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Experimental studies on the terminal velocity of air bubbles in water and glycerol aqueous solution

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ABSTRACT

Terminal rising velocity of a single bubble in stagnant water and glycerol aqueous solution was studied by the techniques of high-speed photography and digital image analysis. The results can be summarized as follows: In water, bubble terminal velocity increases while aspect ratio decreases almost linearly in the region where $d < 0.83$ mm. Then, both terminal velocity and aspect ratio begin to show a widely scattered trend with the bubble diameter in the range 0.83–6 mm. Finally, the level of scattering tends to be weak and the terminal velocity increases gradually while the aspect ratio remains relatively stable when $d > 6$ mm. In the surface-tension-dominated regime, the aspect ratio of a single bubble varies significantly with the value fluctuating from 0.4 to 0.99. The aspect ratio should be taken into account with the bubble diameter when predicting the terminal velocity. In the inertia-dominated regime, the terminal velocity increases gradually with increasing the bubble diameter while their aspect ratios vary between 0.4 and 0.7. In the glycerin aqueous solution, as a whole, the terminal velocity increases with bubble diameter and the trend of the bubble velocity does not show a scattered behavior. In water, the most accurate model for predicting terminal velocity throughout the investigated range is given by Tomiyama et al. (2002), and then followed by Ishii and Chawla (1979).

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1. Introduction

Gas–liquid two-phase flows are widely encountered in many industrial processes, such as power, metallurgical and environmental engineering [1–5]. In gas–liquid two-phase flows, bubble dynamics, especially the bubble shape and rising velocity, are key parameters that affect the behavior of the gas–liquid two-phase flow, such as void fraction, gas residence time and gas–liquid interface transferring properties. Substantial work, including theoretical [6–10], experimental [11–16] as well as numerical attempts [17–20], have been done to improve the understanding of bubble dynamics in their great diversity.

In stagnant liquid, the rising velocity of a single bubble is mainly dominated by the buoyancy and drag forces. The balance of buoyancy and drag forces will be reached and bubble will ascent at a nearly constant velocity, i.e., the terminal ring velocity V_T, after approaching a steady state. In this case, we have:

$$(\rho_l - \rho_g)g\frac{\pi d^3}{6} = C_D\frac{1}{2}\rho_l V_T^2\frac{\pi d^2}{4} \tag{1}$$

where C_D is the drag coefficient. By solving the above equation, we have:

$$V_T = \sqrt{\frac{4d(\rho_l - \rho_g)g}{3\rho_l C_D}} \tag{2}$$

Therefore, the bubble terminal rising velocity can be obtained by available terminal velocity models evaluated directly or by solving Eq. (2) when drag coefficient is known.

Up to now, a lot of work has been done to directly predict the single bubble terminal velocity in viscous liquids [12,21–26], which is summarized in Table 1. In addition, a lot of attempts, which are summarized in Table 2, have been done to calculate the drag coefficient C_D in terms of four dimensionless groups, generally the Morton number ($Mo = (\rho_l - \rho_g)g\mu_l^4/\sigma^3\rho_l^2$), Eötvös number ($Eo = gd^2(\rho_l - \rho_g)/\sigma$), Reynolds number ($Re = \rho_l V_T d/\mu_l$) and Weber number ($We = \rho_l V_T^2 d/\sigma$) [27–33].

It is very difficult to predict the bubble terminal velocity accurately due to the fact that the bubble rising velocity is related to many factors such as fluid physical properties, liquid pollution degree, bubble size, bubble shape, bubble trajectory and injection mode, etc. The study of Clift et al. [7] showed that, the contaminant in liquids affects the gas–liquid interface, which has a great impact on the bubble terminal velocity. Also, Rodrigue [34] studied the

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Nomenclature

$B(x, y)$	background image, Pixel
c	correlation coefficient, –
C_D	drag coefficient, –
d	bubble diameter, mm
E	aspect ratio, –
Eo	Eötvös number $gd^2(\rho_l - \rho_g)/\sigma$, –
$F(x, y)$	output pixel grayscale value, Pixel
g	gravitational acceleration, m/s^2
h	bubble height, mm
$I(x, y)$	result image of subtracting, Pixel
Mo	Morton number $(\rho_l - \rho_g)g\mu_1^4/\sigma^3\rho_1^2$, –
N	number of data points, –
$O(x, y)$	object bubble image, Pixel
Re	Reynolds number $\rho_l V_T d/\mu_1$, –
StD	standard deviation, –
t	time, s
T	temperature, °C
T_h	threshold value
v	bubble instantaneous velocity, m/s
v_x	bubble instantaneous horizontal velocity, m/s
v_y	bubble instantaneous vertical velocity, m/s
V	bubble instantaneous velocity in terminal condition, m/s
V_T	bubble terminal velocity, m/s
V_x	bubble horizontal velocity in terminal condition, m/s
Vy	bubble vertical velocity in terminal condition, m/s
w	bubble width, mm
We	Weber number $\rho_1 V_T^2 d/\sigma$, –

