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# Study of interaction pattern between bubbles at three inline orifices in a submerged pool

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## HIGHLIGHTS

- We present interaction patterns of three inline bubbles.
- Three distinct patterns of bubble release dependent on mutual spacing are reported.
- Symmetric or asymmetric unifications are observed at similar or dissimilar spacing.
- Combinations of similar or dissimilar orifice diameters are tested.
- Drainage of liquid between bubbles and growth of gas interconnections are reported.
- Map of different zones of complete, partial and non-coalescence patterns are shown.

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## ABSTRACT

Experiments have been performed to study evolution and interaction of bubbles over three inline submerged orifices. Complete, partial and non-coalescence patterns are observed during the growth of bubbles at similar and dissimilar spacing and diameter of orifices. When orifices are equispaced and similar in size, symmetric interfacial shape is observed during coalescence, but unequal orifice spacing resulted in asymmetric merging of bubbles. Drainage of liquid before initiation of coalescence and growth of gaseous bridge between bubbles before unification are observed for both symmetric and asymmetric arrangements. Effect of gas flow rate has been observed for equal and unequal spacing. Delay in merge time is one of the important parameter which has been observed in case of unequal orifice spacing distances and its effect is analyzed for different air flow rate into the liquid tank. Scattered regime plot has been shown in order to understand the bubble coalescence and non-coalescence patterns in different zones and combinations of orifice sizes and orifices spacing.



## 1. Introduction

Processes like growth and coalescence of gaseous bubbles at submerged orifices, contains very complex and interesting interplay of interfaces which are commonly observed in gas-liquid two phase flow applications. Interaction of multiple bubbles is having great influence on phenomena, which are related to heat transfer, mass transfer and chemical reaction. Plenty of applications of such processes can be found in gas-liquid separator, biochemical reactors, gas-liquid contractor, gas stripper, bubble absorber, bubble column, fermentator etc. It is very interesting to note that formation of multiple bubbles beneath of the stationary liquid tank through orifices shows some similarity characteristics with the nucleate boiling in the topic of pool boiling (Abarajith et al., 2004). A large volume of research articles have been published related to this topic over the decades. These efforts took route of experimental investigations (Benzing and Myers, 1955; de Nevers and Wu, 1971; Davidson and Schuler, 1997; Camarasa et al., 1999; Xie and Tan, 2003; Bolanos-Jimenez et al., 2008; Das et al., 2011), numerical simulations (Gerlach et al., 2005, 2007; Gordillo, 2008) and theoretical analysis (Wong et al., 1998; Das and Das, 2009). McCann and Prince (1969) first developed mathematical insights to predict bubble frequencies at two adjacent orifices. In another experimental effort, Kupferberg and Jameson (1970) focused on pressure fluctuation of gas due to bubbling from multiple orifices but concluded negligible interaction between bubbles. Narayanan et al. (1974) have performed experiments to observe inline coalescence of bubbles at low Reynolds number ($Re$) and proposed that coalescence of bubbles behaves like

