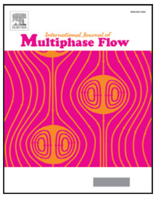
International Journal of Multiphase Flow 97 (2017) 23–32

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

journal homepage: www.elsevier.com/locate/ijmulflow



On the bubble formation under mixed injection conditions from a vertical needle

J.C. Cano-Lozano, R. Bolaños-Jiménez, C. Gutiérrez-Montes*, C. Martínez-Bazán

Área de Mecánica de Fluidos, Departamento de Ingeniería Mecánica y Minera, Universidad de Jaén, Campus de las Lagunillas, 23071, Jaén, Spain

ARTICLE INFO

Article history:
Received 28 March 2017
Revised 21 June 2017
Accepted 26 July 2017
Available online 29 July 2017

Keywords:
Bubble formation
Chamber pressure
Bubble shape
Mixed injection conditions

ABSTRACT

We present an analytical and experimental study of the formation of bubbles from a submerged vertical needle under mixed injection conditions, where neither the gas flow rate nor the feeding pressure remain constant during the process. In particular, we focus on the temporal evolution of the pressure inside the gas injection chamber during the bubble formation process, $p(t)$, modeling it and analyzing the bubble size and shape as functions of the volume of the chamber, V_c, and the mean gas flow rate, Q_i, for a given needle radius, a. Under this configuration, it has been shown that the water column penetrating inside the injection needle plays an important role on the bubble formation process. Consequently, an analytical model that includes the description of the time evolution of the liquid column penetrating inside the needle after the separation of a bubble, and the subsequent pressurization of the gas chamber, has been proposed. The results given by the model agree well with the experimental measurements.

1. Introduction

In the last years, the diversity of industrial, medical and pharmaceutical requirements has promoted the development of new techniques to generate bubbles, and more recently, micro- or nano-bubbles, such as co-flows, cross-flows, or flow-focusing, among others (Rodríguez-Rodríguez et al., 2015). However, the traditional way of generating bubbles inside a quiescent liquid from a submerged orifice, nozzle or needle in a stagnant liquid is still widely used (Kuo and Wallis, 1988; Ohta et al., 2011). In this configuration, the bubble formation can be driven at constant flow rate, constant injection pressure, or mixed conditions. The two first cases, i.e. constant gas flow rate and constant injection pressure conditions, have been extensively analyzed (see for example Clift et al., 1978; Kulkarni and Joshi, 2005). In particular, the first case, in which the gas flow entering the bubble remains constant, is the most analyzed configuration, what is accomplished when the pressure variation inside the bubble is much smaller than the pressure drop along the gas feeding line (Gordillo et al., 2007; Ogũz and Prosperetti, 1993). On the contrary, the constant pressure injection conditions are given when the pressure in the feeding chamber does not vary during the bubble formation process. The latter case has been less studied, although several works can be found, such as Kumar and Kuloor (1976), Satyanarayan et al. (1969), and Tsuge and Hibino (1978), among others. The third configuration, i.e. the formation of bubbles under mixed conditions, where neither the gas flow rate nor the injection pressure are prescribed, is the focus of the current work. It constitutes the least studied configuration, even though these conditions often correspond to those present in many industrial operations, such as the fabrication of aluminum foams (Fan et al., 2013; Liu et al., 2015). In this case, the bubble formation process becomes more complex compared with that at constant flow rate or constant pressure injection conditions. The pressure fluctuations inside the bubble are of the order of the pressure drop along the gas line and, consequently, the flow rate feeding the bubble varies with time (Khurana and Kumar, 1969; McCann and Prince, 1969), preventing the controlled periodic generation of bubbles of a given size (Dzienis and Mosdorf, 2014; Mosdorf et al., 2016; Mosdorf and Wyszkowski, 2011).

