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Numerical simulation of periodic bubble formation at a submerged orifice with constant gas flow rate

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Abstract

Extensive numerical simulations were carried out to study the problem of bubble formation at submerged orifices under constant inflow conditions. A combined volume-of-fluid and level-set method was applied to simulate the formation process, the detachment and the bubble rise above the orifice in axisymmetric coordinates. On the one hand, the operating conditions of the formation process such as orifice flow rate, orifice radius and wettability of the orifice plate were investigated for the working fluids of air and water at 20 °C. On the other hand, the influence of the variation of fluid properties (liquid density and viscosity, surface tension) was examined individually. In this frame, the present work focused on low and medium flow rate conditions, at which the formation takes place in a periodic manner, in contrast to aperiodic or double periodic modes. The results of the computations provide information on the influence of various conditions on the bubble shapes, the bubble volume and the transition from a single to a double periodic formation process. The numerical results were extensively validated with experimental data available in the literature.

Keywords: Bubble; Bubble formation; Period doubling; Orifice; Volume-of-fluid; Numerical analysis

1. Introduction

The formation process of gas bubbles at submerged orifices is of importance in many industrial applications of gas–liquid contacting equipment. To design such systems, an accurate knowledge of the bubble size distribution produced under certain operating conditions is necessary. Different methods are known in the literature to supply the gas to the orifice exit. These methods are distinguished typically by a non-dimensional capacitance number N_C as in Tsuge (1986), which considers the degree of influence of the gas chamber connected to the orifice. For $N_C > 1$ (intermediate or constant pressure regime) the gas chamber below the orifice has an effect on the flow rate supplied to the bubble and thus also on the bubble volume formed, which is encountered, for example, in bubble columns using multihole/sieve plate sparger. For $N_C < 1$ (constant flow regime) the flow rate through the orifice is continuous, thus the formation period is directly given by the ratio of the detached bubble volume and the flow rate. This regime is obtained by providing a large pressure drop between gas chamber and orifice exit by means of a capillary or a porous section (Terasaka and Tsuge, 1993; Jamialahmadi et al., 2001; Zhang and Shoji, 2001). The objective of the present work is to simulate the bubble formation process through direct numerical simulation of the flow field and the interface evolution during the formation and the initial rise of the bubble. The present paper considers the constant flow regime of bubble formation ($N_C < 1$) in detail and compares the numerical results with experimental data.

Many investigations of the basic case of the bubble formation at a single orifice have been reported, as described in review articles by Kumar and Kuloor (1970), Clift et al. (1978), Tsuge (1986) and Kulkarni and Joshi (2005). Different theoretical approaches have been applied to study the problem of bubble formation: in the limit of very low gas flow rates (quasi-static limit), the bubble contour can be predicted analytically from the balance of pressure and capillary forces, as used by Siemens (1954) and Longuet-Higgins et al. (1991). Including the viscous and inertia effects at increasing flow rates, different theoretical models of varying complexity were developed.

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Starting from the one-stage models of Davidson and Schüler (1960a,b) for dynamic formation in viscous and inviscid liquids, improved models have been proposed by means of two-stage and non-spherical models (Tsuge, 1986). In these models the influence of the inflow conditions of the gas through the orifice, i.e., constant gas or constant pressure regime, were intensively investigated. Boundary-integral methods were also successfully employed to examine the formation process, as by Oğuz and Prosperetti (1993), Wong et al. (1998) and Higuera (2005).

In the present approach, full numerical simulations were performed using a combination of the volume-of-fluid and level-set methods (Sussman and Puckett, 2000; Son and Hur, 2002), where a single set of Navier–Stokes equations in an axisymmetric formulation was solved in the computational domain. The parameters studied were the orifice flow rate and radius, the wettability of the orifice material and the influence of surface tension and the liquid density and viscosity. The constant orifice flow rate was increased stepwise until a transition from single periodic (SP) to double periodic (DP) formation was detected, i.e., until the influence of a bubble on the following one is such that the second bubble detaches earlier compared with the SP case. This phenomenon was also observed experimentally by Kyriakides et al. (1997), Zhang and Shoji (2001) and Tufaile and Sartorelli (2002). As a consequence, the trailing bubble of each pair is smaller than the leading bubble and two distinct but constant detachment periods exist which repeat regularly. In this DP regime, the two interacting bubbles may coalesce some distance above the orifice or directly during formation (Zhang and Shoji, 2001), the latter case occurring at higher flow rates is not considered here. The present work focuses on the periodic bubble formation process, but also provides information about the conditions, under which the formation regime changes from a SP to a DP regime.

