International Journal of Multiphase Flow 75 (2015) 163–173

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

journal homepage: www.elsevier.com/locate/ijmulflow

Effect of bubble size on void fraction fluctuations in dispersed bubble flows

Sotiris P. Evgenidis, Thodoris D. Karapantsios *

Division of Chemical Technology, School of Chemistry, Aristotle University, University Box 116, 541 24 Thessaloniki, Greece

ARTICLE INFO

Article history:
Received 24 November 2014
Received in revised form 20 May 2015
Accepted 25 May 2015
Available online 3 June 2015

Keywords:
Dispersed bubble flow
Void fraction
Bubble size
Electrical impedance
Signal analysis

ABSTRACT

It is known that bubble size affects seriously the average void fraction in bubbly flows where buoyant velocities vary considerably with bubble size. On the contrary, there is no systematic literature report about bubble size effects on the intensity and frequency of void fraction fluctuations around the average void fraction. This work aims to provide such information. An electrical impedance technique is employed along with non-intrusive ring electrodes to register void fraction fluctuations down to 10^{-5}. Bubble size fluctuations are estimated from high resolution optical images. Experiments are conducted in co-current upward dispersed bubble flow inside a 21 mm tube with average bubble size between $\sim$50 and $\sim$700 μm. Water and blood simulant are used as test liquids with velocity from $\sim$3 to $\sim$30 cm s^{-1}. The above resemble conditions of Decompression Sickness (DCS) in the bloodstream of human vena cava. It is found that the intensity and frequency of void fraction fluctuations vary appreciably with bubble size at constant gas and liquid flow rates. Moreover, these variations are not random but scale with bubble size. As a first step to quantify this effect, an empirical expression is derived that relates average bubble size to the ratio standard deviation/average value of void fraction.

Introduction

Bubbly (multiple-bubble) flow is a very common type of gas–liquid two-phase flow characterized by the existence of discrete gas bubbles dispersed in a continuous liquid phase. Bubbly flow is encountered in a variety of industrial processes, e.g. chemical and petroleum processing, oil and gas extraction and transportation, nuclear power generation, etc (Das and Das, 2010; Shen et al., 2005). It is also encountered in the human bloodstream during Decompression Sickness incidents, e.g. in astronauts, scuba divers and metro workers (Papadopoulou et al., 2013).

Void fraction (volumetric gas fraction) is a very important physical parameter in all kinds of two-phase flow. Numerous experimental techniques have been developed to measure void fraction in integral or local fashion including quick shut valve methods, image processing methods, X-ray CT scan methods, neutron radiography methods, gamma-ray method, NMR and so on. The aforementioned methods are subjected to various technical restrictions and, additionally, they are hard to apply for capturing high frequency temporal fluctuations of void fraction (Uesawa et al., 2012). Electrical impedance measurements are free of such drawbacks. Electrical impedance depicts quantitatively the distribution of a two phase mixture close to a system of measuring electrodes as much as the electrical properties of the two phase components are sufficiently different from each other, e.g. water and air (Devia and Fossa, 2003).

There are many different possibilities to arrange a system of electrodes –intrusive or non-intrusive- for void fraction measurement purposes (Ceccio and George, 1996). In a few studies, the size of large isolated bubbles has been determined by means of intrusive dual impedance probes in two-phase flow applications (Tang and Fan, 1989; Liu, 1993; Chen et al., 1998). Non-intrusive, flush mounted onto the vessel wall ring electrodes were first employed by Asali et al. (1985), while Andreussi et al. (1988) and Tsochatzidis et al. (1992) developed the theoretical basis regarding the response of this electrode configuration, which has been further employed in several three-phase applications, e.g. Begovich and Watson (1978) and Karapantsios et al. (1993).

It must be stressed that most of the earlier efforts were devoted to accurate measurement of the average void fraction where void fraction fluctuations were seen only as a statistical measure of discrepancy. On this account, it has been realized that the separation distance between electrodes is critical in order to obtain meaningful average data. In many cases examined in literature, the selection of the separation distance between electrodes has been

---

* Corresponding author. Tel./fax: +30 2310997772.
E-mail address: karapant@chem.auth.gr (T.D. Karapantsios).

http://dx.doi.org/10.1016/j.ijmultiphaseflow.2015.05.013
0301-9322/

based on the volume-averaging approach of modeling porous media (e.g. Carbonell and Whitaker, 1984). According to this approach, the size of the probe averaging volume, i.e., the required minimum volume surrounding a probe has to be large enough to average void fraction fluctuations, e.g., due to the finite bubble size, yet small enough to preserve the local character of the measurements (Celmins, 1988). So in most cases void fraction fluctuations caused by a flowing bubble swarm were sacrificed to obtain an accurate average value of void fraction. Nevertheless, large void fraction fluctuations may jeopardize the control schemes in operating industrial equipment. Furthermore, void fraction fluctuations may serve as indicator of process performance, e.g. efficient mixing, degree of dispersion etc.

In common bubbly flows, one would expect average bubble size to affect average void fraction at constant gas and liquid flow rates. But this is different from how average bubble size may affect void fraction fluctuations. The latter has to do with the spatial and temporal characteristics of the sensing probe, i.e., with the disturbance of the electric field as bubbles flow through the measuring volume and pass over the electrodes (Devia and Fossa, 2003). Bubbles flowing close to the surface of electrodes have stronger effect than those far away in the measuring volume but this effect scales also with the size of bubbles with respect to the width of the electrodes. The overall electrical response is an instantaneous average along the total electrode's surface and across the entire measuring volume so the effect of single bubbles is diminished (Tsochatzidis et al., 1992).

