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Experimental study of bubbling regimes on submerged micro-orifices

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ABSTRACT

The dynamic bubble behaviors on submerged micro-orifices are investigated experimentally. The orifice diameters are within the range of 0.11–0.24 mm, and the range of gas flow rate is between 0.167 and 25 ml/min. The experimental data were recorded using a high-speed camera, and images were analyzed with the help of MATLAB. The bubble formation processes on the submerged micro-orifices show some new and different dynamic behaviors, such as multi-bubble coalescence, and the alternate appearance of paring and single bubbles. At low Bond numbers (variation in the orifice radii), with an increase in Weber number (variation in the gas flow rate), a bubble first emerges during a single period stage followed by a multi-bubble coalescence stage. The bubble coalescence processes can be divided into five cases according to the number of coalescing bubbles. With an increase in the gas flow rate, it was found that the complete bubble detachment time and the detachment volume increase. Meanwhile, based on an analysis of the bubble aspect ratio and rising velocity, departing bubbles were shown to suffer stronger oscillations. At a higher Bond number, a bubble first appears in a single form, followed by a period of double bubble behaviors, and back to a period of single form. Finally, a bubbling regime map was constructed to describe the dynamic behaviors of bubbles under the conditions of different Weber and Bond numbers.

1. Introduction

The bubble formation and dynamic on submerged orifices play a significant role in many of the processes in chemical, nuclear, and biomedical systems. The applications of gas-liquid contacting equipment include bubble columns, slurry reactors, and sparged vessels. Therefore, wide investigations into dynamic bubbling behaviors and bubbling regimes have been reported.

The phenomena of bubble formation, growth, detachment, and bubbling regimes on orifices of the millimeter scale (an orifice diameter of greater than 0.3 mm) have been broadly explored through experimental observations, theoretical studies, and numerical simulations.

Dynamic bubble characteristics have been investigated experimentally in many studies, including the bubble size, bubble rising velocity, and bubble regimes, for a given set of conditions (e.g., liquid properties and gas flow rate). It was found that on an orifice with a radius of 0.0260–0.0975 cm, the liquid viscosity has a major effect on the bubble volume. With the augmentation of liquid density, the bubble rising velocity increases and the bubble size decreases [1]. In addition, in a single orifice with a diameter of 1 mm, it was found that the bubble volume increases by more than half with an augmentation of the contact angle (from 68° to 110°) [2]. These two studies focused on the bubble characteristics under different material parameters. Regarding the bubbling regimes, Piassi [3] observed that there are two main types, i.e., the bubble contraction stage and the continuous bubble growth stage, related to the air flow rate and tube length. In addition, McCann [4] found that the bubbling regimes are mainly determined based on the gas flow rate and chamber volume. Single regimes (true single bubbles and bubble pairings) occur under a low gas flow rate, whereas double regimes (double bubbling with a delayed release, double bubbling, and double pairing) occur under a higher gas flow rate and larger chamber volume. These investigations discuss the bubbling regimes in detail and can be used as references for predicting the bubbling regimes. In addition, Tsuge et al. [5] conducted some different investigations regarding the bubble formation from the downward nozzles in a liquid. Their results indicate that the bubble volume is influenced by the orifice angle, nozzle diameter, and gas flow rate.

Based on the results of experimental observations, various theoretical models have been developed to describe the bubble dynamic characteristics [6–16]. Bari et al. [6] compared the experimental results with the calculations using a Young-Laplace equation, which showed a good agreement. Zhang et al. [7] investigated the bubble departing periods (from a single period to a triple

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Nomenclature

Bo	Bond number
C	coalescence bubble
D_0	orifice diameter
F_B	buoyancy force
F_D	drag force
F_I	inertial force
F_M	momentum force
F_P	hydrostatic force of the gas and liquid phase
F_σ	surface tension force
g	gravitational acceleration
h	distance between the top of the bubble and water surface
H/W	bubble aspect ratio
L	leading bubble
M	bubble mass
P	point
P_a	point a
P_b	point b
Q	gas flow rate
r	directions of coordinate axes
R_0	orifice radii
r_0	radius of the bubble contact line
T	trailing bubble
t	time
U	bubble rising velocity
V	bubble volume
We	Weber number
z	directions of coordinate axes

