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Levitation of air bubbles in liquid under low frequency vibration excitement

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Abstract

This experimental study reports the influence of low frequency vibrations, in the range of 50–250 Hz, on the rise of single gas bubbles injected into a column of liquid. Water and a high-viscosity hydrocarbon-oil were used as the liquid phase. For a specified set of operating conditions the bubble can be made to levitate, i.e. held stationary in the column. The bubbles employed had volumes that varied from 0.01 to 0.6 mL. The height of the liquid, h, above the position at which the bubble is levitated was determined for a wide range of operating conditions (bubble volume V_b, vibration frequency, f, pressure above the liquid surface, P, and the vibration amplitude, λ). The experimental values of h are in good agreement with the theoretical model of Baird (1963. Resonant bubbles in a vertically vibrating column. Canadian Journal of Chemical Engineering 41, 52–55).

Keywords: Bubbles; Bubble levitation; Vibration frequency; Vibration amplitude; Acoustic force

1. Introduction

Bubble column reactors are widely used in the chemical industry for carrying out a variety of liquid phase reactions (Deckwer, 1992). For relatively fast reactions, there is often a need to improve the mass transfer between the gas and liquid phases. The mass transfer performance is dictated by both the bubble size and the bubble rise velocity. One method of influencing both the bubble size and the bubble rise velocity is to subject the liquid phase to vibrations, as was demonstrated several decades ago (Baird, 1963a,b; Buchanan et al., 1962; Crum and Eller, 1970, 1975; Harbaum and Houghton, 1960; Jameson and Davidson, 1966) and also in some recent experimental investigations (Abe et al., 2002; Ellenberger and Krishna, 2003; Ellenberger et al., 2005a; Fan and Cui, 2005; Knopf et al., 2005a,b).

In two classic papers (Baird, 1963a; Jameson and Davidson, 1966) it has been shown that single gas bubbles can be held stationary in the column when the downward force due to vibrations balances the buoyancy force. Assuming that (i) the volume of the liquid in the column above the bubble undergoes piston-type pulsations, (ii) radial pulsations extend outwards from the bubble surface to a spherical boundary of radius R_c and (iii) the stationary resonant bubbles are spherical, Baird (1963a) derived a model to predict the distance h between the levitated bubble and the liquid surface. For bubbles with a mean radius of $r_0 < R_c$ this model is given by

$$f = \frac{1}{2\pi r_0} \frac{\left(\dfrac{3\gamma(P+\rho g h)}{\rho}\right)^{1/2}}{\left[1 + (r_0/R_c)\left(\dfrac{4h}{R_c} - 1\right)\right]^{1/2}}, \tag{1}$$

where P is the pressure above the surface of the liquid. Eq. (1) can be solved for the distance h between the levitated bubble and the liquid surface

$$h = \frac{\left(\dfrac{3R_c^2\gamma P}{4\omega^2 r_0^3 \rho} - \dfrac{R_c^2}{4r_0} + \dfrac{R_c}{4}\right)}{\left(1 - \dfrac{3R_c^2\gamma g}{4\omega^2 r_0^3}\right)}. \tag{2}$$

In Eq. (2) ω is the angular frequency defined as $\omega = 2\pi f$.

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The major objective of the current investigation is to provide a comprehensive test of the applicability of Eq. (2) for predicting the height h at which the bubble is "trapped". For this purpose we carried out a comprehensive set of experiments to study the influence of a range of operating parameters (vibration frequency, f, vibration amplitude, λ, operating pressure, P, and liquid density, ρ) on h.

