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Study and characterization of gas-liquid slug flow in an annular duct, using high speed video camera, wire-mesh sensor and PIV

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ABSTRACT

An experimental study is presented on air-water two-phase flow in a 10.5-m-long annular duct with an external diameter of 155 mm and an inner diameter of 60 mm. Particle image velocimetry (PIV) is applied to obtain instantaneous velocity measurements of the flow field. The annular duct inclination is of 5Â° from the horizontal. A CCD camera (2448 *pixel* × 2050 *pixel*, 5 *Mpixel*,12-bit) was positioned in the test section to record the seeding particles. The illumination was provided by a double pulsed PIV laser (Nd:YAG, frequency doubled to 532 nm) with a measured pulse intensity of 70 mJ/pulse. It was used at 15 Hz (resulting in the independence of the velocity samples). Based on the instantaneous local velocities, Probability Density Functions (PDF) and mean velocities are calculated. Two-phase flow arranged in the slug-flow pattern is observed, at superficial velocities of $j_w = 0.154$ m/s and $j_a = 0.044$ m/s. 3000 samples per case are processed using cross-correlation procedure, for the PIV analysis. A home-made Annular Wire-Mesh Sensor (AWMS) was applied to obtain time-signal-measured void-fraction data as a function of the electrical permittivity. The average bubble velocity is estimated by two techniques, (i) High-Speed Video Recording and (ii) Particle Image Velocimetry (PIV) together with the AWMS. A comparison of the two techniques is presented. A new technique based on AWMS for the measurement of bubble-passage frequency, bubble length and slug length is proposed. It was observed: (i) deceleration of the water phase beneath the bubble as it passes, shown by velocity profiles at different bubble locations, (ii) an increase in bubble velocity as air superficial velocity is increased and (iii) the complexity of the flow pattern, shown in details by AWMS cross-sectional images. The new experimental results are of great value for comparison with CFD models and for the development of more refined pressure-drop prediction tools in two-phase annular-duct flows.

1. Introduction

Gas-liquid two-phase flows in concentric annular ducts are found in a wide range of important industrial applications, as in refrigeration and nuclear engineering. In the oil industry, they are observed in well drilling, directional wells with sand screen and wells equipped with electrical submersible pumps. However, there are few studies on characterization and analysis of geometrical and kinematic properties of two-phase gas-liquid flows in big annular ducts. Regarding works on two-phase flow in circular pipes aimed to obtain detailed information on the flow characteristics, one can see the application over the last decades of Particle Image Velocimetry - PIV (velocity profiles and turbulence statistics), Wire-Mesh sensing (In-situ phase fraction, volumetric fraction and flow tomography) and high-speed video recording (flow patterns). Similar works in two-phase annular-duct flow are scarce. The present work describes the application of Particle Image Velocimetry (PIV) and Annular Wire-Mesh Sensor (AWMS) in air-water two-phase flow arranged in the slug flow pattern in a big annular duct, where void fraction measured by the AWMS and instantaneous velocity data obtained via PIV are analyzed. The average velocity of the bubble is calculated using high-speed video recording and compared with the velocity data obtained by PIV together with AWMS.

In works where PIV is applied to study two-phase flows, we can see that significant development of the technique has been reported in the last two decades. Works on water-oil two-phase pipe flow were conducted by Elseth [1], Kumara et al. [2,3] where moment statistics were analyzed, as, velocity profiles fluctuation-velocity (*rms*). They carried out a comparison of results obtained by PIV and Laser Doppler Anemometry (LDA) in a horizontal pipe of 15 *m* long and a diameter of 56 mm. As expected, LDA allowed better results close to the wall. Ayati et al. [4,5] used PIV to measure air-water flow in a horizontal pipe of 31 m long, diameter of 100 mm and compared it with results of direct

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Nomenclature

A_V	dimensionless gain
Q	volumetric flow rate (L/min)
Re	Reynolds number (dimensionless)
v	electrical voltage (V)
D	pipe diameter (m)
j_w	water superficial velocity (m/s)
j_a	air superficial velocity (m/s)
r	radius (mm)
u	axial velocity profile (m/s)
v	radial velocity profile (m/s)
u_i	instantaneous (frame) streamwise or axial velocity (m/s)
v_i	instantaneous (frame) wall-normal or radial velocity (m/s)
v_{ma}	mean velocity in annular duct (m/s)
$\frac{\Delta P}{L}$	pressure drop by unit length (Pa/m)
U_i	PIV instantaneous velocity profile (each frame) (m/s)
N_f	number of frames
$U_{meanPL_b/10}$	velocity profile of each bubble position (P)
$U^*_{i,\,PL_b/10}$	mean value of the instantaneous velocity profile
rms	root-mean-squared parameters (m/s)
u_a	analytical axial velocity profile in annular duct (m/s)
σ_u	error in the estimated mean velocity

Greek letters

α	void fraction (dimensionless)
μ	viscosity (Pa s) (Ns/m^2)
ρ	Density (Kg/m^3)
ε	permittivity (F/m)

Subscripts

min	minimum
i	instantaneous
a	annular
w	water
a	air
HSVC	high speed video recording

Abbreviations

AWMS	Annular Wire-Mesh Sensor
PIV	Particle Image Velocimetry
PDF	Probability Density Functions
LDA	Laser Doppler Anemometry
DNS	direct numerical simulation
QCV	quick-closing-valve
CCD	charge coupled device

numerical simulation (DNS), with very good agreement.

