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Chapter 2

Rise dynamics of bubbles in a liquid

Abstract

The rise trajectories of air bubbles of 4, 5, 7, 8, 9, 12 and 20 mm in diameter rising in a two-dimensional rectangular column filled with water have been simulated using computational fluid dynamics. The simulations were carried out using the Volume-of-Fluid (VOF) technique developed by Hirt and Nichols (1981). To solve the Navier-Stokes equations of motion we used a commercial solver, CFX 4.1c of AEA Technology, UK. The extent of lateral motion of the bubbles decreases with increasing bubble size. The 7, 8 and 9 mm bubble behave like jellyfish. The 12 mm bubble flaps its wings like a bird. The 20 mm bubble assumes a circular cap form and rise vertically without any lateral motion. Video recordings of air bubbles rising in a 2D rectangular column of 0.3 m width and 5 mm between the front and back plates confirm the jellyfish and bird-like motion of bubbles.

1. Introduction

In many applications in chemical engineering it is important to be able to describe the motion of gas bubbles in a liquid. The morphology and rise characteristics of a bubble are strongly dependent on the bubble size and system properties. A generalised graphical representation (Clift et al. 1978, Fan and Tsuchiya 1990) of the rise characteristics is possible in terms of the Eötvös number (Eö), Morton number (M) and Reynolds number (Re*); see Fig. 1. For the air-water system (M = 2.63x10^-11; log(M) = -10.6) we note that increasing the bubble size from say 4 mm (corresponding to Eö = 2.2) to 20 mm (Eö = 54.4) the regime changes from “wobbling” to “spherical cap”. Our objective in this chapter is to examine in detail the transition between these two regimes using Computational Fluid Dynamics. Specifically, we use the Volume-of-Fluid (VOF) technique developed by Hirt and Nichols (1981).

2. Volume-of-Fluid simulations

The VOF model (Delnoij et al. 1997b, Hirt and Nichols 1981, Krishna and van Baten 1999a/1999b, Krishna et al. 1999a/1999c, Tomiyama et al. 1993a/1993b) resolves the transient motion of the gas and liquid phases using the Navier-Stokes equations, and accounts for the topology changes of the gas-liquid interface induced by the relative motion between the dispersed gas bubble and the surrounding liquid. The finite-difference VOF model uses a donor-acceptor algorithm, originally developed by Hirt and Nichols (1981), to obtain, and maintain, an accurate and sharp representation of the gas-liquid interface. The VOF method defines a fractional volume or “colour” function c(x,t) that indicates the fraction of the computational cell filled with liquid. The colour function varies between 0, if the cell is completely occupied by gas, and 1, if the cell consists only of the liquid phase. The location of the bubble interface is tracked in time by solving a balance equation for this function:

\[
\frac{dc(x,t)}{dt} + \nabla \cdot (uc(x,t)) = 0
\]

(1)
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Fig. 1. Shape regimes for bubble rising in a column of liquid. The thick line drawn in this figure, log(M) = -10.6, corresponds to the properties of an air-water system, with Morton number M = 2.63×10^{-11}.

The liquid and gas velocities are assumed to equilibrate over a very small distance and essentially \( u_\alpha = u \) for \( \alpha = L, G \) at the bubble interface. The mass and momentum conservation equations can be considered to be homogenous:

\[
\nabla \cdot (\rho u) = 0
\]

\[
\frac{\partial \rho u}{\partial t} + \nabla \cdot (\rho uu) = -\nabla p - \nabla \cdot \tau + \rho g + F_{sf}
\]

where \( p \) is the pressure, \( \tau \) is the viscous stress tensor, \( g \) is the gravitational force. The density and viscosity used in eqs (2) and (3) are calculated from

\[
\rho = \epsilon_L \rho_L + \epsilon_G \rho_G
\]

\[
\mu = \epsilon_L \mu_L + \epsilon_G \mu_G
\]

where \( \epsilon_\alpha \) denotes the volume fraction of the phase \( \alpha = L, G \). The continuum surface force model, originally proposed by Brackbill et al. (1992), is used to model the force due to surface tension acting on the gas-liquid interface. In this model the surface tension is modelled as a body force \( F_{sf} \), that is non-zero only at the bubble interface and is given by the gradient of the colour function

\[
F_{sf} = \sigma \vartheta(x) \nabla c(x,t)
\]

where \( \vartheta(x) \) is the local mean curvature of the bubble interface:
\[ \vartheta(x,t) = - \nabla \left( \frac{n}{|n|} \right) \]  

(6)

where \( n \) is the vector normal to the bubble interface:

\[ n = \nabla c(x,t) \]  

(7)

The set of equations (1) – (7) were solved using the commercial flow solver CFX 4.1c of AEA Technology, Harwell, UK. This package is a finite volume solver, using body-fitted grids. The grids are non-staggered and all variables are evaluated at the cell centres. An improved version of the Rhie-Chow (Rhie and Chow, 1983) algorithm is used to calculate the velocity at the cell faces. The pressure-velocity coupling is obtained using the SIMPLEC algorithm (Van Doormal and Raithby, 1984).