2. Experimental set-up and procedure

Experiments were carried out in a set-up consisting of a polyacrylate column, a vibration exciter, a power amplifier, a high-speed video camera and a personal computer. A schematic representation of the set-up is given in Fig. 1. The column had an inner diameter of 0.014 m and a height of 1.36 m. Gas injection ports at 0.05, 0.5 and 0.7 m from the bottom of the column allowed for the injection of gas bubbles into the liquid in the column by means of 0.05 or 1 mL syringes. The bottom of the polyacrylate column was firmly screwed onto a shaft projecting from the top of an air-cooled vibration exciter (*TIRAvib* 5220, TIRA Maschinenbau GmbH, Germany). In this way, vertical displacements of the shaft at specified amplitudes (λ) and frequencies (f) fully corresponded to displacements of the column. The vibration exciter was coupled to a power amplifier and the entire vibration set-up was fully controlled from a personal computer (PC) using *SignalCalc 550 Vibration Controller* software (Data Physics Corporation, United States). The frequency range of the vibration exciter is 2–5000 Hz. Depending on the operating frequency, the amplitude could be varied between 0 and 12 mm. Note that the amplitude of vibration, λ, is defined in this paper as the absolute value of the maximum positive or negative displacement of the vibration exciter from its rest position. The vibration exciter was programmed to generate sinusoidal oscillations.

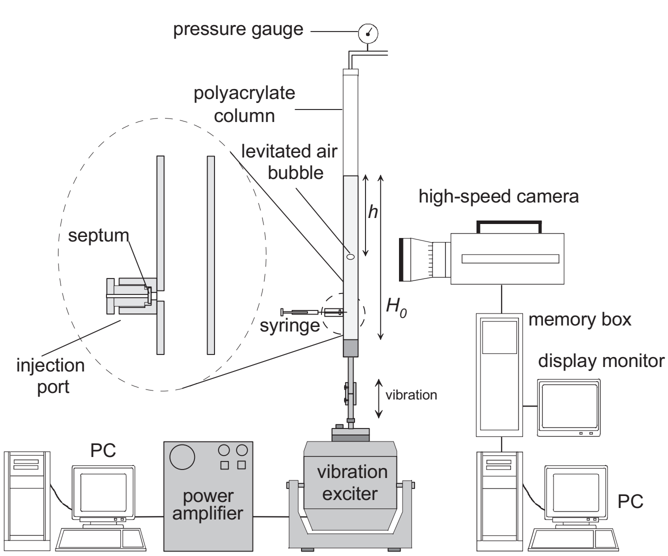

Fig. 1. Experimental set-up of the cylindrical polyacrylate liquid-filled column subjected to low frequency vibrations. Further details on the set-up are available elsewhere (Ellenberger et al., 2005b).

Video movies were made of the injected bubbles by utilizing a Photron Fastcam-ultima 40 K high-speed video camera, which has the capability of recording at between 30 frames per second (fps) and 40 500 fps. The camera was connected to a memory box, which allowed for movies being made to be instantaneously stored, as well as a display monitor, which permitted real-time viewing of the movies. Lighting for the movies was provided by a single *Dedotec dedocool* 250 W Halogen Photo Optic lamp. This lamp had the unique property of providing sufficient illumination without increasing the ambient temperature. After each video recording, data obtained were transferred from the memory box to a PC for analysis.

For all experiments carried out, air bubbles served as the gas phase with demineralised water or Tellus oil utilised as the liquid phase. Tellus oil (Shell, The Netherlands) is a hydrocarbon oil, with a viscosity 75 times greater than that of water. The respective densities (ρ) of water and Tellus oil are 998 and 862 kg/m^3. All experiments were conducted at room temperature. In order to carry out experiments, the polyacrylate column was liquid-filled to a height H_0. The vibration system was then started at a set frequency and amplitude. Once the vibrations became stable, which often took about 10 s, a gas bubble of known volume (V_b) was then injected into the column through one of the three gas injection ports. The clear liquid height (H_0) was varied in the range of 0.4–1.2 m. Bubble volumes ranging from 0.01 to 0.6 mL were used in all experiments. The vibration frequencies (f) employed were in the range of 50–250 Hz. The dimensionless vibration intensity $\Gamma = \lambda\,(2\pi f)^2/g$ was varied from 1.8 to 6. With the exception of one experimental set, all experiments were conducted at atmospheric pressure. Varying the absolute pressure above the liquid phase was done by using a cork-sealed tube, which was placed at the top of the column. Pressures below atmospheric were obtained by connecting the tube to a vacuum system. For pressures above atmospheric, the tube was connected to a pressure-controlled air tap. The atmospheric pressure $P = P_0$ was set to 101 325 Pa and the excess pressure was read from a pressure gauge that was connected to the tube.

