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Levitation of air bubbles and slugs in liquids under low-frequency vibration excitement

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Abstract

This experimental study reports the influence of low-frequency vibrations, in the range of 60–400 Hz, on the rise of single air bubbles and slugs injected into two columns (of diameters 0.014 and 0.05 m), filled with liquids of varying densities (in the range 889–1381 kg m^{-3}) and viscosities (in the range 0.48–1.4 Pa s). For a specified set of operating conditions the bubbles or slugs can be made to levitate, i.e. held stationary in the column. The height of the liquid, *h*, above the position at which the gas bubble is levitated was determined for a wide range of operating conditions (vibration frequency and amplitude, operating pressure, column diameter, liquid density and viscosity). The experimentally determined values of *h* are in good agreement with the theoretical model of Baird [1963a. Resonant bubbles in a vertically vibrating column. Canadian Journal of Chemical Engineering 41, 52–55].

Keywords: Bubbles; Slugs; Levitation; Vibration frequency; Vibration amplitude; Bubble columns

1. Introduction

The performance of bubble column reactors can be enhanced by controlling the bubble size and its rise velocity. One method of influencing both the bubble size and the bubble rise velocity is to subject the liquid phase to low-frequency 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 (Ellenberger and Krishna, 2003; Ellenberger et al., 2005a; Fan and Cui, 2005; Knopf et al., 2005a, b).

In early classic publications (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 gives

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

and for slugs (i.e. the gas bubbles occupy the entire tube cross-section) with a mean volume $V_b = G\pi R_c^2$,

$$f = \frac{1}{2\pi}\left[\frac{\gamma(P+\rho g h)}{G\rho h}\right]^{1/2}, \tag{2}$$

where P is the pressure above the surface of the liquid. Eqs. (1) and (2) can be solved for the distance h between the levitated bubble and the liquid surface:

$$h = \frac{(3R_c^2\gamma P/4\omega^2 r_0^3\rho - R_c^2/4r_0 + R_c/4)}{(1-3\gamma g R_c^2/4\omega^2 r_0^3)}; \quad \text{bubbles} \tag{3}$$

and

$$h = \frac{\gamma P}{\rho(\omega^2 G - \gamma g)}; \quad \text{slugs.} \tag{4}$$

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In Eqs. (3) and (4) ω is the angular frequency defined as $\omega = 2\pi f$.

Ellenberger and Krishna (2007) subjected Eq. (3) to rigorous testing, using water and Tellus oil, as the liquid phase, and found it to be of good accuracy in describing the levitation height of bubbles. The major objective of the current investigation is to subject Eq. (4) to similar rigorous testing, and in particular to see whether the Baird model is successful for predicting the height h at which a slug is “trapped”. For this purpose we carried out a comprehensive set of experiments with air bubbles or slugs injected into three different liquids, with much higher viscosities than used in our earlier publication; this was essential in order to obtain slugs in the columns. Also, to extend the scope of our earlier study, the levitation phenomenon was investigated in columns of two different diameters to study the influence of a range of operating parameters (vibration frequency, f, vibration amplitude, λ and operating pressure, P) on h.

2. Experimental setup and procedure

Experiments were carried out in a setup consisting of two interchangeable polyacrylate columns, a vibration exciter, a power amplifier, a high-speed video camera and a personal computer (PC). A schematic representation of the setup is given in Fig. 1. The two columns had inner diameters of 0.014 and 0.050 m and heights of 1.36 and 0.30 m, respectively. Gas injection ports in the 0.014 m diameter column 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 syringes. Gas injection in the 0.05 m diameter column is done by a stainless steel tube with an inner diameter of 1.5 mm connected to syringes of appropriate volumes. The bottom of the polyacrylate columns 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 setup was fully controlled by a 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.