**Table 1.**

Results of two-dimensional VOF simulations in Cartesian geometry. In all cases the gas phase was air (\( \rho_g = 1.29 \text{ kg m}^{-3} \), \( \mu_g = 1.7 \times 10^5 \text{ Pa s} \)) and the liquid was water (\( \rho_l = 998 \); \( \mu_l = 10^{-3} \); \( \sigma = 0.072 \text{ N/m} \)). The height of water column was 0.09 m.

<table>
<thead>
<tr>
<th>Bubble diameter, ( d_b )/[m]</th>
<th>Column width, ( D_T )/[m]</th>
<th>Grid size, ( \Delta x (= \Delta z) )/[mm]</th>
<th>Time step, ( \Delta t )/[s]</th>
<th>Eötvös number</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.004</td>
<td>0.025</td>
<td>0.125</td>
<td>0.0003</td>
<td>2.18</td>
</tr>
<tr>
<td>0.005</td>
<td>0.025</td>
<td>0.125</td>
<td>0.0001</td>
<td>3.40</td>
</tr>
<tr>
<td>0.007</td>
<td>0.025</td>
<td>0.125</td>
<td>0.0002</td>
<td>6.67</td>
</tr>
<tr>
<td>0.008</td>
<td>0.025</td>
<td>0.2</td>
<td>0.0005</td>
<td>8.71</td>
</tr>
<tr>
<td>0.009</td>
<td>0.04</td>
<td>0.16</td>
<td>0.0003</td>
<td>11.02</td>
</tr>
<tr>
<td>0.012</td>
<td>0.04</td>
<td>0.16</td>
<td>0.0003</td>
<td>19.59</td>
</tr>
<tr>
<td>0.020</td>
<td>0.04</td>
<td>0.16</td>
<td>0.0003</td>
<td>54.43</td>
</tr>
</tbody>
</table>

All simulations reported here were carried out in a rectangular column using a uniform 2D Cartesian coordinate grid; details are given in Table 1. The front of the 2D rectangular grid is formed by the \( x-z \) plane. No account is taken of the variation along the depth of the system, and the simulations are truly two-dimensional. At the two walls, the no-slip boundary condition is imposed. The column is modelled as an open system, so the pressure in the gas space above the initial liquid column is equal to the ambient pressure (101.325 kPa). For the convective terms in the equations hybrid differencing was used. Upwind differencing was used for the time integration. The time step used in the simulations were usually 0.0003 s or smaller. To counteract excessive smearing of the liquid-gas interface by numerical diffusion, a surface sharpening routine was invoked. This routine identifies gas and liquid on the “wrong” side of the interface, and moves it back to the correct side, while conserving volume of the respective phases. In order to avoid “dissolution” of the bubble due to surface sharpening we found it necessary to ensure that each bubble area encompassed a few hundred cells. For simulations of bubble sizes smaller than 12 mm, we found that the rich dynamic features could be captured only by allowing at least 800 grid cells per bubble cross-section. This constraint resulted in grid sizes as small as 0.125 mm for the smallest bubble size we could simulate with adequate accuracy; see Table 1. All simulations were carried out using the parallel version of CFX 4.1c running on a Silicon Graphics Power Challenge machine with six R8000 processors. To give an indication of the required CPU time, the simulation of the rise of a 7 mm diameter bubble for 0.75 s in a column of 0.025 m width and 0.09 m height, involving 144000 grid cells, required about two weeks.
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Fig. 2. Rise of a 20 mm air bubble in a column of 0.04 m width and 0.09 m height. Animations of this VOF simulation can be viewed on our web site http://ct-cr4.chem.uva.nl/single_bubble.