Air and water at 20 °C served as reference working fluids for the computations. Based on their data, the fluid properties were varied individually to study their influence on the formation process. Less information is typically given in the literature about the orifice material used, as discussed by Ponter and Surati (1997), which can make a comparison of different studies difficult. Most of the models available are based on the assumption that the bubble base coincides with the orifice rim during formation, which can be an oversimplification depending on the orifice material employed. Attempts have been made here to examine the influence of the orifice material by means of a static model for the contact line movement. Based on this background, the present study investigated bubble formation at submerged orifices under exactly defined conditions and demonstrated that the present numerical approach can improve the understanding of the process of bubble formation. As an extension to previous studies dealing with the influence of fluid properties on the bubble formation process in the constant flow regime (Kumar and Kuloor, 1970; Terasaka and Tsuge, 1993; Jamialahmadi et al., 2001), the present work considers also the influence of the properties in combination with bubble interactions (pairing) and the wettability of the orifice plate.

The present paper is arranged as follows. In the next section, the problem studied here is described and non-dimensional numbers are used to estimate the importance of the forces influencing the bubble formation process. A short description of the mathematical model and the numerical method is given. The results of a numerical parameter study are provided in Section 3 considering the influence of the operating conditions and the fluid properties. The phenomenon of period doubling of the bubble formation process, i.e., the transition from SP to DP formation, is discussed in Section 3.3. Finally, an existing correlation for the bubble volume based on non-dimensional quantities was used to validate the results with experiments.

2. Analysis

2.1. Problem description

The formation and detachment of gas bubbles at single submerged orifices is considered. Owing to the gas flow through the orifice, the bubble volume increases continuously. When the lift forces exceed the retarding forces (viscous and capillary forces) the bubble detaches and rises upwards. For the low and medium flow rates involved in the present work, the process of growth and detachment is assumed to be axisymmetric, whereby the origin of the (r, z) coordinate system is placed at the center of the orifice rim as indicated in Fig. 1. The flow rate through the orifice of radius R_o is constant and thus independent of the pressure variations in the bubble. This is called the constant flow rate regime in contrast to the constant pressure regime (Clift et al., 1978). The properties of the liquid phase are the density ρ_l and the viscosity μ_l, the respective properties of the gas phase being ρ_g and μ_g. The surface tension σ between the two fluids is assumed to be constant. A static contact angle model is applied to characterize the movement of the triple contact line of the gas–liquid–solid components as described

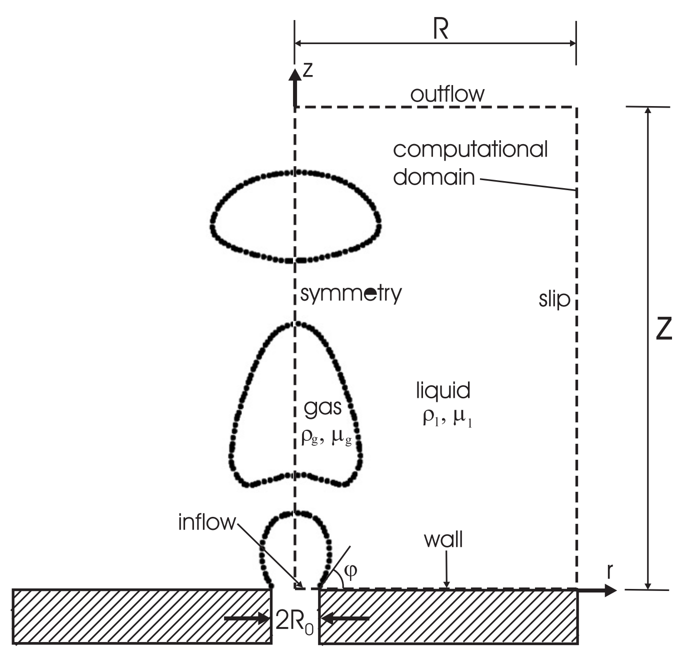

Fig. 1. Computational domain and boundary conditions.