Video movies were made of the injected bubbles by utilizing a Photron Fastcam-ultima 40K high-speed video camera, which has the capability of recording at between 30 and 40 500 frames per second (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

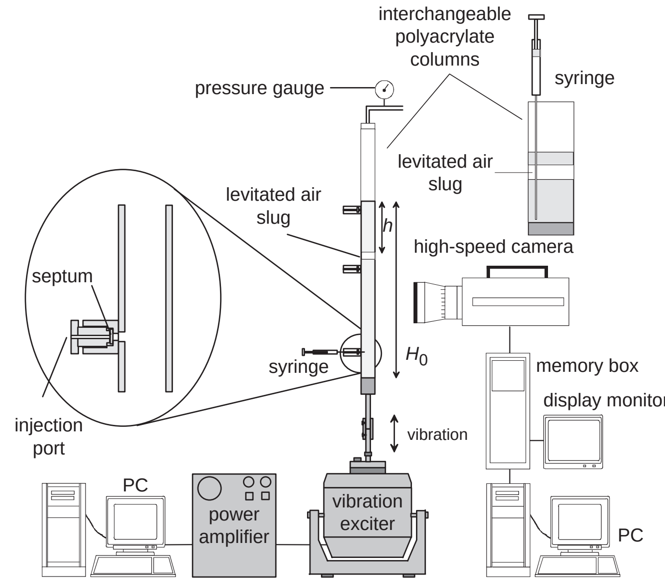

Fig. 1. Experimental setup of the cylindrical polyacrylate liquid-filled column subjected to low-frequency vibrations. Further details on the setup are available elsewhere (Ellenberger et al., 2005b).

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 in three different liquids. (1) Carsinus SS460 oil (Kroon-oil b.v., The Netherlands) with a dynamic viscosity η of 1.4 Pa s and a density ρ of 901 kg m^{-3} at room temperature. (2) Oil mixture consisting of 70% G Carsinus SS460 oil and 30% G Tellus oil 32 (Shell, The Netherlands) with a dynamic viscosity η of 0.48 Pa s and a density ρ of 889 kg m^{-3} at room temperature, and (3) diluted honey (Honeyland b.v., The Netherlands) with a dynamic viscosity η of 0.82 Pa s and a density ρ of 1381 kg m^{-3} at room temperature.

All experiments were conducted at room temperature. In order to carry out experiments, the 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. The clear liquid height (H_0) was 0.13 m in the 0.05 m diameter column and was varied in the range of 0.355–1.13 m in the 0.014 m diameter column. The vibration frequencies (f) employed were in the range of 60–400 Hz. The dimensionless vibration intensity $\Gamma = \lambda(2\pi f)^2/g$ was varied from 5.5 to 12. For safety reasons, the maximum value of Γ was 12, corresponding to an amplitude $\lambda = 0.8$ mm at a frequency $f = 60$ Hz and $\lambda = 0.018$ mm at a frequency $f = 400$ Hz. Note that for experiments carried out at a constant value of Γ the amplitude λ has to be adjusted for each frequency f.

Most of the experiments were conducted at atmospheric pressure. Varying the absolute pressure above the liquid phase was

