al. (2007), Melling (1997), Sveen and Cowen (2004) and Westerweel (1997) cover practically all aspects of PIV.

For most PIV experiments it is desirable that tracer particles are non-toxic, non-corrosive, non-abrasive, non-volatile and chemically inert. Traditionally, oil droplets or solid particles have been used as tracers in gas single-phase flows, e.g. in wind tunnel applications. Melling (1997) presented an overview on existing PIV studies on gas flows based on the seeding particles that were used. He concluded that seeding with liquid droplets offers the advantage of a steadier production rate than is normally feasible with solid particles. Moreover, in experimental cases where the studied flow consists of an additional phase, which in the present case is water, seeding the gas-phase with oil droplets would impose a chemical impact on the surface tension of the water-phase upon contact. This would disturb the natural onset and evolution of interfacial perturbations such as capillary waves and hence, probably affect the prediction of intermittent flow regimes as described by Sanchis et al. (2011).

The novelty of this work lies in the use of small water droplets, 1–6 μm in diameter, as tracer particles in the gas phase. The droplets were generated by a high-pressure atomizing nozzle supplied with filtered tap water. PIV has been utilized for the simultaneous measurement of both phases in stratified air/water flow. The main results are discussed in terms of a qualitative comparison between two cases: (1) smooth interface and (2) small amplitude 2D waves, with emphasis on the gas-phase, since only liquid phase measurements have been documented in existing studies, see Carpintero-Rogerol et al. (2006).

A number of validation tests were carried out in order to justify the seeding technique of the gas phase for this particular application. Amongst others, measurements of gas single-phase flow were conducted at $Re = 45{,}000$ and compared to DNS results obtained by Wu and Moin (2008), showing very good agreement.

This paper is structured as follows; in Section 2 the experimental set-up and measurement technique are described. Sections 3 and 4 contain extensive discussions on the measurement uncertainties and spatial dynamic range of the PIV measurements. Section 5 shows the results from the validation single-phase experiment. Section 6 contains the main results of the two-phase flow experiments where two cases are qualitatively compared. Section 7 contains the concluding remarks.

Finally, it is emphasized that the present study is supposed to be the first in a series of experiments aimed at clarifying the interaction between different stratified flow patterns (sub-regimes) with the turbulent flow structure of both phases and, eventually, providing more accurate closure parameters to Biberg's mathematical model (2007).

2. Experimental set-up and measuring technique

The PIV experiments were conducted in a horizontal 31 m PVC pipe with an internal diameter $D = 10$ cm. The pipe consisted of adjacent sections, each with a length of 3.5 m connected by annular joints that ensured tightness. All joints were rigidly attached by collars to vertical beams that supported the whole structure. The test fluids were air and water at atmospheric pressure with an average temperature of 22 °C. Fig. 1 shows the disposition of the pipe elements.

Water was injected at the pipe bottom through a 5 cm I.D. tee branch. Honeycomb flow straighteners were placed right before and after the contact point between the liquid and gas phases. At the outlet, the pipe discharged into a separating tank at atmospheric pressure in which both the water and air were recirculated from the bottom and top exits of the tank, respectively.

Furthermore, water was circulated with a maximal volumetric flow rate of 90 m^3/h, and a frequency-regulated fan produced the airflow. The water and air mass flow rates were measured with an Endress Hauser Promass and an Emerson MicroMotion Coriolis flow meter with ±0.2% and ±0.05% accuracy, respectively. Bulk