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Experimental studies on the shape and motion of air bubbles in viscous liquids

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ABSTRACT

This paper is concerned with single bubble dynamics over a wide experimental data set in stagnant water and glycerol aqueous solution. The bubble trajectory in three-dimensional space was deduced by analyzing the bubble characteristics in two-dimensional plane captured by a single high-speed camera and the bubble trajectory in the water was ascertained by this method. Bubble shape, trajectory and terminal velocity in water, which closely related and strongly influenced by each other, are not only determined by bubble diameter, but also dramatically influenced by nozzle diameters, i.e. the bubble dynamics is sensitive to the disturbance of detachment process. The bubbles remain spherical and rise up rectilinearly when their diameters are small enough. Otherwise, the bubbles begin to deform to ellipsoidal, oblate ellipsoidal, or cap shape, with surface wobbling strongly, and proceed in a zigzagging, helical, nearly zigzagging or helical motion. In this case, periodic oscillations occur at the velocity and aspect ratio of the bubbles. Moreover, there exists an inverse function relationship between them, a large deformation, i.e. a small aspect ratio will lead to a high velocity and vice versa. However, in glycerol aqueous solution, bubble shape, trajectory and velocity is stable under a certain bubble diameter. In the water, bubble shape is mainly dominated by the inertial force and surface tension, and the influence caused by the viscous force could be neglected. The influence of gravity should be taken into consideration if the bubble diameter is large enough. However, the bubble shape is mainly dominated by the viscous force, surface tension and inertial force in the glycerol aqueous solution. Available correlations in the literature do not give fully satisfactory results in predicting aspect ratio, and new correlations combined Weber number with Eötvös number and Weber number with Reynolds number were proposed to correlate bubble shape in water and glycerol aqueous solution, respectively, showing that a good relevance between them in the range of the present experimental data set.

1. Introduction

A lot of work had been performed to study the single bubbles rising behavior in stagnant liquids, which revealed the key parameters that affect the gas–liquid two-phase flow are bubble size, shape, trajectory, and velocity [1–3]. It has guiding significance for in-depth study of bubble dynamics in gas–liquid two-phase flow to solve many engineering problems. Researches on the bubble dynamics have been conducted for decades, and many achievements have been accomplished by using theoretical analysis [4–8], experimental measurement [9–14] and numerical simulation [15–20], showing that the interactions between gas and liquid, i.e. viscous force, gravity, surface tension, and inertial force, mainly dominate the behavior of bubble dynamics.

The bubble shape, which is a quite important parameter of the bubble dynamics, is mainly related to the physical properties of fluid, bubble size, bubble velocity, etc. Since the regime map of the bubble shape, aimed at describing the relationship between bubble shape and dimensionless parameters Eötvös number ($Eo = gd^2(\rho_l - \rho_g)/\sigma$), Reynolds number ($Re = \rho_l V_T d/\mu_l$) and Morton number $\left(Mo = (\rho_l - \rho_g)g\mu_l^4/\sigma^3\rho_l^2\right)$ has been proposed by Grace [1], various researchers [1,3,17,18,21,22] have carried out plenty of studies on the bubble shape in different fluids and their results mostly coincide with the regime map of the bubble shape. Almost all the studies adopted aspect ratio, E, defined as the ratio of minor to major axis of the bubble, i.e. the ratio of height to width, to describe the bubble shape, and successfully obtained a series of empirical correlations by correlating aspect ratio to Eötvös number [23,24], Weber number $\left(We = \rho_l V_T^2 d/\sigma\right)$ [23,25–28] and Tadaki number ($Ta = ReMo^{0.23}$) [29–31], which indicates that it is reasonable to correlate aspect ratio as a function of different

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Nomenclature

a	undetermined coefficients (–)
b	undetermined coefficients (–)
c	undetermined coefficients (–)
d	bubbles diameter (mm)
Do	inner diameter of nozzle (mm)
e	undetermined coefficients (–)
E	aspect ratio (–)
Eo	Eötvös number (–)
g	gravitational acceleration (m/s^2)
h	bubble height (mm)
IL	dimensionless number (–)
Mo	Morton number (–)
n	number of data points (–)
r	correlation coefficient (–)
Re	Reynolds number (–)
SSE	residual sum of squares (–)
StD	standard deviation (–)
T	Temperature (°C)
Ta	Tadaki number (–)
V	bubble velocity (m/s)
V_h	bubble horizontal velocity (m/s)
V_T	bubble terminal velocity (m/s)
V_v	bubble vertical velocity (m/s)
w	bubble width (mm)
We	Weber number (–)
t	time (s)
x	bubble horizontal position (mm)
z	distance above the nozzle surface (m/s)