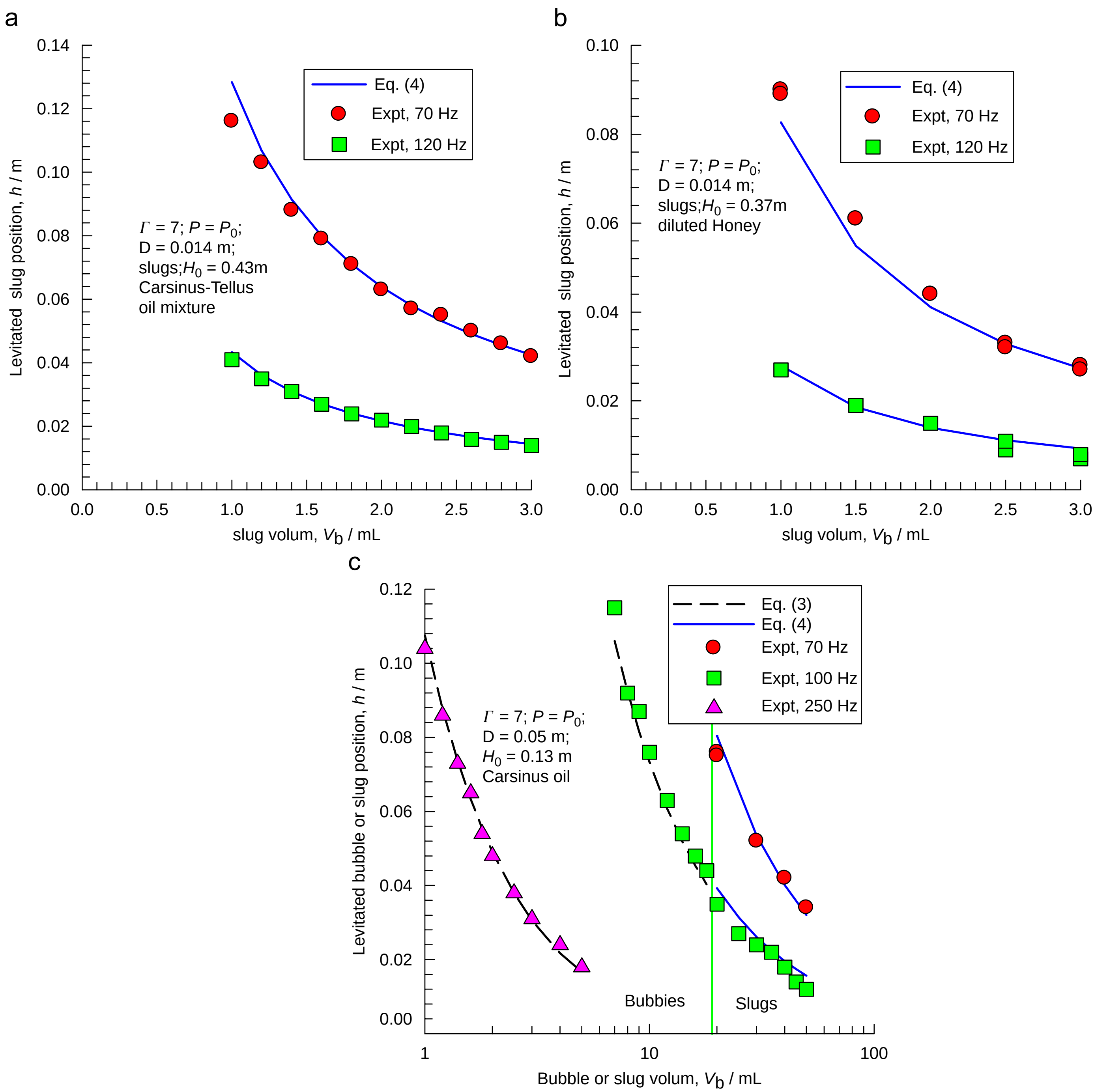

Fig. 2. Influence of bubble volume V_b on the height h at which the bubble is levitated in columns filled with (a) Carsinus oil–Tellus oil mixture, (b) diluted Honey, and (c) Carsinus oil.

done by using a cork-sealed tube, which was placed at the top of the column and 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 setup, including photographs, can be viewed on our website (Ellenberger et al., 2005b). The website also includes video recordings of the slug levitation phenomenon.

3. Results and discussion

Figs. 2a and b show the influence of varying slug volume V_b on the height h at which the air slugs are levitated at two different frequencies, 70 and 120 Hz in the 0.014 m diameter columns filled with either (a) Carsinus oil–Tellus oil mixture or (b) honey. With increasing slug 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