Greek symbols

$\Delta\rho$	density difference, kg/m^3
μ	dynamic viscosity, kg/s^2 m
ε	mean error, –
ρ	density, kg/m^3
σ	surface tension, N/m

Subscripts

g	pertains to the gas phase
l	pertains to the liquid phase
x	pertains to the horizontal position
y	pertains to the vertical position

influence of the surfactant on the bubble terminal velocity and pointed out that the surfactant could promote the formation of a rigid gas–liquid interface, which will lead to an increased drag force resulting in lower terminal rising velocity than that with the same diameter in pure water. Aybers and Tapucu [35,36] measured the bubble instantaneous velocity in water and the results showed that the instantaneous velocity reaches the maximum value after detaching from the nozzle for a certain distance, and then decreases very slowly. Sam et al. [37] measured the axial velocity profiles of single bubble in water/frother solutions and found that the velocity increases rapidly first and then decreases continuously over 4 m in the absence of frother. In the presence of frother, a third stage was observed with a constant (terminal) velocity. Zhang et al. [38] studied single bubble velocity profiles for a 0.8 mm diameter bubble in solutions of Triton X-100 by numerical simulation and the results were similar and consistent with the experimental data. The authors attributed this behavior to the progressive accumulation of impurities at the bubble interface along the rising path. Therefore, the concept of terminal velocity becomes questionable if contamination occurs. However, this would be of little practical interest if we just want to study the accuracy of the available terminal velocity models rather than the influence of the contaminants on velocity profiles. The research of Tomiyama et al. [12] showed that the bubble terminal velocity in water is closely related to the method of the bubble injection, which can be divided into "controlled injection" and "direct injection". Celata et al. [39,40] studied the bubble rising velocity by using the above mentioned injection modes in pure water, polluted water and pure FC-72 liquid. The results indicated that the purity of the liquid has a great effect on the bubble terminal rising velocity and the bubble shape. In addition, the bubble aspect ratio was found to be related to the terminal velocity each other. Okawa et al. [41] studied the motion of spherical and ellipsoidal bubbles whose diameters vary from 0.6 to 3.7 mm in water at room and high temperatures. It is confirmed that the bubble velocity is affected by the method of injection in water at room temperature. At high temperature, the method of injection also affects the bubble velocity with less extension. The study of Rodrigue [34] showed

Table 1
Correlations for bubble terminal velocity.

Investigator	Correlations	Remarks
Stokes [21]	$V_T = \frac{1}{18}\frac{\rho_l - \rho_g}{\mu_l} g d^2$ (3)	For small bubbles
Davies and Taylor [22]	$V_T = 0.707\sqrt{gd}$ (4)	For large bubbles without consideration of viscosity and surface tension
Haberman and Morton [23]	$V_T = \frac{1}{18}\frac{\rho_l - \rho_g}{\mu_l} g d^2 \left[\frac{3\mu_l + 3\mu_g}{2\mu_l + 3\mu_g}\right]$ (5)	For small bubbles considering the effect of the inherent circular flow within the bubble
Mendelson [24]	$V_T = \sqrt{\frac{2\sigma}{d(\rho_l + \rho_g)} + \frac{(\rho_l - \rho_g)}{\rho_l}\frac{gd}{2}}$ (6)	For intermediate-large bubbles in pure liquids
Jamialahmadi et al. [25]	$V_T = \frac{U_H U_M}{\sqrt{(U_H)^2 + (U_M)^2}}$ (7)	For bubbles in pure liquids over a wide range of gas–liquid properties. In Eq. (7), U_H equals to the V_T in Eq. (5) and U_M equals to the V_T in Eq. (6)
Fan and Tsuchiya [26]	$V_T = (V_{T1}^{-n} + V_{T2}^{-n})^{-1/n}$ (8) $V_{T1} = \frac{\rho_l g d^2}{K_b \mu_l}$ (9) $V_{T2} = \sqrt{\frac{2q\sigma}{d\rho_l} + \frac{gd}{2}}$ (10) $K_b = \max(12, K_{bo} Mo^{-0.038})$ (11)	For bubbles in both pure and contaminated systems. In Eqs. (8)–(11), K_{bo} is equal to 14.7 for aqueous solution and 10.2 for organic mixtures or solvents; n is equal to 1.6 for purified liquids and 0.8 for contaminated liquids; q is equal to 1.2 for single liquid and 1.4 for multi-liquids
Tomiyama et al. [12]	$V_T = \frac{\sin^{-1}\sqrt{1-E^2} - E\sqrt{1-E^2}}{1-E^2}\sqrt{\frac{8\sigma}{\rho_l d}E^{4/3} + \frac{\Delta\rho g d}{2\rho_l}\frac{E^{2/3}}{1-E^2}}$ (12)	For bubbles in pure and contaminated Newtonian liquids

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