Greek symbols

μ	dynamic viscosity (kg/s^2 m)
ρ	density (kg/m^3)
σ	surface tension (N/m)

Subscripts

g	pertains to the gas phase
h	pertains to the horizontal position
l	pertains to the liquid phase
v	pertains to the vertical position

dimensionless parameters. Meanwhile, bubbles rising in liquids performed rectilinear, zigzag or helical motions [32–35]. Saffman [36] studied the motion of air bubbles in water and pointed out that bubbles always keeps rectilinearly up with its diameter less than 1.4 mm, otherwise, it is sensitive to disturbance and the trajectory changes from linear to zigzag or helical. Benjamin [37] studied the ratio of the helical radius of the bubble motion to the bubble equivalent radius. Similarly, de Vries et al. [33] also got this parameter by experimental study, but the result was almost 23 times greater than Benjamin's. Brücker [38] investigated the bubble shape oscillation and trajectory transition process, which indicates that, the bubble rises rectilinearly in the initial rising process. After the bubble rises more than 25 mm, the oscillating of bubble surface is strong and the bubble trajectory changes from linear to helical. Ellingsen and Risso [39] studied the bubble motion characteristics in quiescent water. Tomiyama et al. [11] investigated the bubble trajectories and the rising process in different fluid, and the results showed that the bubble formation process has significant influence on the trajectory, deformation and velocity. The above research work revealed that the bubble formation process may be the reason leading to different rising trajectories. Also, for the same size of bubbles, they show different trajectories during the rising process, suggesting that the bubble rising process is influenced by different factors, which are far from fully understood. Therefore, further work should be carried out to reveal the mechanics. In addition, the rising velocity is also one of the fundamental parameters in gas–liquid two-phase flow. Although a lot of research work [11,31,40–43] has been made on the prediction of bubble terminal velocity, it is very difficult to predict the bubble terminal velocity accurately, due to the fact that the bubble rising terminal velocity is related to many factors such as fluid physical properties, liquid pollution degree, bubble size, bubble shape, bubble trajectory and injection mode. The study of Clift et al. [2] showed that, the contaminant in the liquid affect the interface between the bubble and liquid, which has a great impact on the bubble terminal velocity. Rodrigue et al. [44] also studied the influence of the surfactant on the bubble terminal velocity and pointed out that the surfactant could promote the formation of bubble rigid surface, leading to the drag increasing and due to the result that the bubble rising terminal velocity less than that of the same diameter in water. Aybers and Tapucu [45,46] measured the bubble instantaneous velocity in water, showing that after the bubble detached the nozzle for a certain distance, the bubble velocity reached the maximum value, and then decreased slowly, finally reached stable. The research by Tomiyama et al. [11] showed that the bubble terminal velocity is closely related to the ways of bubble injection, which are divided into "controlled injection" and "direct injection". Celata et al. [47,48] studied bubble rising velocity under different injection modes in pure water, polluted water and pure FC-72 liquid. The result indicated that the purity of liquid has a great effect on the bubble terminal rising velocity and the bubble shape. The bubble aspect ratio interacts with the bubble terminal velocity each other. Okawa et al. [24] researched the motion characterization of spherical and ellipsoidal bubble diameter within 0.6–3.7 mm in room and high temperature water, and confirmed that the bubble velocity is affected by the way of injection in room temperature water. In high temperature water, the way of injection also affects the bubble velocity, but the effect of the initial deformation under different ways of injection to the bubble velocity decreases compared in room temperature water. Rodrigue et al. [44] showed that the bubble terminal velocity and the diameter are in the linear relationship under different concentration glycerin water liquid. At the same time, because of the liquid viscous force, the bubble terminal rising velocity decreases with the viscosity increasing.

In this study, a single bubble dynamics was investigated experimentally in water and glycerin water solution using the high-speed photography instrument combined with digital image processing algorithm. The aim of this paper is to discuss the bubble dynamic behavior in different liquid phase, including water and glycerol aqueous solution, to confirm the influence of Mo, Eo, Re, We and other dimensionless numbers on the bubble characteristics. It mainly focuses influence of buoyancy, inertial force, surface tension, viscosity, nozzle diameter, and physical properties of the continuous phase on the bubble shape, trajectory and velocity.

2. Experiment

2.1. Experimental apparatus and procedure

The experimental apparatus is shown schematically in Fig. 1.

The experiments were carried out in a rectangular organic glass tank filled with different liquids, water or glycerin aqueous solution. The width, depth and height of the tank were 150, 150 and 500 mm, respectively. The stainless steel nozzle with a flat opening was installed at the center of the bottom of the tank. The distance