Chemical Engineering Science 112 (2014) 72–78

Contents lists available at ScienceDirect

Chemical Engineering Science

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

Friction factor of microbubbles in capillary tubes at low Reynolds numbers

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HIGHLIGHTS

- Rheological properties of microbubbles in capillary tubes are determined.
- Fanning friction factors of microbubbles in capillary tubes are measured experimentally in laminar region.
- Non-Newtonian Reynolds number can be used to describe Fanning friction of microbubbles.

ARTICLE INFO

Article history:
Received 4 January 2014
Received in revised form
22 February 2014
Accepted 15 March 2014
Available online 20 March 2014

Keywords:
Microbubbles
Capillary tube
Rheology
Fanning friction factor
Pseudoplastic behavior

ABSTRACT

The small size of microbubbles, along with their stability, has made them popular in many applications. Most of the applications involve the flow of microbubbles through capillary environments. In this study, the rheological behavior of microbubbles has been examined using their flow index in capillary tubes, in $Re < 50$. The flow indexes of microbubbles have been calculated from the experimental pressure drop measured along the capillary tube. Microbubbles presented pseudoplastic behavior. Flow index was only influenced by bubble void fraction and did not show any dependency on the geometrical conditions of the tube. From the measured pressure drops along the capillary tubes, the Fanning friction factor has been calculated. It has been found that, in low Re numbers, Poiseuille's equation underestimates friction factor. In this work, for the first time,the non-Newtonian Re was employed to calculate the Fanning friction factor for microbubbles suspensions in capillary tube. A very good agreement between experimental data and the linear equation of friction factor with non-Newtonian Re has been observed.

1. Introduction

The small size and stability of microbubbles have made them suitable for a wide variety of applications. The small size distribution of microbubbles has also made them better candidates for microflotation due to their higher surface area, as compared to conventional bubbles (Cassell et al., 1975). Higher surface area together with longer residence time in water will result in faster dissolution of oxygen in aerobic biochemical reactions (Terasaka et al., 2011). In addition, their small size and stability has made them applicable for drug delivery and in vivo ultrasound imaging in human body (Zhao and Middelberg, 2011; Pitt et al., 2004). To prevent drilling mud loss in drilling high permeability reservoirs, their stability has helped them to act as sealing agents (Ivan et al., 2001). Microbubbles have also been proposed as a means of leak-free injection with higher dissolution in saline aquifers for CO_2 sequestration (Xue et al., 2011). Most of these applications involve microbubble laminar flow in capillary environments, either in porous media or in human veins. Therefore, their properties in capillary environments in laminar flows play an important role in their utilization.

One of the factors which influence physical properties of microbubbles, especially in capillary environments, is the friction factor. For a single phase flow, in the laminar region, the Fanning friction factor is calculated by Poiseuille's equation as

$$f = \frac{16}{Re} \tag{1}$$

It has been indicated by several investigators that the presence of bubbles in a liquid increases the wall friction factor of the fluid in the laminar region (Valukina and Kashinskii, 1979; Burdukov et al., 1975; Valukina et al., 1979). These researchers have shown that the increase of wall friction factor, due to the presence of bubbles (Bubble size = 0.1–1 mm) in tubes (D = 15 mm), is more pronounced when the flow takes place in lower Reynolds numbers ($100 < Re < 1000$). Therefore, an underestimation is observed

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http://dx.doi.org/10.1016/j.ces.2014.03.012
0009-2509/

in the results of friction factors for bubbly flow obtained by Poiseuille's equation of friction factor (Eq. (1)). Investigations done on smaller bubble sizes (40 μm) have also confirmed the same underestimation by Poiseuille's equation in friction factor for microbubbles in the laminar region (Eq. (1)) (Chernyshev, 1997).

Recently, there has been a great concentration on the reduction of friction factor caused by microbubbles in tubes (Kawara et al., 2007; Serizawa, 2005). These investigations have shown that this decrease in friction factor moves the transition region from laminar to turbulent flow to higher Re numbers, as compared to single phase flow. However, these researches have not focused on the increase of friction factor in microbubbles at low Re numbers ($Re < 50$).

In this study, the Fanning friction factor of microbubbles was measured experimentally by means of the pressure drop along capillary tubes at low Re numbers ($Re < 50$). Besides friction factor, the flow index of microbubbles in each case was calculated from the measured pressure drops. In order to eliminate the underestimation of Poiseuille's equation for the friction factor, for the first time, a non-Newtonian Reynolds number (Metzner and Reed, 1955) is applied to microbubbles to reach a linear relationship between the Fanning friction factor and the Reynolds number.

