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Scaling of the bubble formation in a flow-focusing device: Role of the liquid viscosity

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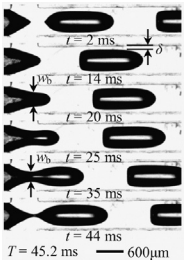
HIGHLIGHTS

- The bubble formation in a flow-focusing device is studied.
- The role of the liquid viscosity on bubble formation is investigated.
- A power-law relation between bubble size and operating parameters is obtained.
- A scaling law is proposed for the prediction of bubble size.

GRAPHICAL ABSTRACT



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ABSTRACT

The present work studies the bubble formation in viscous liquids with the viscosity ranging from 5 to 400 mPa s by using a high-speed digital camera. The experiment was carried out in a flow-focusing device with square cross-section of 600 × 600 μm. Results show that the viscous shear stress strongly influences the dynamics of bubble formation, including the shape and size of bubbles. The bubble size follows power-law relations with the gas flow rate, the flow rate and viscosity of the liquid phase respectively, indicating that bubbles formed in viscous fluids are controlled by a combination of squeezing mechanism and shearing mechanism. Therefore, the bubble size can be predicted by a power-law function depending on the flow rate ratio of gas and liquid phases φ representing the squeezing mechanism and capillary number Ca representing the shearing mechanism. In addition, the dynamics of bubble formation in viscous liquids in a flow-focusing device is also analyzed.

1. Introduction

In recent years, gas–liquid two-phase flow in microfluidics has been widely applied in various fields such as in materials synthesis, emulsion, chemical mixing and reaction (Ferrara et al., 2009; Hartman et al., 2010; Kashid et al., 2011; Seemann et al., 2012; Tadmor et al., 2011; Tumarkin et al., 2011; Utada et al., 2005). Among the regimes of the gas–liquid two-phase flow, the Taylor flow with the length of bubble larger than the channel width attracts more and more attentions due to the wide range of operating conditions, little liquid back-mixing and high monodispersities (Kreutzer et al., 2005; Li et al., 2011; Sobieszuk et al., 2012; Xu et al., 2008). Therefore, the control and predication of the Taylor bubble size are crucial problems for the application of microfluidic technique (Garstecki et al., 2006, 2005; Thorsen et al., 2001).

The bubble size is determined during its formation which is supposedly controlled by one of the two mechanisms (Garstecki et al., 2006; Thorsen et al., 2001): the squeezing mechanism or the shearing mechanism. Garstecki et al. (2006) proposed the squeezing mechanism for bubbles formed in T-junctions under low cappillary numbers, and insisted that bubbles are formed under the squeezing pressure. The frequency of the bubble formation is

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Table 1
Scales of the parameters of a and b in the literature.

a	b	Ref.
1	1	de Menech et al. (2008)
1	2	Fu et al. (2010a)
1.5	1.5	Garstecki et al. (2006)
0.64	0.32	van Steijn et al. (2007)

determined by the channel width and the liquid flow rate. In T-junctions, the bubble size is proportional to the flow rate ratio: $L/w = a + b\varphi$, in which L, w and φ represents the bubble length, channel width and flow rate ratio for gas and liquid phases, respectively; a and b are adjustable parameters relevant to the geometry of the channel. This mechanism was confirmed by many experiments as shown in Table 1. For the flow-focusing device, the bubble size can be predicated by a function of $L/w \propto \varphi^{\alpha}$, where α is an adjustable parameter related to the geometry of the channel (Christopher et al., 2008; Dietrich et al., 2008; Gupta and Kumar, 2010). This postulate was also identified by experiments with $\alpha \in (0.25{,}1/3{,}0.37{,}1)$ (Dang et al., 2013; Dietrich et al., 2008; Fu et al., 2010a; Ganan-Calvo and Gordillo, 2001; Garstecki et al., 2004, 2005; Lorenceau et al., 2006). The shearing mechanism is evidence that the bubble breaks up under the balance between the surface tension and viscous shear stress when the shear stress is large enough to deform the gas–liquid interface (Thorsen et al., 2001). The bubble size can be predicated by a power-law function with the capillary number Ca: $L/w \propto Ca^{\beta}$, where β is an adjustable parameter depending on the geometry of the microchannel. Some experiments were carried out to prove the supposition with $\beta \in (-1, -0.25)$ (de Menech et al., 2008; Fu et al., 2010b; Thorsen et al., 2001).