Experimental studies were performed by Vestøl and Melaaen [6], Birvalski et al. [7] and Birvalski et al. [8] in air-water, in horizontal pipe, where mean radial and axial velocity profiles and turbulence-statistic profiles were measured with PIV.

Westerweel et al. [9] and Toonder et al. [10] analyzed turbulence statistics, using DNS, PIV and LDA, comparing mean axial velocity profiles, axial and radial turbulence intensities, again in a circular pipe.

Similar works using PIV to obtain two-phase flow statistics in slug flow and in a big concentric annular duct were not found in the literature. In this work, an air-water two-phase flow arranged in the slug-flow pattern in an upward-5-degree-inclined concentric annular duct is studied. New velocity profiles are obtained via PIV over the diametrical vertical plane at the bottom side of the duct.

The Wire-Mesh Sensor (WMS) is an intrusive tomographic method that allows high temporal sensitivity and good spatial sensitivity for the study of two-phase flows. An experimental analysis applying WMS can be seen in the work of Jones and Zuber [11], which showed that the probability density function (PDF) of the void-fraction may be used as an objective and quantitative flow-pattern discriminator for the three dominant flow patterns, bubbly, slug, and annular flow. The WMS was first described by Johnson [12], as an intrusive sensor for measuring the fraction of water in oil, based on fluid conductivity. Prasser et al. [13] ensured the elimination of crosstalk between the electrodes and a WMS was developed for application in nuclear power plants, in which water-steam flow is subjected to high temperatures and pressures.

Silva et al. [14] developed a WMS based on the permittivity of the fluid, which expands the range of substances that can be identified. Also, the technology has been applied in sensors of several different shapes by Damsohn and Prasser [15], Damsohn and Prasser [16], Belt et al. [17] and Höhne et al. [18], but the operation principles and the associated electronic circuits are still the same. Rodriguez et al. [19] used a wire-mesh sensor based on capacitance (permittivity), measurements were made to characterize the oil-water flow in a 26.2-mm-i.d. 12-m-long horizontal glass pipe.

A comprehensive review of the literature was carried out in the study of Velasco and Rodriguez [20], with relevant and recent implementations, remarkably in gas-liquid and liquid-liquid flows, comparing it with other techniques. In addition, it was shown how the sensor can be adapted to each application and its different geometries, pointing out its flexibility. Rodriguez et al. [21] investigated dispersed and stratified oil-water flow patterns experimentally, using gamma densitometry and a wire-mesh sensor (WMS), water and oil holdups, chordal and cross-sectional phase distributions were measured in an 82.8 mm i.d. horizontal pipe, using mineral oil and brine at mixture velocities between 0.07 and 2.9 m/s.

In the literature, most of the works are in tubes and rectangular channels. In the present work, we propose an Annular Wire-Mesh Sensor (AWMS) that is used in an innovative annular geometry and was synchronized with the PIV system and a High Speed Video Camera, in order to characterize the bubble passage over time and to find its velocity.

Probes based on electrical conductivity techniques were used to determine statistics as Probability density function, which was used to analyze the signal in the time domain in both concentric and eccentric annular ducts, to identify flow patterns in air-water, two-phase as bubbly, slug, and churn flow [22–27].

Ozar et al. [28] applied a sensor based on a conductive probe to analyze the void fraction in an annular duct positioned vertically.

With the objective of studying different flow patterns and their behavior in a vertical annular duct, a sensor called impedance meter, similar to a conductive probe, was used in order to analyze PDF parameters, by Sun et al. [29] and Julia et al. [30].

Escudier et al. [31] analyzed the friction factor in the velocity profiles in a horizontal concentric annular duct, taking into account the phenomenological behavior of the transition from laminar to turbulent flow.

The behavior of the pressure drop in different ranges was analyzed by Kelessidis et al. [32] in a concentric and eccentric annular duct for laminar transitional and turbulent flow. Whilst Brighton and Jones [33] measured velocity profiles, locating the maximum point and the average in a turbulent flow for each profile in an horizontal annular duct. Wongwises and Pipathattakul [34] used a high-speed camera to study the fluid phenomenology in two-phase flow patterns, pressure drop and void fraction were measured, in horizontal and inclined annular duct.