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Gas–liquid flow of sub-millimeter bubbles at low void fractions: Experimental study of bubble size distribution and void fraction

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ABSTRACT

This work studies gas–liquid flow of small bubbles (<1 mm) at low void fractions (<10^{-1}) that is encountered in human bloodstream during Decompression Sickness and is also relevant to two-phase applications such as flow boiling in macro-channels. Two fundamental parameters are experimentally investigated: Bubble Size Distribution (*BSD*) and void fraction. Experiments are conducted in co-current upward bubbly flow. Water and blood simulant are used as test liquids, while bubble size is controlled using prescribed surfactant (*SDS*) concentrations. *BSDs* are determined employing digital image analysis of bubbly flow images captured at three radial positions across the flow cross-section. Volumetric and cross-sectional area averaged void fraction is measured at three axial locations along the flow by Differential Pressure (ΔP) and Electrical Resistance Tomography (*ERT*), respectively. *BSDs* are well-fitted by the log-normal distribution. *ERT* and ΔP measurements are in fair agreement, with void fraction being practically equal along the flow. The influence of gas/liquid phase velocities and surfactant concentration on the measured void fraction and *BSDs*' average value and width is discussed in detail. Interestingly, high *SDS* concentration in blood simulant results in the formation of bubble clusters, whose role on the examined parameters is investigated.

1. Introduction

Gas–liquid flow is the most common type of two-phase flow that covers numerous phenomena of both industrial and academic significance. Bubbly flows are specific cases of two-phase flows where the gas phase is dispersed in the form of numerous, discrete bubbles inside the continuous liquid phase. In common processes, bubbles vary widely in size and shape and are much smaller than the diameter of their container. Bubbly flow is observed frequently in diverse engineering systems covering petroleum processing, oil and gas extraction and transportation, boilers, steam generators in nuclear reactors, electronic cooling and various types of chemical reactors (Julia and Hibiki, 2011; Shen et al., 2017). Also, it can be encountered in the human bloodstream during either open heart surgery with extracorporeal circulation due to hardware malfunction (Mino et al., 2015) or during Decompression Sickness incidents, e.g. in scuba divers, metro workers and astronauts (Papadopoulou et al., 2015; Oikonomidou et al., 2018). The former case typically refers to a few bubbles of fixed size scaling from millimeters to micrometers that accidentally enter the blood circulation during surgery whereas the latter case refers to a cloud of growing bubbles of sub-millimeter size that form directly inside the blood by desorption of dissolved breathing nitrogen in the blood.

Void fraction (volumetric gas fraction) and Bubble Size Distribution (*BSD*) are fundamental two-phase flow parameters. They enable the computation of interfacial area, which is the main parameter for the evaluation of heat and mass transfer at the interface. Additionally, void fraction and *BSD* information are necessary to properly set-up a Computational Fluid Dynamics model. Consequently, the concept of void fraction and *BSD* have been attractive for researchers resulting in several measuring techniques (Besagni and Inzoli, 2016; Bhagwat and Ghajar, 2014).

BSD in a two-phase system can be measured by several methods divided mainly in two categories: intrusive and non-intrusive. Intrusive methods include capillary suction probes, conductivity probes, optical fiber probes and wire-mesh sensors. Non-intrusive methods employ interferometric particle imaging, laser Doppler velocimetry, phase Doppler anemometry and other particle image techniques. In general, non-intrusive techniques are preferred over the intrusive ones because they do not disturb flow conditions (Karn et al., 2015). A classical non-intrusive method is applied in this study, which is the photographic technique in association with digital image analysis. Due to its simplicity, flexibility and low cost, the classic photographic method is the preferred tool for precise bubble size measurement (Gaillard et al., 2015). However, implementation of this method faces several

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Nomenclature

α	void fraction
ΔP	Differential pressure
$\Delta P_{0,Usl}$	pressure difference when $U_{sg} = 0$ ($\alpha = 0$)
$\Delta P_{local,1}$	differential pressure sensor providing local measurement of void fraction for a flow length of 7.0 cm, at a distance $z/D = 10$ from the gas injection point
$\Delta P_{local,2}$	differential pressure sensor providing local measurement of void fraction for a flow length of 7.0 cm, at a distance $z/D = 55$ from the gas injection point
$\Delta P_{overall}$	differential pressure sensor providing overall void fraction measurement in the vertical tube for a flow length of 87.0 cm, at a distance $z/D = 33$ from the gas injection point
μ	scale parameter of log-normal distribution
μ_l	liquid dynamic viscosity
ρ_l	liquid density
σ	shape parameter of log-normal distribution
BSD	bubble size distribution
CV	coefficient of variation
C_{SDS}	concentration of SDS
D	internal pipe diameter
$D_{1,0}$	arithmetic mean bubble diameter
$D_{3,2}$	Surface weighted mean bubble diameter
$D_{4,3}$	Volume weighted mean bubble diameter
DCS	Decompression Sickness
ERT	Electrical Resistance Tomography
ERT1	ERT probe for void fraction measurement at a distance $z/D = 10$ from the gas injection point
ERT2	ERT probe for void fraction measurement at a distance $z/D = 30$ from the gas injection point
ERT3	ERT probe for void fraction measurement at a distance $z/D = 55$ from the gas injection point
$ERT_{average}$	average value from *ERT1, ERT2, ERT3* void fraction measurements
R	correlation coefficient
r	radial distance from the pipe center
SDS	Sodium Dodecyl Sulfate
U_{sg}	gas superficial velocity
U_{sl}	liquid superficial velocity
Re_l	liquid phase Reynolds number (defined by $\rho_l U_{sl} D/\mu_l$)
z/D	normalized axial distance