To our knowledge, there is no report in literature that systematically quantifies the effect of bubble size of a flowing bubble swarm on void fraction fluctuations. In order to obtain such information without compromising the accuracy of the average void fraction measurement, techniques of superb sensitivity are required. Such information is also important when one wants to estimate average void fraction values from electrodes placed not far apart along the flow which usually leads to intense void fraction fluctuations. Closely spaced electrodes may be required due to spatial constraints or because of the evolving nature of the flow (not fully developed flow). On the other hand, it is extremely useful if one can obtain simultaneous information on the average void fraction and the average bubble size (from void fraction fluctuations). The latter is the motivation for this study.

Herein, we exploit electrical impedance measurements of high temporal and spatial resolution taken with non-intrusive ring electrodes in order to correlate void fraction fluctuations to bubble size in a co-current upward bubbly flow. The examined conditions resemble bubbly flow in human vena cava during Decompression Sickness (DCS). However, the methodology can be extended to any kind of bubbly flow. Since the measurement of void fraction values lower than 10^{-2}, that interest mostly the present study, fall within the noise level of conventional electrical techniques (Karapantsios and Papara, 2008), a novel electrical impedance technique has been developed (Evgenidis, 2011). Innovative hardware and signal analysis/processing have improved the sensitivity about two orders of magnitude compared to conventional techniques allowing capturing of void fraction fluctuations down to 10^{-5}.

In the following section, the experimental setup is outlined along with the employed measuring technique. A section follows on experimental results and discussion on the performance of the technique.

Materials and methods

Measurements are conducted in vertical co-current upward bubbly flow. Flow is provided by a fully controllable flow loop made of PMMA tubing capable of generating steady and pulsatile flow at various liquid/gas flow rates and bubble sizes. Only steady flow is employed in this study. The main part of the loop consists of a vertical tube 1.6 m long with $D = 21$ mm. This is the diameter of human vena cava where bubbles gather during a decompression incident (Vann et al., 2011). In Fig. 1, the small orthogonal blocks along the vertical tube stand for test sections of electrical, optical, acoustical and pressure diagnostics. These sections are separated by flanges and so can be interchanged. Diagnostics are meant for void fraction measurement and identification of bubbles characteristics. In this work, acoustical measurements were not performed.

The liquid phase is recirculated through the flow loop by means of a progressive cavity pump (MD 025-6L, Motovario S.p.A.) providing cavitation-free and pulseless flow even at low rates. The temperature of the flowing liquid remains constant at the desired value within ±0.1 °C, using a heater/circulator (HAAKE C10-P5/U, Thermo Electron Corporation, HC-1, Fig. 1) which is immersed in the liquid tank (T-1, Fig. 1). The gas phase is injected through a cylindrical glass micro-porous filter (ROBU®; 10 mm diameter, 20 mm length, 1.6 μm nominal pore size) located at the center of the bottom of the vertical tube, where the two phases come in contact. The liquid enters the vertical tube through the annulus formed between the filter and the tube walls. Bubbles enter the flow after being sheared-off from the side walls of the filter by the annular liquid flow. The top side of the filter is plugged with glue to avoid entrance of larger bubbles into the flow.

Void fraction measurements are conducted with a patented ultra-sensitive electrical impedance technique (Karapantsios et al., 2014). A sinusoidal voltage signal (V_i) with a frequency of 25 kHz and amplitude of 2 Vp–p is applied to a ring electrode in order to excite electrically the bubbly flow inside the tube, generating an input current passing through the medium. For gas/liquid two phase systems where the electrical conductivity of the two components is so distinctly different it is known that in the 10–100 kHz region the phase shift (capacitive component) of the signal is close to zero and this offers inherent advantages in signal conditioning/processing (Tsochatzidis et al., 1992; Fossa, 1998; Karapantsios and Papara, 2008). Frequency scanning showed that an excitation frequency of 25 kHz provides the lowest phase shift (less than 1°) and thus almost pure resistive behavior. The input current creates a voltage drop due to the finite (but variable) resistance of the two-phase medium (R_m) and exits from another ring electrode. This electrode is connected to the one end of a termination resistor (R_t), while the other end of the resistor is grounded. R_m and R_t constitute a voltage divider and the voltage across the termination resistor is the measured output voltage V_o. V_i and V_o are recorded by a high-resolution 24 bit data acquisition card (E-MU 1616m, CREATIVE Professional) with a sampling frequency of 192 kHz. The recorded AC signals are digitally filtered applying a band pass filter centered at 25 kHz with 1 kHz bandwidth. This reduces the total noise and makes possible to accurately measure very low voltage differentials. The envelope of the filtered AC signals is then digitally extracted by taking the absolute value using a Matlab routine. This process is non-linear and therefore creates high frequency artifacts, which are removed by applying a low pass filter with cut-off frequency of 100 Hz. The so-filtered envelope of the signals V_i and V_o is the actual peak voltage amplitude of the signals without any loss of information or distortion. Since R_m and R_t constitute a voltage divider, R_m is simply calculated from the relation $V_o/V_i = R_t/(R_m + R_t)$. For the range of void fraction values studied in this work (10^{-3}–10^{-1}), Maxwell's model (Maxwell, 1892) is chosen for void fraction determination from electrical impedance data. The final output of data reduction is several records of 60 s-long void fraction time series for different experimental conditions.