Superscripts

$*$	Dimensionless quantity

Subscripts

d	detachment
f	formation
g	gas
l	liquid
p	period
w	waiting

Greek symbols

δ	bubble height
θ_0	contact angle
ρ	density
σ	surface tension

period) at an orifice with a 2 mm diameter, and established a model that can be used to predict the bubble size under relatively low airflow rate conditions. Terasaka et al. [8] developed a model to elaborately describe the bubble behaviors in a viscous liquid undergoing field stress. Byakova et al. [9], Ramakrishnan et al. [10], Satyanarayan et al. [11], Khurana et al. [12] and Jamialahmadi et al. [13] experimentally investigated the effects of the control parameters on the dynamics of bubble formation, and developed a theoretical model for predicting a bubble evolution. It was found that the bubble frequency varies considerably for different orifices (with diameters of 1, 2, and 3 mm), pool heights (70, 90, and 150 mm) and gas flow rates (4.0–8.0 ml/s). The bubble frequency increases with the augmentation of the gas flow rate, but decreases with the augmentation of orifice diameters and pool heights [9]. It was also observed that under a constant gas flow rate, the increasing gas flow rate, chamber volume, orifice diameter, surface tension, and liquid viscosity enlarge the bubble detachment volume. However, under constant pressure conditions, the bubble detachment volume only increases with the augmentation of pressure [10–12]. In addition, a nonlinear correlation, based on the Radial Basis Function (RBF) neural network architecture, was used to predict the bubble size [13]. The model proposed by Pinczewski [14] is based on a modified Rayleigh equation for bubble formation, and shows good agreement with previous experimental data in many aspects, such as the bubble growth rate, formation time, chamber pressure fluctuations, and bubble shape. Das et al. [15] proposed a mechanistic model considering the evolution of non-spherical bubbles at the orifice mouth, which shows reasonable agreement between the model prediction and experimental results. Wraith [16] investigated the bubbling mechanism through a single orifice (from 3.17 to 9.53 mm in diameter) submerged in an inviscid liquid and applicable at a high gas injection rate. The bubbling process was divided into two stages: hemispherical bubble expansion at the initial stage, and transformation into a spheroid at the second stage. A great deal of theoretical progress has been made in predicting bubble behaviors, and significant agreement between a theoretical prediction and experimental results has been shown. However, the global characteristics of a bubble formation are complex, and each model is only fit for certain conditions, and therefore further research is needed.

Through numerical simulations, Islam et al. [17,18], Georgoulas et al. [19], Ma et al. [20], and Zhang et al. [21] have applied a combined volume-of-fluid and continuum surface tension (VOF-CSF) method to investigate a dynamic bubble formation. The changes in bubble shape over time have been validated through experimental observations available in the literature [17]. A higher Bond number can accelerate the bubble coalescence [18]. In addition, the bubble detachment diameter and detachment time at an orifice (diameter of 1 mm) are significantly influenced by gravitation acceleration, surface tension, and liquid density, whereas the dynamic viscosity has a minimal effect. Moreover, the bubble detachment diameter and detachment time reduce with an increase in gravity level and liquid density [19]. Dou Ma et al. and Zhang Yujie et al. conducted two-[20] and three-dimensional [21] numerical simulations of bubble formation, and discussed the effects of gas velocity, orifice diameter, surface tension, liquid viscosity, and liquid density on the bubble formation and bubble coalescence regimes. The coupled level set and volume-of-fluid (CLSVOF) method have also been widely used. Chakraborty et al. [22] used the CLSVOF method to examine the bubble dynamics in an orifice, with a diameter of 0.72–3 mm, submerged in a high-density liquid metal. In addition, the influence of the Weber number on the period, including the pairing and coalescence bubbling period, were discussed. Ohta et al. [23] showed that in the bubble formation processes, the effects of the leading bubble on the following bubble are small for a lower gas velocity but large for a higher gas velocity. Gerlach et al. [24] numerically simulated the bubble formation process. Their results showed that the bubble volume increases with the augmentation of viscosity and surface tension, and reduces with an increase in liquid density. The increasing gas flow rate can weaken the influence of the density and surface tension, but enhance the influence of viscosity. Buwa et al. [25] found that the bubbling regimes transit from period 1 (the period with successive bubbles) to period 2 (with a pairing