challenges. For instance, a large number of bubbles may be overlapping (~40%) even at low void fraction (~1%). In that case, many image-processing algorithms underestimate bubble size (Besagni and Inzoli, 2016). Various studies have addressed this problem and have proposed different methods for dealing with overlapping bubbles (Lau et al., 2013; Zabulis et al., 2007).

Non-invasive techniques for the measurement of void fraction include pressure drop, dynamic gas disengagement, conductimetry, light attenuation, neutron/γ-ray/X-ray absorption, ultrasound attenuation, NMR and γ- or X-ray/capacitive or resistive/ultrasonic tomography (Kanizawa and Ribatski, 2017; Uesawa et al., 2012). Among these techniques, two well-established methods for void fraction determination in two-phase systems are of interest to this study: Differential Pressure (ΔP) and Electrical Resistance Tomography (*ERT*) for volumetric and cross-sectional area averaged void fraction estimation, respectively, inside a vertical pipe. The use of these two methods allows the comparison of void fraction measurements at different sites along the flow and further increases the confidence to void fraction measurements.

Measuring void fraction via a pressure difference is simple. This technique does not require a transparent fluid or vessel and also does not have requirements on liquid electrical properties. It can be used to measure the overall average void fraction in a multiphase column, as well as the local average void fraction in a column section. Thus, it can be used to probe the axial void fraction variation in a column (Han et al., 2016; Tang and Heindel, 2006).

ERT is considered the most powerful tool among other available tomography techniques due to its high-speed capability, low construction cost, high safety and suitability for small or large vessels (Jin et al., 2013). It provides temporal–spatial information of multiphase flow at one or multiple measuring cross sections of a vessel. *ERT* is sensitive to the resistance change of a fluid and thus it is suitable for gas–liquid two-phase flow when the liquid phase is a conductive fluid. Several works have been carried out for concentration profile visualization and void fraction determination in gas–liquid two-phase systems employing *ERT* (Fransolet et al., 2005; Jin et al., 2010; Jin et al., 2006; Meng et al., 2010).

The objective of this study is to experimentally investigate void fraction and bubble size distribution in vertical co-current upward two-phase flow, where the examined conditions resemble bubbly flow in human vena cava during Decompression Sickness, *DCS* (Vann et al., 2011). Better understanding of bubbly flow characteristics is expected to facilitate CFD modeling of *DCS* and therefore to contribute in the prevention and treatment of the disease. Such bubbly flow conditions, combining sub-millimeter bubbles and low void fractions ($<10^{-1}$), are also encountered in other two-phase flow applications, e.g., flow boiling in macro-channels (Maurus et al., 2002; Yoo et al., 2016). The present work is a follow-up of Evgenidis and Karapantsios (2015) that: a) expands 70% the previous data set to more experimental conditions, b) applies two commercial techniques, Electrical Resistance Tomography and Differential Pressure, instead of a custom-made electrical impedance technique for cross-sectional area averaged and volumetric void fraction determination, respectively, c) investigates void fraction evolution along the vertical pipe and d) provides comparative bubble size distributions to enhance the study of liquid properties and phase velocities on bubble size features. The next section presents the employed experimental techniques and materials. A section follows with experimental results on bubble size distribution and void fraction where descriptive statistics are used to describe and compare the data. Finally, a discussion is made regarding the influence of liquid phase physical properties and phase velocities on void fraction and bubble size.

2. Materials and methods

Measurements are conducted in a vertical co-current upward bubbly flow provided by a fully controllable flow loop. The liquid phase is recirculated through the flow loop by means of a progressive cavity pump (MD 025-6L, Motovario S.p.A.). The main part of the loop consists of a vertical tube 1.6 m long with internal diameter $D = 21$ mm. This is the diameter of human vena cava where bubbles gather during a decompression incident (Vann et al., 2011). Moreover, $D = 21$ mm is within the range of macro-channel diameters studied in flow boiling applications. Gas phase is injected through a cylindrical glass microporous filter (ROBU®; diameter: 12 mm, nominal pore size: 1.0–1.6 μm) located at the center of the bottom of the vertical tube, where the two phases come in contact. The top filter wall is covered with glue to avoid large bubbles exiting and so the only bubbles allowed to enter the liquid flow are those generated and sheared-off at the side filter wall. Continuous formation of bubbles facilitates in-vitro study of developed bubbly flow in human vena cava where bubbles gather during *DCS*. More details about the flow loop operation are found in Evgenidis and Karapantsios (2015). Along the vertical tube, successive test sections of