COMPUTATIONAL MODELING OF BUBBLE GROWTH FROM A SUBMERGED ORIFICE WITH CONSTANT AIRFLOW RATE

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ABSTRACT

This study investigated the single bubble evolution in immersed orifice with a view the effect of bubble shape changes with time and variation of pressure in the liquid during the bubble move upward during the bubble growth, pinch-off region and detachment has been investigated by using computational fluid dynamics. The orifice diameter varies from 0.5mm to 2mm. Measurement of an arc is created and Young- Laplace equation has used to the estimation of the pressure of liquid varies in the gas liquid surface where the bubble is evolved. The present work is focused on different wetting conditions at low gas flow rate and wetting region of the orifice with orifice base was studied for the working fluid of air and water at 20°. Analytical simulations of bubble formation with constant flow rate and constant gravity where the formation of bubble occurred when the inertia force is going to be leading force which was coupled with level set and volume of fluid (CLSVOF). Simulation data on the transition of bubble formation by using the capillary number with different wetting condition.

KEYWORDS: Computational Fluid Dynamics, Multiphase, Bubble Formation

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INTRODUCTION

The bubble evolves from the immersed orifice has a most useful factor in a different industries usage like chemical and bio-chemical reaction and in the various other equipment worldwide used in metal casting or metal production industry and big industries of casting used to suppress the bubble formation at casting process and spend crore of rupees to diminish the bubble formation during casting process. Bubble evolution process is a state transformation process like during water boil and other metallurgical process. Due to its industrial application and day-to-day life application the bubble evolution is a great research topic of researchers that have been widely used in the last 5 decades. Different analytical models Kumar and Kuloor, 1970 and Kulkarni and Joshi, 2005) studied the two model which is one-stage model and two-stage model was developed and two-stage model give more precise result as compare to one-stage model, to give the volume of a bubble formed by solving the different forces developed when the bubble move forward like buoyant force, pressure force and gas momentum and constraining forces acting on a bubble e.g. surface tension, drag and inertia forces. The analytical model predicts the bubble volume in this state (Gaddis and Vogelpohl, 1986; Jamiallahmadi et.al., 2001. Surface tension is near to zero except at the initial stage of evolution of bubble and inertia force get to be exceed from the surface tension force. Earlier models of Davidson and Schuler (1960a, b) bubble evolution in viscous and non-viscous liquids, better models suggested by use of two-stage and non-spherical models (Tsuge, 1986). The present work main center of study on the bubble evolution process but also provide all data about the conditions under which the formation state changes is used based on the concept of a fractional. The present work considers wettability of the orifice plate. Buwa et al. (2007) studied the bubble formation on an orifice of 2-10mm, combined with the numerical

simulation. Gerlach et al. (2007) found the transformation from initial bubble to second bubble formation in their numerical simulation. (Quan and Hua, 2008; Das and Das, 2009; Chakraborty et al., 2009; Ohta et al., 2011; Chakraborty et al., 2011) on nozzle and orifice results are motivational. Nowadays, software work is preferred because it is easy to get the result in a better way so recent years many analytical results of bubble formation and variation of in liquid movement have been organized by volume of fluid (VOF) used to deal with intricate geometry. Zhou et al. (2011) take VOF method to analyze the bubble evolution, rate of increase of volume and disengagement of bubble with the nozzle. This study main focused on the outcome of wet region of the wall where the bubble gets evolved. Researcher put the force to make this study for clear understanding of bubble formation and how to bubble shape varied with time and how the velocity variation occurs when the liquid gets disturb.

2. PROBLEM DESCRIPTION

The evolution and disengagement of bubble at immersed orifice under water and gas flow through the passage of nozzle and cubic measure of bubble increases continuously. When the buoyant force exceeds the drag force the bubble detaches and rises upwards. The process of evolution and disengagement is taking to be symmetric where by center of the bubble at the (x, y) coordinate system. assumed to be axisymmetric, we take the constant R_0 radius of bubble at nozzle and we do not put any pressure in our simulation so we say that it is not depend on pressure variation on the bubble. This is known as the constant flow state and it contradict the constant pressure state (Clift et al., 1978). The various properties of the liquid state are the density ρ_l and the viscosity μ_l , the corresponding properties of the gas state being ρ_g and μ_g . The surface tension σ value taken to be constant 0.072 N/m. Gas-liquid and solid phase occur in the three-phase contact line and we applied a static contact angle movement to describe the movement of bubble with respect to triple contact line

Figure 1: 2-d Domain for Bubble flow Water-air Interface

upward and it is called a gas-liquid periphery. Initially, the bubble phase is fixed in the nozzle that the contact line of the nozzle rim. We make many assumptions in the bubble flow so that we calculate the number of forces acting on the bubble. Since we know the gas flow rate. An analytical solution of this study, the continuity and Navier-Stokes equations for an incompressible Newtonian fluid are clarified with the defined parameters. We demonstrate the bubble area in different phase initially the bubble at the triple contact line than after it becomes wet when it moves and gas density is very negligible as compared to act forces. We assumed to be reduced the gas flow rate on the bubble and the equilibrium between the force.