Although both the squeezing mechanism and shearing mechanism for bubble formation could estimate well the bubble size in corresponding experiments, they have significant divergence on evaluating the role of liquid properties during bubble formation. The squeezing mechanism supports that the effect of the liquid viscosity on the bubble formation is negligible. Further the shearing mechanism emphasizes that the liquid viscosity plays a key role on the bubble formation, as it affects the viscous shear stress exerted on the gas–liquid interface. In fact, analogous to the inconsistent arguments, there are also some incompatible experimental results. Pancholi et al. (2008) identified the significant role of the liquid viscosity on the bubble formation and observed that the bubble size was inversely proportional to the viscosity of the highly viscous liquids in T-junctions. Fu et al. (2011) also revealed that the way of bubble formation in non-Newtonian fluids was significantly different from that in Newtonian fluids, and they attributed the difference to the high viscosity of non-Newtonian fluids. In other experiment, Fu et al. (2009) observed a slight decrease of bubble size with the increase of the liquid viscosity, which was confirmed by Dang et al. (2013). In addition, Dietrich et al. (2008) even observed that the bubble size increased with the increase of the liquid viscosity.

Overall, understanding of liquid viscosity on the bubble formation in microfluidic devices remain confused: the role of the liquid viscosity on the bubble formation is significant revealed by the shearing mechanism but it is negligible evidenced by the squeezing mechanism. In addition, most of previous studies were carried out for bubbles formed in liquids with low viscosities. But the highly viscous fluids are encountered in many applications such as the reaction between gas and viscous liquids in chemical engineering, the transport of the highly viscous liquids in polymer engineering, the puffing of the materials in food engineering and the ferment processes in bioengineering (Chen et al., 2012; Cubaud and Mason, 2012; Frank et al., 2007; Nghe et al., 2011; Nie et al., 2008; Skurtys et al., 2008). Therefore, it is necessary to study the mechanism of bubble formation in highly viscous liquids.

This work aims to study the bubble formation in viscous liquids with the viscosity ranging from 5 to 400 mPa s. The effect of the liquid viscosity on the bubble formation is studied, and a correlation is proposed to predict the size of bubbles formed in viscous liquids in a flow-focusing device. At last, the mechanism for the effect of the liquid viscosity on the bubble formation is revealed.

2. Experimental procedures

The experiment was carried out in a square cross-sectional microchannel of 600×600 μm. The channel was fabricated in a polymethyl methacrylate (PMMA) plate by precision milling, and then sealed with another PMMA plate by screws. Stainless steel tubes ($d_i = 1$ mm) were used to connect the inlets and outlet of the microchannel to tygon tubes (ID = 1.02 mm), which were employed to transport fluids from the supplies to the microchannel. The gas and liquid flow rates were controlled respectively by syringe pumps (PHD 2000, Harvard Apparatus, America).

The dispersed phase was infused to the main channel, and the continuous phase to the two lateral channels to generate Taylor bubbles in the flow-focusing region as shown in Fig. 1a. It took at least 300 s to ensure that the flow was stable after a new flow condition was set. The scene of bubble formation was magnified by a microscope (ECLIPSE Ti–U, Nikon, Japan), and recorded by a high-speed digital camera (MotionPro Y5, IDT, USA). The highest frequency of the camera is 100 kfps (kilo frame per second), with a shortest exposure time of 1 μs. During the experiment, the freqency of the camera was adjusted adapting to the operating condition to obtain engough photographs in each period of bubble formation.

Nitrogen was used as the dispersed phase and a series of deionized water with glycerol solutions as the continuous phase. To ensure the constant viscosity during the experiment, the cold light (TI-DH Dia Pillar Illuminator 100 W) supplied by the microscope maintained no more than 5 s for every shooting. The viscosity of continuous phase was measured by Ubbelohde viscometer (iVisc, LAUDA, Germany). The surface tension σ of the continuous phase in air was measured by the pendant drop method (OCAH200, Data Physics instruments GmbH, Germany) and the contact angle θ of the continuous phases on a flat PMMA surface was measured in the same apparatus with a value about 70°. The density of the continuous phase was mearued using a pycnometer. The detailed physical properties for the continuous phase were listed in Table 2.

3. Results and discussions

The bubble size is mostly characterized by the length, radius or volume of the bubble. In this paper, the bubble volume V_b is adopted. In the light of the periodic process of bubble formation, the bubble volume can be obtained by a correlation of $V_b = Q_g/f$, where Q_g is the gas flow rate, f is the frequency for bubble formation, and the value f is an average for ten periods of bubble formation. In addition, dimensionless parameters of the capillary number Ca ($Ca = u\mu/\sigma$) and the Reynolds number Re ($Re = \rho uw/\mu$) are defined to identify the relevant forces for the bubble formation. The adopted variations are dimensionless to eliminate the dimensional effect.

3.1. Dynamics of bubble formation

The dynamics of bubble formation is depicted in a series of viscous liquids as illustrated in Fig. 1. Under low capillary numbers