To achieve the mixed injection conditions, since the pressure drop along the gas line has to be reduced, a feeding gas chamber has been usually placed right before the needle or orifice. Under this configuration, it has been found that the volume of the gas chamber, V_c, plays a significant role when both the gas flow rate feeding the bubble and the injection pressure do not remain constant, a phenomenon first reported by Hughes et al. (1955) and Davidson and Schuler (1960). In fact, Park et al. (1977) classified the formation regimes in terms of the gas chamber volume as *small chamber region*, in which the bubble volume does not depend on the chamber volume, being the constant gas flow rate conditions the lowest limit; *medium chamber region*, where the

---

* Corresponding author.
E-mail addresses: jccano@ujaen.es (J.C. Cano-Lozano), rbolanos@ujaen.es (R. Bolaños-Jiménez), cgmontes@ujaen.es (C. Gutiérrez-Montes), cmbazan@ujaen.es (C. Martínez-Bazán).

http://dx.doi.org/10.1016/j.ijmultiphaseflow.2017.07.016

bubble volume increases linearly with the chamber volume; and *large chamber region*, in which the bubble volume does not depend on the chamber volume, with the constant pressure conditions as the highest limit. The gas chamber volume can be classified in terms of the capacitance number (Hughes et al., 1955), defined as

$$N_c = \frac{g(\rho_l - \rho_0)V_c}{\pi\, a^2 \rho_0\, c^2} = \frac{g(\rho_l - \rho_0)V_c}{\pi\, a^2\, \gamma\, P_m}, \tag{1}$$

where c is the speed of sound, g the gravitational acceleration, ρ_l the liquid density, ρ_0 the gas density at ambient conditions, γ the ratio of specific heats (polytropic coefficient), a the radius of the orifice and P_m the mean absolute pressure inside the chamber. This dimensionless number defines the relation between the actual volume of the chamber and the chamber volume corresponding to the transition between the small and the medium chamber region (Park et al., 1977). Thus, the *small chamber region* takes place for $N_c \lesssim 1$ ($N_c < 0.85$, according to Hughes et al., 1955) and the *large chamber region* for $N_c \gtrsim 10$, being the exact value determined by the orifice radius, the physical properties of the fluids or the pressure above the liquid (Park et al., 1977).

The bubble formation from an orifice that connects a liquid pool with a gas chamber has been described as a two-stage process, namely a holding stage and a formation stage (Khurana and Kumar, 1969; Tsuge and Hibino, 1978), with the holding stage starting with the release of the previous bubble and finishing when the new bubble starts to grow. Furthermore, the pressure inside the gas chamber increases during the holding stage until the bubble starts to form, and it decreases when the bubble inflates during the formation stage. These pressure variations taking place inside the gas chamber can be used to describe the bubble formation process and have been commonly measured using microphones (Xiao and Tan, 2005; Xie and Tan, 2003) or pressure transducers (Park et al., 1977; Ruiz-Rus et al., 2017; Ruzicka and Drahos, 2009a). In this regard, the formation stage has been studied and analytical models, which are able to reproduce the pressure variation inside the chamber, have been proposed (Terasaka and Tsuge, 1990; Tsuge and Hibino, 1978). The previous studies are mostly focused on the bubble formation from orifices. However, the inclusion of needles generates a flow resistance that prevents the weeping phenomenon (see for instance Stanovsky et al., 2011) and allows to create bubbles in a more controlled manner. Therefore, there are many techniques of controlled bubble generation that require the use of needles, such as co-flow, cross-flow, flow-focusing or forcing bubbling by a vibrating needle (see Rodríguez-Rodríguez et al., 2015). This configuration, which may induce a bubble formation dynamics different from that using orifices, has been less studied. In particular, Ruzicka and Drahos (2009a), Dzienis and Mosdorf (2014) and Dzienis et al. (2016) performed experiments using a transparent needle that allowed them to measure the time evolution of the meniscus along the needle length. They reported that, when a needle is used, the liquid penetrates inside it, being this motion essential to explain the dynamics of the bubble formation under these conditions. Moreover, Ruzicka and Drahos (2009b) and Dzienis and Mosdorf (2014) proposed a theoretical model to study the complete bubble formation process. Their model is based on a balance of forces, in which the bubble growth is predicted by applying the spherical Rayleigh–Plesset equation, and the meniscus motion modeled as a liquid piston-in-cylinder mechanical analogy. In the present work, a different approach is proposed, based on the governing equations for the gas and liquid, to model the holding stage, whereas the bubble growth is obtained experimentally.