2. Materials and methods

2.1. Generating microbubbles

To generate microbubbles, a modified high speed mixer was used, based on the microbubble generator introduced by Sebba (1994). In the generator introduced by Sebba, the impeller of the mixer consisted of a flat disc. However, the impeller employed in the present work was modified, as illustrated in Fig. 1, to create more agitation, generating microbubbles faster and at lower rpm of the mixer. This figure also shows the experimental set-up to measure the pressure drop along the capillary tube, the details of which will be presented in the next section.

In order to entrain air bubbles into the liquid, baffles were designed around the impeller by perforating the casing around the impeller. The perforation entrained bubbles into the liquid with the agitation of the impeller. The impeller was mounted 5 cm below the liquid surface to generate microbubbles. The speed of the impeller was found to affect generation of microbubbles. In low spinning speeds, the generated bubbles did not demonstrate sufficient stability. On the other hand, high spinning speeds generated bubbles with small bubble size distribution, which is not suitable for microstudies. In this study, 13,000 rpm was found to generate microbubbles with both good stability and size distribution.

As confirmed by previous investigators, the spinning time also affected the generation of microbubbles (Save and Pangarkar, 1994). The effect of spinning time was examined to find the optimum spinning time, which was found to be 5 min. Microbubbles generated with the spinning time of less than 5 min did not have sufficient stability. Spinning times beyond 5 min did not improve the stability of microbubbles. The generated microbubbles were found to be stable for at least 12 h, which was enough to complete a set of experiments.

In order to find the size distribution of the produced microbubbles, pictures were taken by a microscope (Scioptic LTM-402) with a maximum magnification power of 1000×. The size distribution and a sample picture are shown in Fig. 2. The size of the bubbles were found using a scale (arrow) in the taken pictures. The units of the scale were first measured by a known object. The bubbles were then analyzed with the defined scale. The produced bubble were found to have a narrow size distribution, between 1 and 7 μm. Size distribution of microbubbles is a parameter that depends on the method of microbubble generation. Fig. 2 shows a skew normal distribution with a positive skewness for the generated microbubbes. The same results have been obtained previously by several investigators (Wan et al., 2001; Tseng et al., 2006). The average size of microbubbles was calculated to be 2 μm.

2.2. Constituents of microbubble suspensions

In the experiments air was used as the gas phase and a surfactant solution was used as the liquid phase. The surfactant solution consisted of two surfactants. According to literature, a combination of a hydrophilic and a solid hydrophobic surfactant

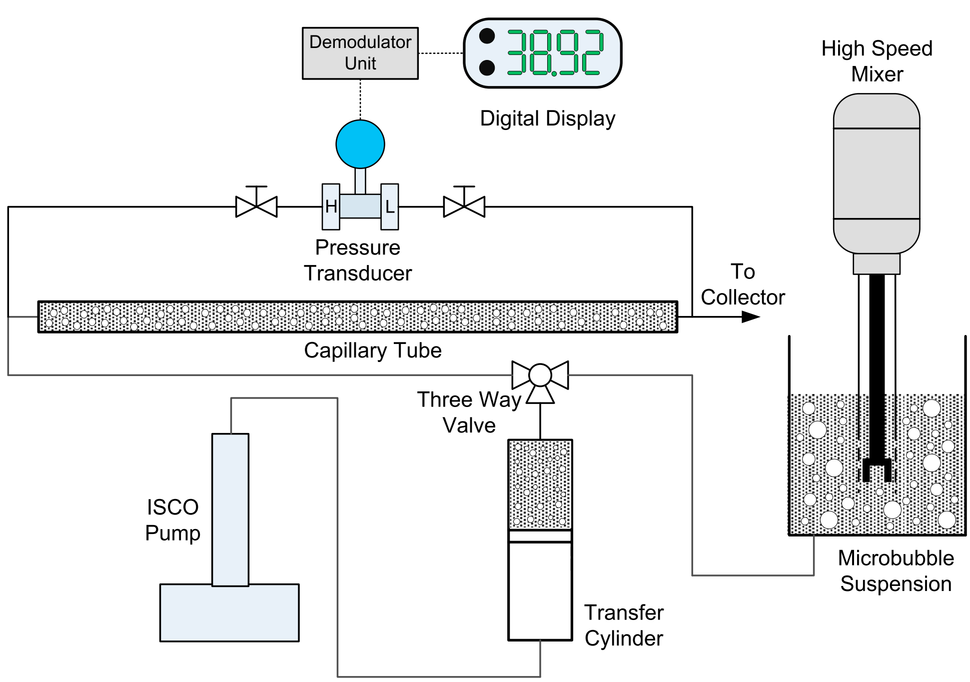

Fig. 1. Schematic diagram of pressure drop measurement set-up.