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Towards the understanding of bubble-bubble interaction upon formation at submerged orifices: A numerical approach

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HIGHLIGHTS

- We present the bubble-bubble interaction patterns when emerged from submerged orifices.
- Three distinct patterns of bubble release dependent on mutual spacing of the orifices are reported.
- Hydrodynamic reasons of different merging regimes are described using velocity vectors around the bubbles.
- A map of different zones as a function of *Mo*, orifice diameter and spacing has been proposed.
- Effect of van der Waals force has been established in connection of bridge thinning by virtue of gas inertia.

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ABSTRACT

Present study reports numerical investigations on the bubble evolution at submerged orifices and their mutual interactions in quiescent liquid under constant inflow condition of air. In finite volume based 3D domain, breaking and making of interfaces are tracked using volume of fluid (VOF) solver. Binary interaction dynamics is studied for a wide range of fluid properties ($3.85 \times 10^{-11} < Mo < 4.645 \times 10^{-6}$), orifice diameters (1, 1.5 and 2 mm) and spacings (2–10 mm). Apart from observed coalescence and non-coalescence, fusion of bubbles before and after pinch off from orifice mouth at different *Mo* are presented. Using velocity patterns inside the bubble, explanation of different merging pattern is proposed. A 3D map for distinct behaviour while merging, in terms of *Mo*, orifice diameter and spacing is also tried. Finally, effect of velocity of gaseous phase on merging between sister bubbles are assessed numerically.

1. Introduction

The process of evolution of bubbles from orifice mouth pair and their subsequent coalescence is a common phenomenon in multiphase flow. Application lies in different fields, namely, gas-liquid reactors in petrochemical industry, nuclear reactors, cosmetic industry, mineral processing, etc. In addition, evolution of gas bubbles from submerged orifices also shows resemblance to nucleate pool boiling. On the other hand, coalescence of bubbles can be interlinked with control of interfacial area and mass transfer rate in gas-liquid bubble columns. Interaction of gaseous bubbles is prime and fundamental reason of instabilities in two phase flow that affects performance of various components like boilers, reactors, and oil and gas wells. A continuous activity over last few decades has been observed by the researchers on bubble evolution process at a submerged orifice. One can observe a sequential development in this topic based on experimental investigations (Xie and Tan, 2003; Das et al., 2011), numerical simulations (Gerlach et al., 2005, 2007) and theoretical analysis (Wong et al., 1998; Zhang and Tan, 2000; Das and Das, 2009). Experimental investigation and theoretical modelling of formation of gaseous bubbles through submerged orifice has been studied by Das et al. (2011). They have measured the bubble frequency as the function of gas flow rate as well as shown a reasonable agreement between the model prediction and the experimental observation. But in their study the process of coalescence (Shah et al., 1982) is not tackled from fundamental physics. Stewart (1995) has performed experiments on approach, contact, coalescence or breakup of freely rising ellipsoidal gaseous bubbles in a tank. The coalescence process has been studied (Prince and Blanch, 1990; Camarasa et al., 1999; Pohorecki et al., 2001; Liu et al., 2015; Jingliang et al., 2013) in the central region of the bubble column, where bubble break-up and coalescence processes reach an equilibrium which determines the bubble

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Table 1
Fluid properties used for simulation.

Properties	Liquid 1	Liquid 2	Liquid 3	Liquid 4	Liquid 5	Liquid 6
ρ (kg/m^3)	999	1064	1110	1160	1200	1230
μ (Pa s)	0.0011	0.0020	0.0030	0.0046	0.0090	0.020
$\rho_{gas} = 1.225$ kg/m^3 and $\mu_{gas} = 1.789 \times 10^{-5}$ Pa s						
σ (N/m)	0.072	0.064	0.064	0.062	0.064	0.065
Mo	3.85×10^{-11}	5.625×10^{-10}	2.735×10^{-9}	1.585×10^{-8}	2.045×10^{-7}	4.645×10^{-6}