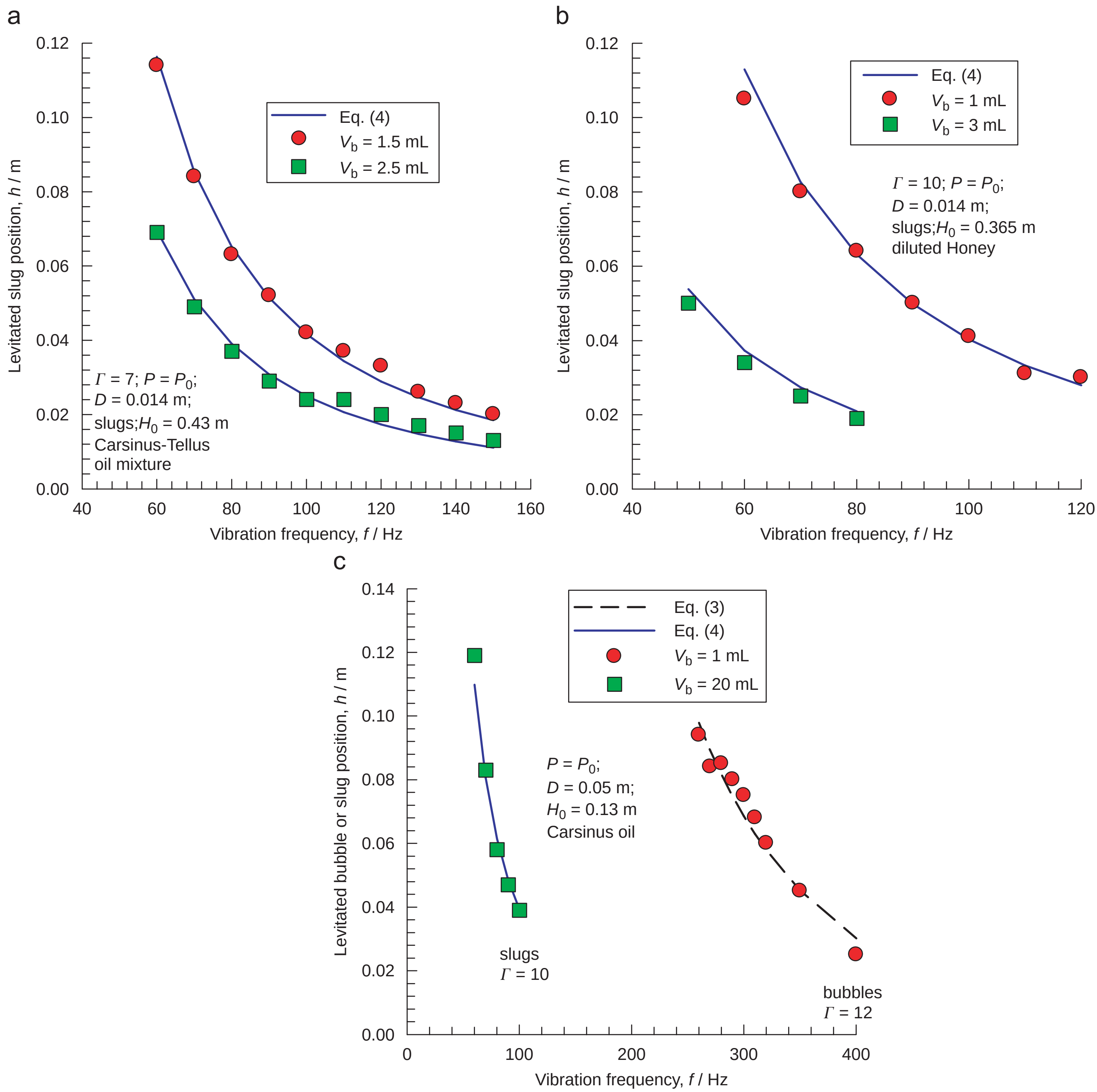

Fig. 3. Influence of vibration frequency f on the height h at which the bubble is levitated in column filled with (a) Carsinus oil–Tellus oil mixture, (b) diluted Honey, and (c) Carsinus oil.

V_b. In all experiments slugs were obtained and Eq. (4) predicts the correct trend of the h–V_b dependence for air slugs remarkably well for both sets of liquids used. Fig. 2c shows results obtained in the 0.05 m diameter column with Carsinus oil using vibration frequencies of 70, 100 and 250 Hz. For $V_b > 19$ mL slugs were formed and for $V_b < 19$ mL single air bubbles were realised. The calculations of h using either Eqs. (3) and (4), also indicated in Fig. 2c, provides a good description of the levitation height for either bubble or slug.

Figs. 3a and b show the influence of the vibration frequency f on the levitation height h for experiments in which the slug or bubble volume was kept constant. In this series of experiments, for each frequency f the amplitude λ is adjusted to maintain the dimensionless acceleration Γ at a constant value as specified in the legend. For experiments in the 0.014 m diameter column, slugs were obtained with both liquids used: (a) Carsinus oil–Tellus oil mixture and (b) honey. Eq. (4) captures the right trend of the dependence of h on f; with increasing frequency the