![Time, t [s]] 0.0235 0.0955 0.1675 0.2395 0.3115 0.3835

Fig. 3. Snapshots obtained with 2D VOF simulations of the rise trajectories of bubbles in the 4 – 12 mm size range. (a) Snapshots of 4 mm bubble at times \( t = 0.0415, 0.0955, 0.1495, 0.2035, 0.2575, 0.3115, 0.3655, 0.4195, 0.4735, 0.5275, 0.5815, 0.6355 \) and 0.6895 s from the start of the simulations. (b) Snapshots of 5 mm bubble at times \( t = 0.0285, 0.0825, 0.1365, 0.1905, 0.2445, 0.2985, 0.3525, 0.4065, 0.4605, 0.5145, 0.5685, 0.6225, 0.6765 \) and 0.7305 s. (c) Snapshots of 7 mm bubble at \( t = 0.0285, 0.1005, 0.1725, 0.2445, 0.3165, 0.3885, 0.4605, 0.5325, 0.6045 \) and 0.6765 s. (d) Snapshots of 9 mm bubble at times \( t = 0.0415, 0.1135, 0.1855, 0.2575, 0.3295 \) and 0.4015 s. (e) Snapshots of 12 mm bubble at times \( t = 0.0595, 0.1315, 0.2035, 0.2755, 0.3475, 0.4195, 0.4915 \) and 0.5635 s. (f) Snapshots of 20 mm bubble at times \( t = 0.1675, 0.2395, 0.3115 \) and 0.3835 s. Animations of all these VOF simulations can be viewed on our web site http://ct-cr4.chem.uva.nl/single_bubble.

Initially a circular shaped bubble is placed near the bottom of the column filled with liquid and the simulations started. As illustration, the time trajectories of a 20 mm circular bubble placed in a column of 0.04 m width and 0.09 m height are shown in Fig. 2. The bubble first adjusts itself to a circular cap shape and in doing so, there is breakage of bubbles at the edges. The circular shape form is attained after about 0.1 s from the start of the simulations. For bubbles smaller than 20 mm, no bubble breakage was observed and the time trajectories are shown in Fig. 3. The 4 and 5 mm bubbles show meandering trajectories. The 7 mm bubble oscillates from side to side when moving up the column. The 8 and 9 mm bubbles behave like jellyfish. The 12 mm bubble flaps its “wings” like a bird. The 20 mm bubble has a vertical
trajectory. These rich dynamic features can be viewed by looking at the animations on our web site http://ct-cr4.chem.uva.nl/single_bubble/. As the bubble size increases the amplitude of these excursions in the x-directions decrease; see Fig. 4.

Fig. 4. Comparison of the x-trajectories obtained with 2D VOF simulations of bubbles in the 4 – 20 mm size range.

Fig. 5. The experiment set-up for observing the rise characteristics of single gas bubbles in a 2D rectangular column of water.
3. Experimental

The jellyfish and bird-like motions of the bubbles are intriguing and in order to verify these Urseanu (2000) tracked the rise characteristics of air bubbles in a 2D rectangular column of water. Her experiments are reported here for comparison with the VOF simulations. The column was made up of two parallel glass plates of 0.3 m width and 4 m height; see Fig. 5. The distance between the glass plates was 5 mm. There was provision to inject gas bubbles via a central tube of 2 mm diameter in the distributor. The bubble trajectories were recorded on video at 25 frames per second using the image capturing set-up described in an earlier study (De Swarte et al., 1996).

The re-traced video images for bubbles of 9.7, 12.3, 13.7 and 15.5 mm in size are shown in Fig. 6. Though there is no one-to-one correspondence with the VOF simulation results seen in Fig. 3 we several qualitative agreement in the dynamic features. The 9.7 mm bubble meanders from side to side. The 12.3 mm bubble exhibits jellyfish like characteristics. Close observation of the edges of the 13.7 mm bubble confirms the vertical oscillation of the edges of the bubbles, analogous to the flapping of the wings of a bird. When the bubble size increases to 15.5 mm, these vertical oscillations of the edges vanish and the bubble moves more-or-less in a vertical line.

![Fig. 6. Re-traced video recordings of the rise characteristics of 9.7, 12.3, 13.7 and 15.5 mm bubbles observed in a 2D rectangular column shown in Fig. 5.](image)

4. Conclusions

We have demonstrated that the Volume-of-Fluid (VOF) simulation technique is a powerful tool for studying the rise characteristics of air bubbles in a 2D rectangular column of water. Bubbles in the 4 – 12 mm size range reveal rich dynamic features. When the bubble size increases from 4 mm to 20 mm, there is a gradual decrease in the lateral movement. There are also several qualitative changes in the bubble morphology and rise characteristics. In particular the jellyfish like behaviour of 7 – 9 mm bubbles and the vertical oscillations of the
edges of bubbles in the region of 12 mm are noteworthy. These features were confirmed experimentally by Urceanu (2000) using video-imaging techniques.