Further details of the experimental set-up, including photographs, can be viewed on our website (Ellenberger et al., 2005b). The website also includes video recordings of the bubble levitation phenomenon. From the video recordings it appears that at levitation conditions the bubble seems to split into small clusters and then recombines; the whole process is in dynamic equilibrium. This aspect deserves further investigation but is outside the scope of the present investigation.

3. Results and discussion

Fig. 2a shows the influence of varying bubble volume V_b on the height at which the bubble is levitated in a column filled with water and vibrated at frequencies of 100 and 200 Hz. With increased bubble volume the buoyancy force increases and therefore the bubble is levitated at positions closer to the liquid surface, i.e., the height h decreases with increasing V_b. The theoretical model of Baird (1963a), Eq. (2), predicts the correct trend of the $h - V_b$ dependence. Also, the magnitude of

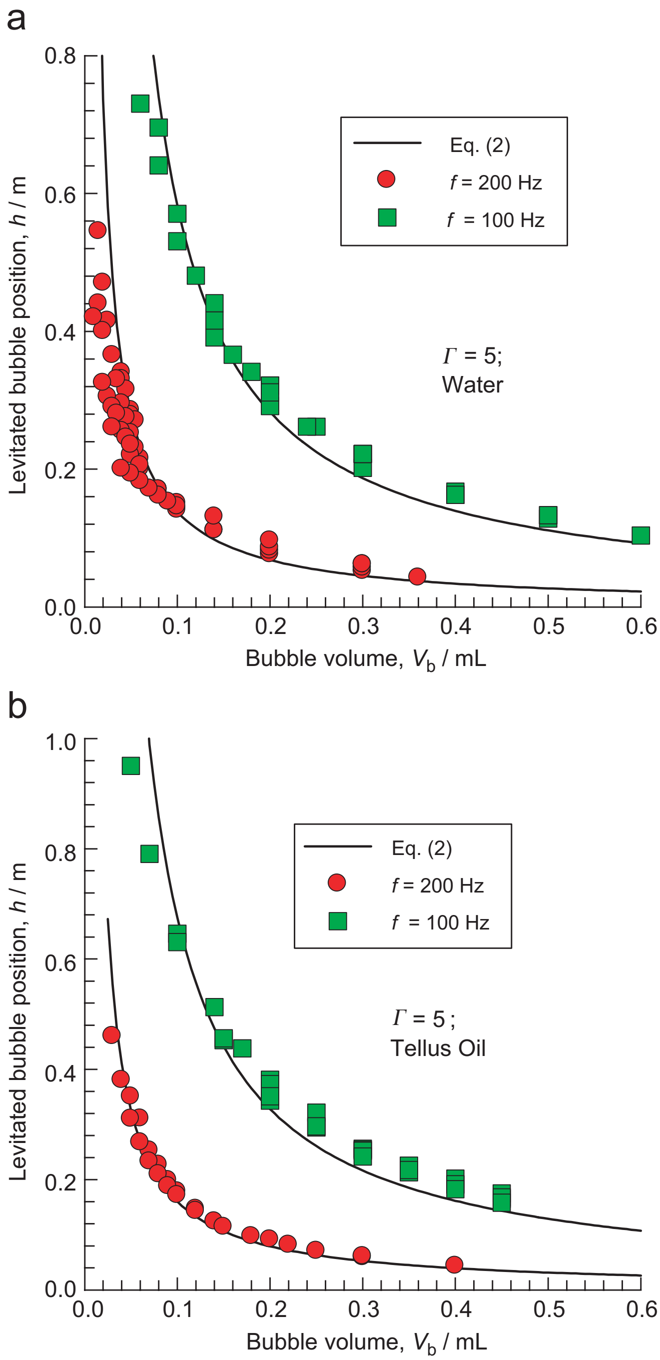

Fig. 2. Influence of bubble volume V_b on the height h at which the bubble is levitated in (a) water, and (b) Tellus oil. Experimental results at two different vibration frequencies, 100 and 200 Hz. In both cases the vibration intensity Γ was maintained constant at 5.