$$\sum F - F_B + F_{CP} + F_C + F_D = 0 \quad (1)$$

For the analytical solution of the problem, Navier-Stokes and continuity equations are used to calculate the incompressible Newtonian fluid under certain conditions. When the bubble moves forward than certain forces will act on the bubble periphery and dimensionless number are calculated with the help of the forces which act on the bubble. Initially, the bubble is evolved than the equilibrium will be established between the buoyant force and surface tension i.e.,

$$2\pi R_0 \sigma = V_B (\rho_l - \rho_g) g \quad (2)$$

Where g is the gravitational force act opposite to the bubble movement. The fraction of two forces is defined by the Bond number

$$Bo = \frac{\rho_l g R_0^2}{\sigma} \quad (3)$$

Where ρ_g was negligible, since $\rho_g \ll \rho_l$ here, Eq. (1) indicates that at quasi-static flow rate volume rate of bubble expanded with the nozzle semidiameter and also surface tension but it decreases with the increase of density change. The viscous force developing on the bubble nearly equal to the drag force when the bubble gets to be expanded. Here, in the domain the bubble size so the surrounding water velocity gets change and this velocity can be calculated by the $\dot{Q}/V_B^{2/3}$, appearing in a viscous force of the order $\dot{Q}\mu_l/V_B^{1/3}$ where $\dot{Q}$ is the rate of flow of air. The division of viscous to capillary forces is predicted by the capillary number.

$$Ca = \frac{\mu_l \dot{Q}}{\sigma R_0^2} \quad (4)$$

If we compare the viscous force with the capillary force which is proportional to the gas flow rate and viscosity. The fraction of capillary number and the bond number is $Ca/Bo^{1/3}$. The capillary and Bond numbers were taken in the present work are Ca , Bo and Reynolds number $Re = \rho_l \dot{Q}/(\mu_l R_0)$. The term $1/Bo^{1/3}$ used in the present work is 1.45 where by values of Ca are below 0.1, e.g. for the standard working fluids (air and water) under the conditions $R_0 = 1\text{ mm}$ and $\dot{Q} = 100\text{ ml/min}$, $Ca = 0.023$. Hence the buoyancy and capillary force are involved in all the cases where the flow rate of gas is considered. This was giving a clear understanding of the static contact angle ϕ_s at the three-phase contact line at the base of the domain where orifice/nozzle is fixed triple-phase touch at the orifice plate. As we saw in the analytical results show that the wetting region of the passage (orifice) base may have a great impact on the bubble dimensions with the flow rate of gas. Forces developed when the bubble is moving upwards.

3 ANALYTICAL MODELING

In this study, the mass conservation laws and momentum of incompressible Newtonian liquid are as follow:

$$\nabla \cdot \mathbf{u} = 0$$

$$\frac{\partial \rho(H) \vec{u}}{\partial t} + \nabla \cdot (\rho(H) \vec{u} \vec{u}) = -\nabla p + \rho(H) \mathbf{g} + \nabla \cdot (\mu(H) (\nabla \vec{u} + (\nabla \vec{u})^T)) + F_s + \rho \vec{g} \quad (5)$$

Where surface tension force term F_s , p is the pressure, $\mathbf{g} = (-g, 0)$ is the gravity force which acts in opposite direction with the bubble direction, $\rho(H)$ and $\mu(H)$ are the density and dynamic viscosity, defined by

$$\rho(F) = \rho_l H + \rho_g (1 - H), \quad (6)$$

$$\mu(F) = \mu_l H + \mu_g (1 - H). \quad (7)$$

The subscript (*l*) and (*g*) give the liquid and gas phase, respectively

$$F_s = \sigma k(\varphi) \nabla H(\varphi) \quad (8)$$

Surface tension (σ). $k(\varphi)$ is the simple average arc formed mean by the interface, φ (level-set function) and, Heavy side function $H(\varphi)$.

$$H(\varphi) = \begin{cases} 1 & \text{if } \varphi > 0, \\ 0, & \text{otherwise} \end{cases} \quad (9)$$

The level-set function φ is defined with F , because the number of formulae arise for this calculation and simple average arc $k(\varphi)$ in the surface tension force term, Eq. (9). φ is described as the function of distance which is measured from the periphery (see, e.g., Sussman et al., 1994). The liquid region is that where $\varphi > 0$ that region is the liquid region and where $\varphi < 0$ that region is the gas region. The periphery is constantly given by the $\varphi = 0$ contours. The average arc in Eq (8)

$$k = \nabla \cdot \frac{\nabla \varphi}{|\nabla \varphi|} \quad (10)$$

The surface tension force is used to calculate the volume of the bubble by using interface curvature k and is used in a fixed region around the periphery by using the δ function.

