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Rising behavior of single bubble in infinite stagnant non-Newtonian liquids

Xiaofei Xu, Ju Zhang, Fengxia Liu, Xiaojuan Wang, Wei Wei, Zhijun Liu*

R&D Institute of Fluid and Powder Engineering, Dalian University of Technology, Dalian 116024, China

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ABSTRACT

This work is an experimental study of the rising behavior of single air bubbles in infinite stagnant non-Newtonian liquids. Aqueous solutions of carboxymethyl cellulose (CMC) are selected to study the effect of rheological properties. The high speed photography is employed to record the bubble motion in CMC solutions. The bubble size, rising trajectory, bubble shape and velocities are determined by digital image processing technique. As expected, the rheological properties have great influence on the rising behavior of single bubble. In the less concentrated CMC solutions, the bubble rising process can be divided into three stages according to spatial evolution of bubble shape. The deformation changes the trajectories of rising bubbles and bubble hydrodynamics. As the solution concentration increases, the transitional stage gradually disappears. In the most concentrated CMC solution, the first continuous shape flattening stage is directly followed by a rising process with bubble shape basically constant, the rectilinear path and constant rising velocity. Dimensional analysis is performed to formulate a general dimensionless correlation for the deformation and motion of bubbles in infinite liquids by considering the rheological properties.

1. Introduction

The behavior of bubbles in non-Newtonian fluids is of particular interest for many areas of chemical engineering operations. Typical examples of applications include polymer devolatilization, wastewater treatment, fermentation, cavitation, bubble column, composites processing, plastic foam processing, etc (Duran et al., 2016; Passos et al., 2015; Amimia et al., 2013; Kilonzo and Margaritis, 2004; Brujan and Williams, 2006). There are strong academic and industrial motivations towards developing a comprehensive understanding of the bubble motion phenomena involved in these processes, since they are closely related with the efficiency of mass and heat transfer processes, and chemical or biological reactions. However, compared with the understanding of bubbles in Newtonian fluids, fundamental knowledge is still missing about the rising behavior of bubbles in non-Newtonian fluids.

Due to the complex flow mechanism of bubble phenomena and the influence of the rheological properties of the liquid, a complete theoretical analysis of the bubble rising behavior is still impossible. Numerous investigations available in the literature were essentially experimental information on the rising behavior of single bubbles due to the difficulties in predicting the characteristics of the multiple bubbles, although the bubble populations are ubiquitous in the practical applications and the interactions between bubbles are essential. Previous studies related to the single bubble rising behavior were focusing on the parameters, such as bubble shape, rising path and terminal rising velocity for the bubble with different bubble size and the ambient non-Newtonian liquids with different rheological properties. These parameters are important in sizing reactors and processing system involving bubbles. Amirnia et al. (2013) carried out experiments to study the influence of the bubble size on the terminal rise velocity and shape of small air bubbles (bubble volumes range from 1 µl to 4000 µl). Figueroa-Espinoza et al. (2008) investigated the effect of confinement on the bubble motion of a single bubble in silicon oil and found that the Reynolds number and the confinement had great influence on the bubble ascending trajectory and drag coefficient. Böhm et al. (2014) also studied the rising behavior of single bubbles in narrow rectangular channels. They found that the rheology of the liquids had significant influence on the rising behavior. In the shear-thinning liquid, the bubbles followed mostly a straight rising trajectory with negligible oscillations and the distance between channel walls mainly had an influence on the terminal rise velocity. Fujiwara et al. (2004), Sanda et al. (2007) and Zaruba et al. (2007) applied two cameras arranged perpendicular to each other to obtain a 3D structure of the bubble and the rising path, providing a more reliable way to evaluate the bubble shape and rising path. Funfschilling and Li (2006) studied the influence of the injection period on the bubble terminal rise velocity and the

* Corresponding author.
E-mail address: liuzj@dlut.edu.cn (Z. Liu).

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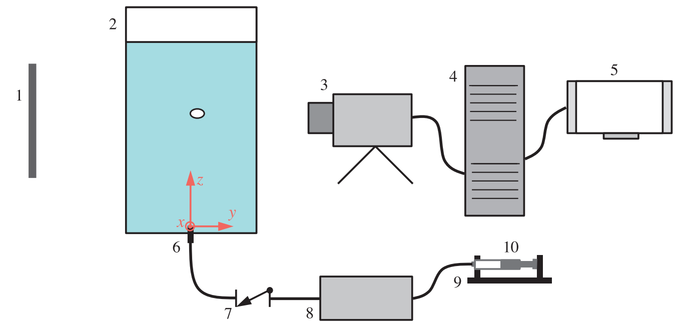

Fig. 1. Sketch of the experimental apparatus.

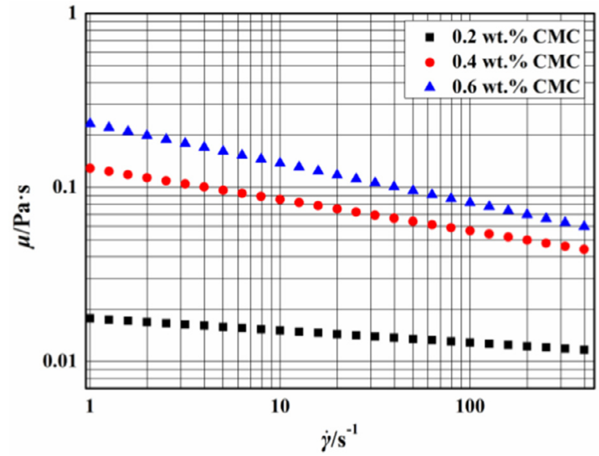

Fig. 2. Viscosity as a function of shear rate for CMC solutions at different weight percentages.