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analysis of weightless solid spheres for $Re < 7$ and toroidal wakes for $Re > 7$. Titomanlio et al. (1976) have experimented on two closely spaced orifices, ejecting $N_2$ bubbles in water and observed simultaneous bubbling from the orifices without interaction. Similar kind of study is performed by Bhaga and Weber (1980) in viscous liquid where inline merging of gaseous bubbles are observed. Chesters and Hofman (1982) have developed an analytical model to study the flow dynamics of liquid bridge, generated during approach of bubbles towards each other for low Weber number. Miyahara et al. (1983) showed that by increasing the number of orifices, dependence of gas chamber volume on bubbling pattern can be eliminated. A model has been developed to study the bubble coalescence and break up in distilled water by Prince and Blanch (1990), which showed good agreement with experimental observations. They have considered bubble coalescence due to turbulence, buoyancy and laminar shear. Chesters (1991) have studied drainage of liquid film in between immobile, partially-mobile and fully mobile bubbles and predicted probability of coalescence. Stewart (1995) performed experiments to observe the approach, contact and coalescence or splitting of bubbles in a system of low viscosity liquids. Rising, bouncing and merging of two equal sized bubbles under pure water or aqueous surfactant solutions has been studied experimentally by Duineveld (1998), who found out the Weber number range for bubble bounce back and successful coalescence. Ruzicka et al. (2000) showed bubble formation from two neighbouring orifices having synchronous and asynchronous modes at very low and high flow rates, respectively. Li et al. (2001) conducted experiments on interaction and coalescence of bubbles rising in non-Newtonian fluids by using birefringence measurements and PIV. Martin et al. (2007) have explained the phenomena of coalescence between bubbles at sieve plates and showed merging affects the mass transfer rate. 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. Gupta and Kumar (2008) performed investigation on merging of multiple bubbles in inline arrangement using lattice Boltzmann method. Using vortex pattern of the leading bubble, they have explained three different stages during merging of the bubble, namely, collision, drainage of liquid film between two adjacent bubbles to a critical thickness and puncture of liquid film. Fan and Yin (2012) have performed experiments on growth of two bubbles in CMC aqueous solution and employed He-Ne laser light source to record real time video. Jingliang et al. (2013) have experimented on coalescence of bubbles, formed on the heated surface due to a sequence of microheaters in different positions and observed four different kind of merging events. They have also found out three bubbles interact in a repulsive manner when the interval distance is more than a critical distance in non-Newtonian fluid. In one experimental investigation, Zhao et al. (2015) have studied coalescence of two $CO_2$ bubbles at capillary orifices, submerged in microalgae suspension and compared with results of air-water combination. It has been observed that more time is required for merging in microalgae suspension and easy detachment has occurred due to lower surface tension than water. In very recent year, Fan et al. (2016) have simulated evolution and coalescence of bubbles at two adjacent nozzles in carboxymethyl cellulose aqueous (CMC) solutions by using combined level set and volume of fluid method. They have proposed four different stages of merging process i.e. (i) growth, (ii) rapid mergence, (iii) radial expansion, (iv) vertical stretching. Feng et al. (2016) have performed both numerical as well as experimental investigation on inline coalescence of bubbles at low Reynolds number. They have obtained that the drainage time is directly proportional to liquid viscosity and the association time shows dependence on liquid viscosity and surface tension. Recently, Rana et al. (2017) have modelled the growth and coalescence of binary gaseous bubbles at submerged orifices beneath the liquid tank and established the 3D regime plot which addresses the unique behaviour of coalescence and non-coalescence pattern of bubbles in different zones. Despite of isolated efforts, due to very complex interplay of interfaces, the physics of multiple bubbles growth, coalescence and departure at submerged orifice is not yet studied in detail. The unique merging pattern of bubbles makes the phenomena more interesting and challenging. The present work focuses on the triple merging of gaseous bubbles at the orifices which are beneath the liquid tank in inline arrangement. The variation of orifice diameters and orifice spacing distances shows the unique merging pattern of bubbles.

## 2. Experimental details

To explore the dynamics of evolving bubbles in close vicinity with each other, three orifices allowing air entry in a row have been considered below a liquid tank. An overview of the experimental facility is shown in Fig. 1. Over the orifices a 15 cm high liquid column is maintained in a cross sectional area of $15 \times 15$ cm$^2$. Square cross section of the tank is considered to avoid cylindrical error in visualization. Tank is chosen large enough (>30$D_o$ in lateral and >100$D_o$ in vertical direction; $D_o$ is the orifice diameter) to avoid wall effect and interface disturbances during bubble bursting at free surface. Open top liquid tank is developed for the experimental study to ease addition and removal of working fluid. Glass windows are provided in each side of the tank to facilitate the visualization. Demineralized water is used in all experiments in order to minimize the effect of liquid contamination on the bubble formation process. At 20 °C, density, viscosity and surface tension of water are measured as 1000 kg/m$^3$ 0.001 Pa-s and 0.07 N/m respectively. For formation of gaseous bubbles, air is supplied to a bottom plenum from an oil free compressor through flow control valves, metering rotameter and bypass lines. The volume of air plenum ($15 \times 15 \times 5$ cm$^3$) is kept more than 10,000 times of individual bubble so that pinch off of an air mass will not change average

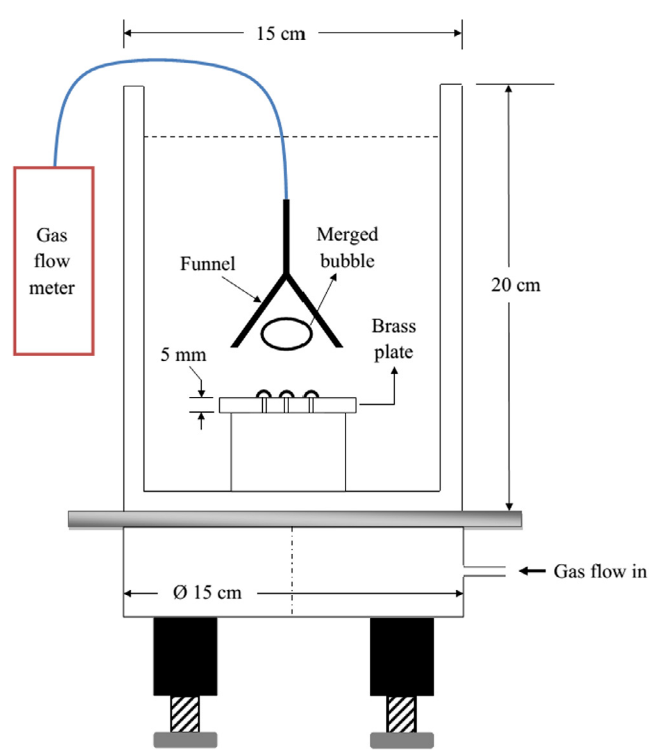


**Fig. 1.** Schematic representation of the experimental arrangements.