mean diameter, responsible for the superficial area available for transport phenomena between the gas and liquid phase. But the study of hydrodynamics for evolution and interaction of bubbles from adjacent submerged orifices remains far from fully understood despite of its wide range of applications. Though some of the earlier researchers investigated on bubble formation at multiple orifices, different stages in bubble merging as approach, film drainage, contact and unification are not addressed properly. Titomanlio et al. (1976) experimented on two orifice bubbling using N_2 in water and observed simultaneous bubbling from the orifices without interaction. They also found orifice pitch has significant effect on bubble size released from orifice mouth. Miyahara et al. (1983) showed that by increasing the number of orifices, dependence of gas chamber volume on bubbling pattern can be eliminated. Ruzicka et al. (2000) found bubble formation from two neighbouring orifices has synchronous and asynchronous modes at very low and high flow rates respectively. Amongst the analytical models, McCann and Prince (1969) developed mathematical insight to predict bubble frequency of two adjacent orifices. They have considered motion of liquid between bubbles for predicting interactions. But their model did not appear to work well for close orifice configurations. Kupferberg and Jameson (1970) focused on chamber pressure fluctuation due to multiorifice placement but concluded negligible interaction between bubbles. Few studies (Martin et al., 2007, 2008; Fan and Yin, 2014) have been performed on the coalescence of gaseous bubbles at orifices experimentally in last 10 years. Martin et al. (2007) have explained the phenomena of coalescence of bubbles at sieve plates and showed merging affects the mass transfer rate. They have developed empirical correlations to describe the effect of bubble coalescence on mass transfer, bubble oscillation and superficial area distribution. In another effort, Martin et al. (2008) have performed experiments to investigate the relative effect of orifice configuration at sieve plate on bubble coalescence by varying liquid properties and gas flow rate. In addition, they have adopted amalgamation of mechanistic and statistical approaches to predict the dynamics of bubble behaviour which helps to identify the degree of coalescence. Chesters and Hofman (1982) studied formation of dimple and simultaneously thinning of liquid film between bubbles during coalescence in pure liquid. They have found out the equivalent bubble radius of two merging bubbles of different radii. Duineveld (1998) proposed that bubble pair rising with high speed in liquid like pure water or aqueous solutions collides between themselves which may results in merging or separation by bouncing back. From literature it can be observed that though isolated efforts are here and there mainly by experimental observations, no systematic study has been performed numerically to understand merging dynamics of bubbles. Present effort is step advancement towards that.

To explain the shape and dynamic behaviour of bubbles which are forming, coalescing and detaching at submerged orifices into the homogeneous liquid, mutual influence of some independent non-dimensional numbers, namely, Eotvos number ($Eo = g\rho d^2/\sigma$), Morton number ($Mo = g\mu^4/\rho\sigma^3$) and Capillary number ($Ca = \mu V/\sigma$) are to be studied. Here ρ and μ are the density and viscosity of quiescent liquid, respectively, with consideration of $\rho \cong \Delta\rho$. It is expected that shape, detachment time, coalescence time, intensity of oscillation during fusion of bubbles, overall flow rate of air, etc. can be correlated with *Eo*, *Mo* and *Ca* numbers. Both *Mo* and *Eo* play very important role in giving the bubble shape and behaviour (Grace, 1973). But, as *Eo* is dependent on length scale, one can classify the liquids based on *Mo* to obtain different shapes of the bubbles, irrespective of orifice configurations. Volume of bubble evaluated from the orifice depends on diameter and air flow rate. This can be captured by variation of *Eo* and *Ca*. The dynamic behaviour of bubble depends on its shape, for example ellipsoidal bubbles observed in low *Mo*, exhibit an unsteady wobbling rising path but approximately spherical bubbles are found in high *Mo* which follows a steady and stable rising path. In this paper, we tried to observe growth and subsequent merging of bubbles, if possible, at neighbour orifices using finite volume based numerical simulations. Apart from orifice spacings and diameters, fluid parameters (Table 1) are also varied to observe mutual dependence of *Mo*, *Eo* and *Ca* numbers. In next section, we described the details of the numerical tool.

2. Numerical methodology

2.1. Computational domain

Fig. 1 shows the working domain inside which a pair of growing and interacting bubbles is studied. 3D rectangular chamber with dimension of $20 \times 20 \times 20$ cm^3 is constructed numerically having

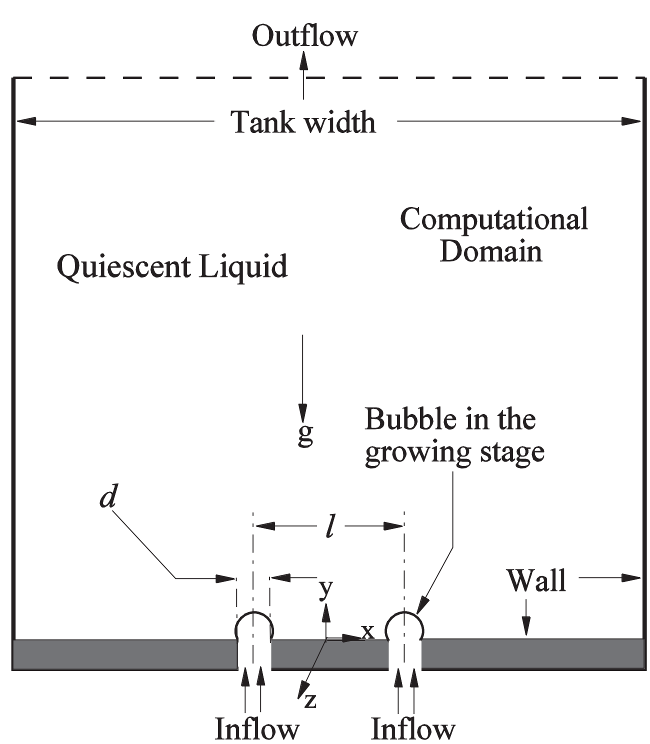

Fig. 1. Computational domain with boundary conditions X-Y plane.