$$F_\sigma = \sigma k(\varphi) \delta(\varphi) \nabla \varphi \quad (11)$$

$$\delta(\varphi) = \begin{cases} 0 & , \text{ if } |\varphi| > 0 \\ \frac{1}{2} (1 + \cos(\frac{\pi \varphi}{\epsilon})) & , \text{ if } |\varphi| \leq \epsilon \end{cases} \quad (12)$$

The quick scheme (Leonard, 1970) is available for the advection equation in the LS method, which is third-order scheme while the calculation of different equations again and again by using the WENO scheme (Liu et al., 1994) with 25 artificial iterations. The simple law (Patankar and Spalding, 1972) is used to pressure-velocity coupling in the continuity and momentum equations.

3.1 Coupling VOF with LS (CLSVOF)

Coupling VOF with LS used to conserve the interface profile with volume fraction α , and LS function has no conservation of mass because LS function lost distance parameter after solving advection equation. Both methods have equally benefit and counter benefit so we coupled both methods.

3.2 Problem Definition

Computational Setup

The bubble evolution from a nozzle of 1mm radius in a container of filled with water and the airflow rate is 100ml/min applied in the nozzle where the bubble is formed with constant flow rate $\dot{Q}$. At the inlet, a laminar velocity profile x-direction is the symmetric region as sketched in Fig. where R_c and D_{eq} are the nozzle/orifice radius and equivalent diameter of a bubble, respectively. The boundary condition at the mid of line $x=0$ and at the left and right extreme position $r = R$ as symmetric extreme conditions i.e., $u=0$ and, Where $V_0 = \frac{\dot{Q}}{\pi R_0^2}$ is the mean velocity at the nozzle/orifice.

The dimensionless number is based upon the flow properties of the gas. We should take the interface of the three-phase contact line at the orifice plate. In this study, we take different contact angle with wetting conditions and non-wetting

conditions, this means the contact angle $\varphi < \varphi_s$, the bubble bottom side starts to increase externally and the moving contact lines keeps the constant contact angle $\varphi = \varphi_s$, which does not depend on the bubble movement and the direction of the bubble. We fixed the contact line for $\varphi > \varphi_s$ and using the fixed contact angle during the contact line movement by fixing all the domain confined condition $\partial\varphi/\partial z = -\cos\varphi_s$. The computational domain describes the fig. as $R = 5D_e/2$ and $Y = 10D_e$, which is nearly equal to the area $10 \times 20 \text{ mm}^2$ where D_e is equivalent to spherical bubble diameter. The cell size of the mesh is 0.25 mm this step size is taken by (Buwa et al., 2007 ; Chakraborty et al., 2009 ; Gerlach et al., 2007). The time step taken in this study was 1×10^{-6} to satisfy the CFL constraints provided.

4. RESULTS

4.1 Influence of Wetting Conditions

We are here study the constant flow of air through the orifice/nozzle $\dot{Q}$, the orifice radius R_0 and we provide a different static contact angle φ_s (wet region) on the bubble formation is predicted by the help of static contact angle. In these studies, we should keep the properties of fluid were kept constant at the standard value of an air-water system at 20°C . We are restricted in numerical efforts orifice radii at $R_0 = 1$ and 1.5mm were studied. We are studied in this investigation 100ml/min was gas flow rate where $\varphi_s = 50^\circ, 0^\circ$ (wettingliquid) and

Figure 4.1.: Different Instant of Bubble Formation, $\varphi_s = 0^\circ, R_0 = 1\text{mm}$ and $\dot{Q} = 100\text{ml/min}$.

Figure 4.2: Different Instant of Bubble Formation at $\varphi_s = 50^\circ, R_0 = 1\text{mm}$ and $\dot{Q} = 100 \text{ ml/min}$.

Figure 4.3: Different Instant of Bubble Formation $\varphi_s = 110^\circ$, $R_0 = 1\text{mm}$ and $Q = 100\text{ ml/min}$

4.2 Contact Angle Variation with Time

The contact angle variation is change with each time step initially the bubble contact angle is high and when the initially $t=0$ and when the time steps is increasing with time than contact angle with time decreases and when the contact angle is initially decreases where the necking region begins to start where contact angle decreases to start and after that the contact angle begins to increase their variation of contact angle graph like parabola .