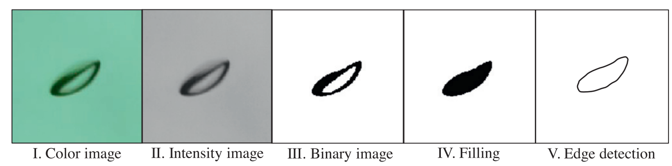

Fig. 3. Procedure for detecting the edge of the bubble.

bubble shape in different non-Newtonian fluids (CMC solutions—inelastic shear thinning fluid; PAAm solutions—elastic shear thinning fluid), and pointed out that the viscoelastic characteristics of the non-Newtonian fluids and the inject period had great influence on the bubble terminal rise velocity and shape. In particular, a more detailed review on the effects of fluid's viscoelasticity on bubble shape and velocity can be found in the book of Chhabra (2007). To the best of our knowledge, very few investigations on the evolution of bubble shape, rising path and velocities in non-Newtonian liquids, as well as the relationship between these parameters have so far been reported in the literature.

The purpose of this paper is to investigate the behavior of single air bubbles issued from a submerged nozzle in non-Newtonian CMC solutions. The instant images of bubble motion are recorded by using high speed photographic technique. With the benefit of digital image processing technique, parameters such as bubble size, rising path as well as the spatial evolution of bubble shape and velocities with height are obtained. The variations of parameters and the relationship between these parameters are discussed. The bubble deformation and motion are also characterized by Reynolds number, Weber number and Morton number based on dimensional analysis.

2. Materials and methods

2.1. Experimental set-up and procedure

The experimental set-up is shown in Fig. 1. Experiments were carried out in a plexiglass tank with a height of 600 mm and an interior horizontal cross-sectional area of 300 × 300 mm^2. The tank is large enough to neglect the wall effects on the bubble motion. The top of the tank was open to atmosphere. Each experimental run started by filling the tank with the fluid up to 500 mm above the nozzle's top edge. Nozzles with different inner diameter D_i=1.1, 1.5 and 2.0 mm were used in the experiments. A ruler was aligned with the nozzle as a referential dimension. Air delivered by a syringe pump (WZS-50F2, Zhejiang University Medical Instrument Co., Ltd) was injected through the nozzle to form bubbles. A check value was introduced to prevent the liquid from running back to the syringe.

A Photron FASTCAM SA4 high-speed CMOS camera connecting to the computer via gigabit Ethernet was used to monitor the motion of the bubbles formed by the nozzle. LED panel light was positioned on one side of the tank, and the camera was placed on the opposite side to capture the bubble shape projected on the vertical plane (*x, z*). The light source could provide uniform backlight to guarantee the profiles of bubbles clearly recorded by the camera. The camera was equipped with a 60 mm f 1: 2.8D Nikon AF Micro-Nikkor lens. For the present experiments, images were recorded at a frame rate of 2000 Hz with a resolution of 1024 by 1024 pixel which provided a field view of 70 × 70 mm.

In addition, the gas flow rate was fixed at 20 ml/h during the experiments. It is low enough to ensure that the bubble volume at detachment was controlled by a static balance between the surface tension and buoyancy. In addition, the distance between the successive bubbles was far enough to neglect the interaction. All the runs were conducted at atmospheric pressure and ambient temperature conditions (18±1 °C). CMC solution was used for non-Newtonian fluid and its weight percentage was set at 0.2%, 0.4% and 0.6%. The viscosities of the solutions were measured by a coaxial cylinder rheometer (BROOKFEILD R/S-CC) in a shear rate range from 1 to 500 l/s. Fig. 2 shows the viscosity of CMC solutions at different shear rate. All CMC solutions had a shear-thinning rheological behavior following an Ostwald-de Waele approach. Viscoelasticity is also an important property for CMC solutions. The CMC solutions behave as viscoelastic materials at high concentration, especially for the case when the apparent viscosity exceeds 1 Pa·s (Ghannam and Esmail, 1997; Benchabane and Bekkour, 2008). Therefore, the viscoelastic effects on the bubble rising behavior can be neglected in the present study. The surface tensions were measured by Krüss tensionmeter K100. To prove the significant effect of non-Newtonian rheology on the bubble rising behavior, the same experiments were also conducted in deionized water. Physical properties and rheological parameters of different weight percentage of CMC solutions and deionized water are listed in Table 1.

2.2. Image processing

A scheme was developed in the MATLAB environment to automatically detect the interface and compute various bubble characteristics. Fig. 3 shows the process to obtain the edge of the bubble. Firstly, the color image captured by the camera was converted to the grayscale intensity image. Subsequently, a global threshold computed by Otsu's method (Otsu, 1979) was used to convert the intensity image to the binary image. Finally, the binary image was denoised and the hole in the binary image was filled to obtain the outline of the bubble.