Under the above-mentioned conditions, the present work aims to characterize the bubble generation from a submerged vertical needle in a stagnant liquid under mixed injection conditions as a function of the gas chamber volume, V_c, and the feeding gas flow rate, Q_i. Thus the experimental facility is described in Section 2; a mathematical model developed to determine the time evolution of the gas chamber pressure is proposed in Section 3 and, in Section 4, the results are discussed. Finally, conclusions are provided in Section 5.

2. Experimental set-up and techniques

The experimental facility used in the present work is sketched in Fig. 1(a). It is similar to those used to study the formation of bubbles from an orifice in previous works (Antoniadis et al., 1992; Khurana and Kumar, 1969; Park et al., 1977; Terasaka and Tsuge, 1990; Tsuge and Hibino, 1978), but including a submerged vertical needle to inject the gas into the liquid pool (Bolaños-Jiménez et al., 2008; Sano and Mori, 1976; Thoroddsen et al., 2007). It basically consists of a $30 \times 30 \times 50$ cm^3 Plexiglas reservoir filled with distilled water (liquid), where the air flow (gas) was supplied through a short needle of radius a connected to the gas feeding chamber also made of Plexiglass, what allowed us to observe if water penetrated inside the chamber during the process, phenomenon known as weeping. The size of the liquid pool was much larger than the bubble size, ensuring that wall effects were negligible in our experiments. The gas chamber was pressurized by injecting a constant flow rate of gas, Q_i, through a long capillary tube, avoiding therefore that the air-supply line behaved as a secondary chamber. The air was supplied from a compressed air bottle to the feeding chamber through a gas line equipped with a filter, a regulator valve and a mass flow meter (Aalborg, range $0 - 100$ ml/min). The range of injected gas flow rates covered in the experiments reported here varied from $Q_i = 10$–50 ml/min. The gas flow rates employed here avoided the formation of groups of bubbles and the possible coalescence phenomena (McCann and Prince, 1971), as well as the weeping phenomenon. In all, four cylindrical gas chambers of 2 cm of diameter and volumes $V_c = 10$, 20, 30 and 40 cm^3, respectively, were employed. As for the injection needle, a stainless steel needle with inner radius $a = 0.42$ mm and length $L = 2$ cm was used, with a volume of 0.8 cm^3, including the needle holder. It should be mentioned that our experimental observations indicated that, in our case, the solid-liquid-gas contact line was always pinned at the inner edge of the needle when the bubble was growing. Finally, the liquid level was kept constant at $H = 17$ cm above the needle (see Fig. 1b).

The experiments were performed by recording images of the global bubble formation process at frame rates that varied from 1000 to 15000 fps, depending on the conditions, with two high-speed cameras FASTCAM Photron placed 90° from each other, as shown in Fig. 1(a). The use of two cameras focusing on two perpendicular planes allowed us to confirm that the bubble formation was axisymmetric. These recordings provided the time evolution of the bubble volume, $V_b(t)$, that was obtained as follows. First, the bubble interface was extracted from the images applying standard edge detection algorithms (see Fig. 2). Once the bubble silhouette was determined, since the bubble is confirmed to be axisymmetric, the volume at each time was obtained as $V_b(t) = \int_0^{z_{top}(t)} \pi r_s^2(z) dz$, where $r_s(z)$ represents the radial distance of the interface as a function of z, and z_{top} is the vertical distance of the bubble top. Moreover, two different pressure transducers (UNIK 5000 GE, ranges of gauge pressure from 0 to 7000 Pa and from -7000 to 7000 Pa, accuracy ±0.04% of the full scale), synchronized with the two high-speed cameras, were used to measure the time evolution of the pressure inside the chamber, $p(t)$, during the bubble generation process. Thus, we were able to measure the time evolution of the gas chamber and correlate it with the bubble growth.

With the above description, the different parameters characterizing the experiments (Fig. 1b) are the inner radius of the needle, a, the surface tension at the gas-liquid interface, σ, the liquid density,