Figure 4.4: Contact Angle Variation with Time

The bubble grows upwards as time-lapse. We take the different static contact angle $\varphi_s = 0^\circ, 50^\circ$ and 110° and check the variation of angle with the orifice rim of the plate when the bubble grows upwards, Initially contact angle decreases with time and when the bubble necking region begins than the contact angle of the bubble with orifice rim increases drastically

4.3 Bubble volume Variation with Time

Figure 4.5: Bubble Volume with Time

The bubble dimension in mm^3 variation concerning time, we make the assumption as a bubble volume take as a spherical volume which we take as linear variation relation i.e., $V(t) = V_0 + Q_g t$ this relation we consider to calculate the bubble volume in each time step. We take as a reference paper to take this assumption (bubble generation in quiescent and co-flowing fluid) and we consider the bubble volume consider as spherical shape. This linear line is generated from the above linear relation and the other volume is calculated volume at each time step at different static contact angle φ_s . Volume (1) is predicted for $\varphi_s = 0^\circ$ calculated volume for simulation data, volume (2) is predicted for the $\varphi_s = 50^\circ$ calculated volume for generated data by simulation and volume (3) is predicted for the $\varphi_s = 110^\circ$ calculated volume for generated data for the simulation.

4.4 Bubble Diameter Variation with Time

Diameter variation concerning time as the bubble volume varies with time than bubble diameter is change with respect to time than we calculate the bubble diameter variation concerning time we take the relation to calculate the bubble diameter variation with time $D_b(t) = D_0^{3/2} + (6Q_g/\pi)t^{1/3}$

Hence, we calculate the bubble diameter variation with respect to time using above relation take from reference paper (study of bubble formation under constant flow condition)

Figure 4.6: Change in Diameter with Respect to Time

φ_s^0	$V_b(\text{mm}^3)$ VOF (100ml/min)	$V_b(\text{mm}^3)$ VOF (10ml/min)	Analytical data (Gerlach et al. (2005) $Q \rightarrow 0$)	Analytical data Fritz (1935) $Q \rightarrow 0$
0	190.4	39	35	0
50	217.9	39	35	12
110	167.82	139	126	126

We made table to compare different result for different static contact angles φ_s at an orifice of $R_0 = 1\text{mm}$ under gas flow rate 100ml/min

As we saw in the simulation the bubble volume increases with increases in each timestep we plot the graph volume v/s time and we calculate the volume in each time step, initially the surface tension F_c developing on the downward direction and surface tension force acting on the periphery of the bubble after some time steps bubble volume increases due to which buoyancy force F_b also increases as a comparison to capillary forces due to which bubble moves upward and

bubble periphery widening due to surface tension of bubble and as the bubble moves upwards the necking region is going to start formed and we the snapshot the necking region is going to begins almost 0.07 sec near to start in each bubble static contact angle but the diameter in each contact angle is different due to surface tension varies concerning contact angle because surface tension force is usually expressed in the form of $2\pi R_0 \cos \theta$. As we calculate the different surface tension in each different time step with different contact angles.

Pinch-off time

Pinch-off time in each static contact angle $\varphi_s = 0^\circ, 50^\circ$ and 110° near to 0.09 sec but at that timestep that the base diameter is vary at each static contact angle $\varphi_s = 0^\circ$ the base diameter is 1.6mm, $\varphi_s = 50^\circ$, the base diameter is 1.4mm and $\varphi_s = 110^\circ$ is 1.5mm and we see in this simulation the base diameter also varies alongside the variation of the static contact angle φ_s and due to which capillary force inertia force and surface tension force is varied as the bubble dynamics

Bubble volume with contact angle

Bubble volume varies with the contact angle and we calculate the bubble volume in different static angle $\varphi_s = 0^\circ$, the bubble dimension (mm^3) at the time step 0.09 is 235.4 mm^3 , $\varphi_s = 50^\circ$, the bubble volume at the time step 0.09 s is 217.9 mm^3 and $\varphi_s = 110^\circ$ the bubble dimension (mm^3) the time step 0.09 s is 167.82 mm^3 and we get the result that the bubble volume is varied with the static contact angle φ_s and the bubble volume increase with decrease with static contact angle φ_s . And this is easily seen in the above plot.

CONCLUSIONS

The result of the numerical study of bubble formation at the single immersed orifice and constant inflow condition (100ml/min) was presented. Bubble volume increases with decreasing static contact angle φ_s . The bubble volume increases almost linearly at each static contact angle $\varphi_s = 0^\circ$, $\varphi_s = 50^\circ$ and $\varphi_s = 110^\circ$ as we compare the result 10ml/min with the 100ml/min then I will get that the bubble volume increases with increases good wetting condition but if we move from good to the poor wetting condition than the bubble volume decreases at the pinch-off time that predicts the bubble volume at 100ml/min is increases at good wetting condition but it decreases when it moves from good to poor wetting condition and surface tension play an important role to move the bubble and bubble periphery widening and detachment

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APPENDIX 1.1

S.No.	Date	Presenters
1	13/11/2020	Sachin Kumar