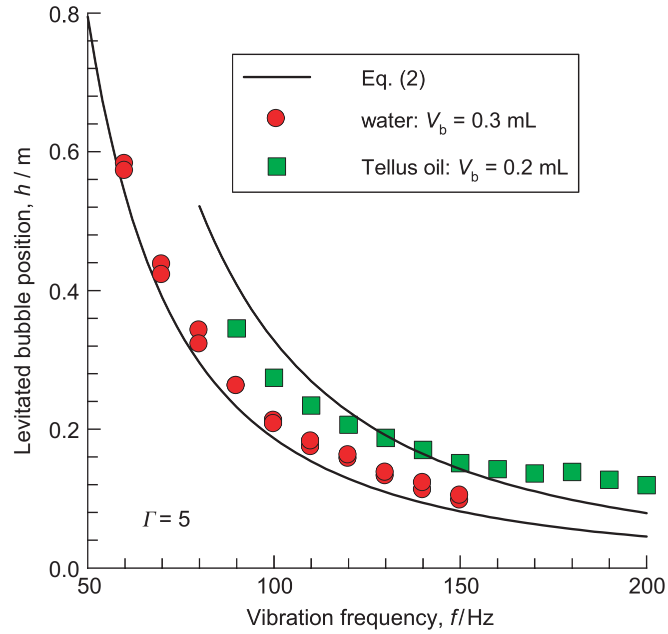

Fig. 3. Influence of vibration frequency f on the height h at which the bubble is levitated in water and in Tellus oil. Experimental results at fixed bubble volumes $V_b = 0.3$ and 0.2 mL in water and Tellus oil, respectively. In both cases the vibration intensity Γ was maintained constant at 5.

h is reasonably well predicted. The same conclusions hold for the experimental results with Tellus oil; see Fig. 2b, suggesting that the influence of liquid density is properly captured by the model.

Fig. 3 shows the influence of the vibration frequency f on the levitated height h for experiments in which the bubble volume was kept constant. The Baird model captures the right qualitative trend of the dependence of h on f; with increasing frequency the levitated position decreases. The vibration exciter used in our experiments can be programmed to vary the frequency at a prescribed rate. Fig. 4 shows the response of a levitated bubble to a 5 Hz per second change in frequency, when the frequency is continuously alternated between the limits of 100 and 130 Hz. The position of the levitated bubble responds practically instantaneously to changes in vibration frequency, going up when the frequency decreases and going down when the frequency increases. The bubble appears to "dance" as it continuously moves upwards and downwards along the column; video recordings of this phenomenon can be viewed on our website (Ellenberger et al., 2005b). Eq. (2) is able to retrace the up and down motion of the bubble in response to the frequency variations; witness the continuous solid line.

The Baird model also anticipates an influence of the pressure P acting above the liquid surface. Increasing P serves to counter the influence of buoyancy and leads to an increase in h. This is borne out in the experiments that were carried out with Tellus oil; see Fig. 5. Eq. (2) is seen to provide a good quantitative prediction of the influence of P.

The Baird model does not anticipate any influence of the vibration amplitude on the position at which the bubble is levitated. Experimental data for water, however, show a slight increase in h with increasing λ; cf. Fig. 6. The threshold value below which no levitation occurs is $\lambda = 0.045$ mm; this corresponds to a vibration intensity $\Gamma = 1.8$.

The total height of clear liquid in the column, H_0, is also not anticipated to influence the value of h. Experiments with water ($f = 200$ Hz; $V_b = 0.3$ mL) and Tellus oil ($f = 100$ Hz;

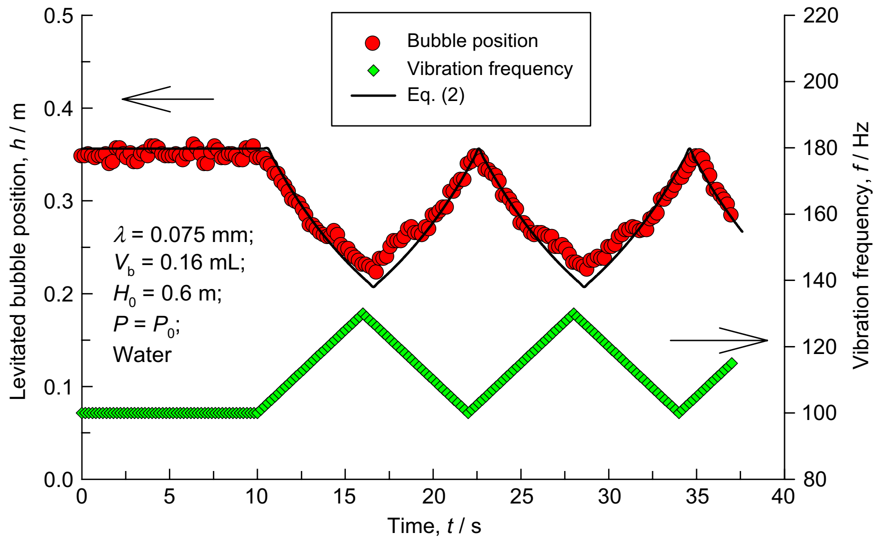

Fig. 4. Response of a 0.16 mL levitated bubble to time-dependent changes in vibration frequency. The frequency is alternated between the limits of 100 and 130 Hz at a rate of 5 Hz per second based on a program specification on the *SignalCalc 550 Vibration Controller* software. The calculated levitated bubble height using Eq. (2) is also shown.

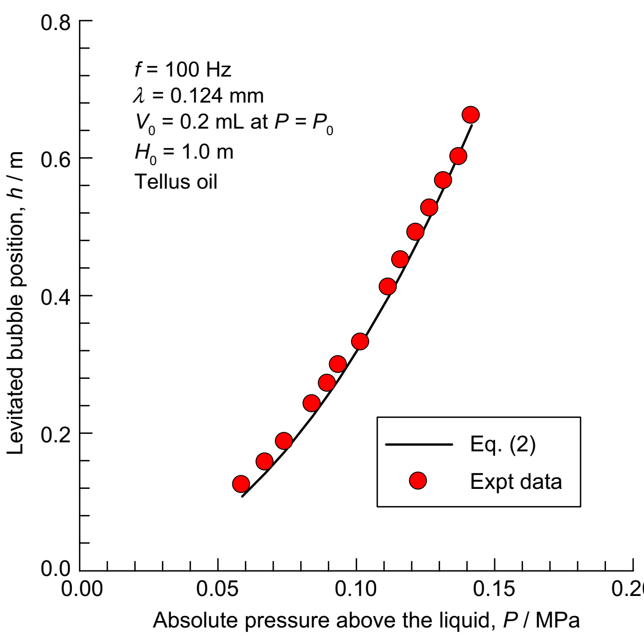

Fig. 5. Effect of absolute pressure above the levitated bubble on the position in the column, at which a bubble is levitated h, using Tellus oil as the liquid phase. Position $h = 0$ corresponds to the top of the liquid. Bubble volume $V_0 = 0.2$ mL (when $P = P_0$); frequency $f = 100$ Hz; amplitude $\lambda = 0.124$ mm. The volume of the injected bubble changes with the absolute pressure above the liquid phase, going from $V_0 = 0.144$ mL to $V_0 = 0.347$ mL for the range of pressures employed.

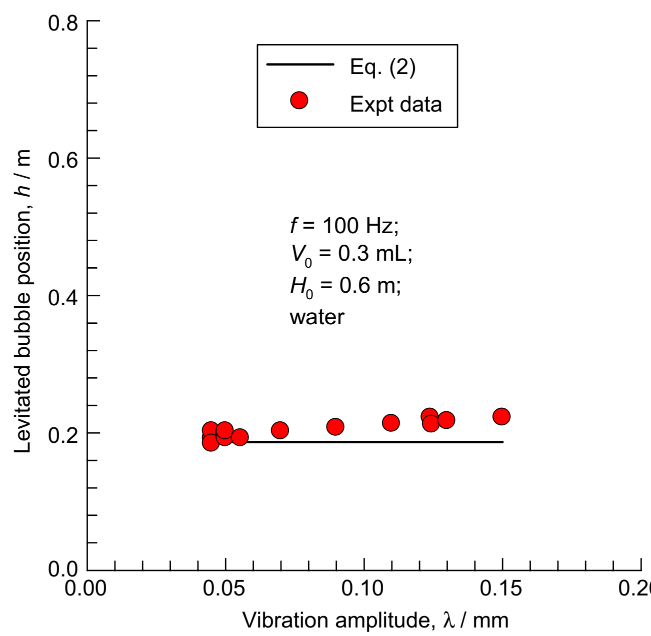

Fig. 6. Influence of the vibration amplitude λ on the levitated bubble height h. Experiments with water at 100 Hz vibration frequency. The continuous solid line represents calculations using Eq. (2).

$V_b = 0.3$ mL) carried out with varying H_0 appear to confirm this conclusion; see Fig. 7.

4. Conclusions

A study on the levitation of single air bubbles in liquid, in a 0.014 m diameter polyacrylate column, under the influence of low frequency vibration excitement was carried out. The following major conclusions can be drawn:

1. The position of a levitated bubble h is strongly influenced by the bubble volume V_b. Increasing V_b has the effect of increasing the buoyancy and causes a bubble to be levitated closer to the top of the liquid surface.
2. The position of a levitated bubble h is strongly dictated by the frequency of the vibration exciter f. Increasing the

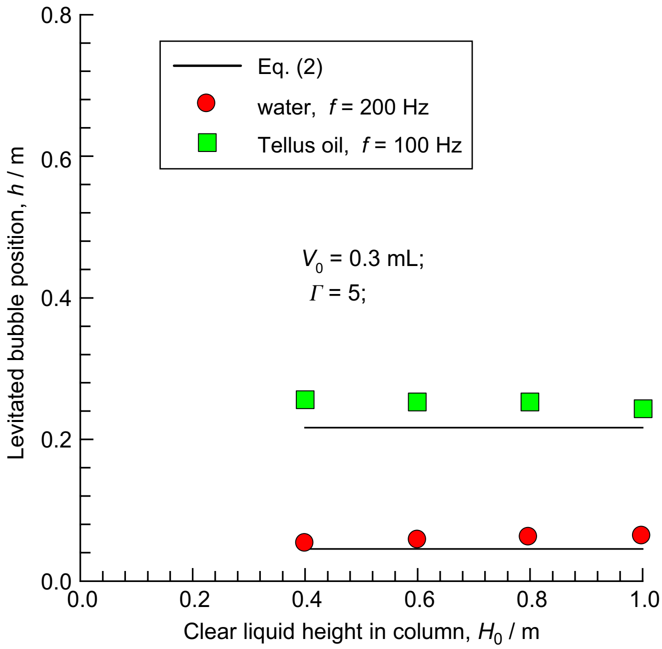

Fig. 7. Dependence of the levitated bubble height h on the clear liquid height in the column H_0. Experiments with water ($f = 200$ Hz; $V_b = 0.3$ mL) and Tellus oil ($f = 100$ Hz; $V_b = 0.3$ mL).

frequency causes a bubble of a given volume to be levitated closer to the top of the liquid surface.

3. By alternating the vibration frequency in a prescribed manner, a bubble can be made to "dance" up and down in the column.
4. The levitation height h is also dependent on the absolute pressure above the liquid P. Increased P tends to counteract the buoyancy effect.
5. The vibration amplitude has a small effect on the levitation height.

In all cases the model of Baird (1963a) is able to predict the correct qualitative trends and also provides a reasonably good quantitative prediction of levitation. The practical exploitation of bubble levitation phenomena will be the subject of follow-up investigations.

Notation

f	vibration frequency, Hz
g	acceleration due to gravity, 9.81 m/s^2
h	distance below liquid surface at which gas bubble is levitated, m
H_0	clear liquid height, m
P	pressure above the liquid surface at top of column, Pa
r_0	equilibrium bubble radius, m
R_c	column radius, m
t	time, s
V_b	bubble volume, m^3

Greek letters

γ	adiabatic constant; specific heat ratio for air = 1.4, dimensionless
Γ	vibration exciter intensity ($\Gamma = \lambda(2\pi f)^2/g$), dimensionless
λ	vibration amplitude, m
ρ	liquid density, kg/m^3
ω	angular frequency $=2\pi f$, s^{-1}

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