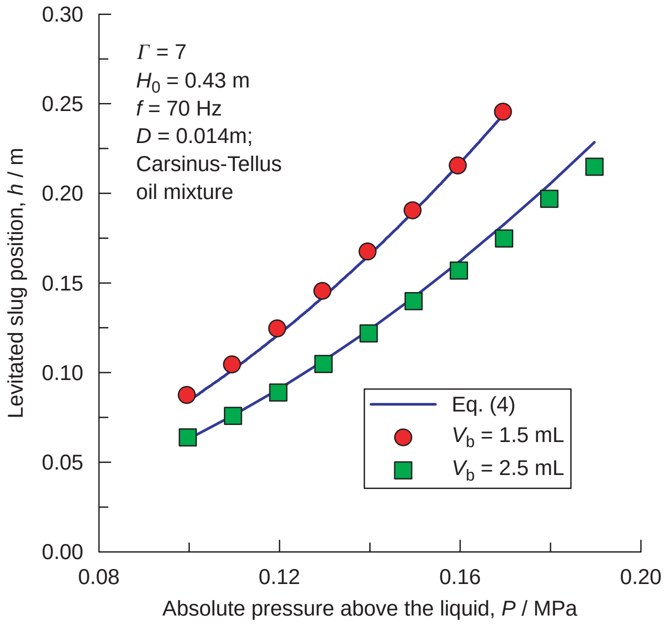

Fig. 4. Effect of absolute pressure above the levitated bubble on the position in the column, at which a bubble is levitated h in the 0.014 m diameter column filled with Carsinus oil–Tellus oil mixture. Position $h = 0$ corresponds to the top of the liquid. Bubble volumes are $V_b = 1.5$ and 2.5 mL (when $P = P_0$); frequency $f = 70$ Hz; vibration intensity $\Gamma = 7$. The volume of the injected bubble changes with the absolute pressure above the liquid phase.

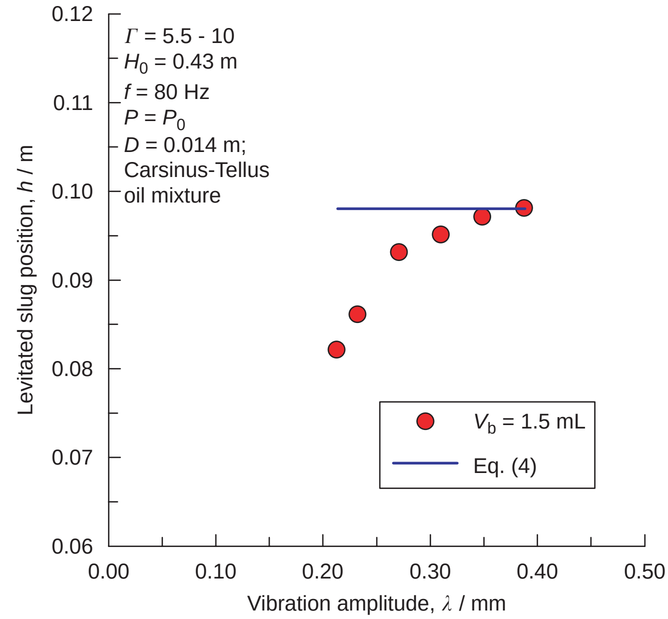

Fig. 5. Influence of the vibration amplitude λ on the levitated bubble height h in the 0.014 m diameter column filled with Carsinus oil–Tellus oil mixture. Experiments at 80 Hz vibration frequency. The continuous solid line represents calculations using Eq. (4).

levitated position decreases. Fig. 3c shows the corresponding results obtained in the 0.05 m diameter column with Carsinus oil. With $V_b = 1$ mL single *bubbles* were obtained and the levitation height could be described reasonably well with Eq. (3). With $V_b = 20$ mL, *slugs* were obtained and the experimental results agree very well with predictions of Eq. (4).

Eq. (4) 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 shown Fig. 4 for two different slug volumes V_b injected in the 0.014 m diameter column filled with Carsinus oil–Tellus oil mixture. Eq. (4) is seen to provide a good quantitative prediction of the influence of P.

Eq. (4) does not anticipate any influence of the vibration amplitude on the position at which the slug is levitated. Our experimental data for Carsinus oil–Tellus oil mixture in the 0.014 m diameter column, however, show an increase in h with increasing λ; cf. Fig. 5. Despite the fact that there is no theoretical model to describe the influence of the vibration amplitude on the levitated bubble position, the general trend is as follows: The minimum value of the dimensionless acceleration $\Gamma = \lambda(2\pi f)^2/g$ needed to match the theoretically derived prediction of the levitated bubble position h is higher if the bubble volume V_b decreases. Our experiments show out that bubble levitation below $\Gamma = 1$ is impossible.

The total height of clear liquid in the column, H_0, is also not anticipated to influence the value of h. Our experiments ($f = 80$ Hz; $V_b = 1.5$ and 2.5 mL) for Carsinus oil–Tellus oil mixture in the 0.014 m diameter column, at two different

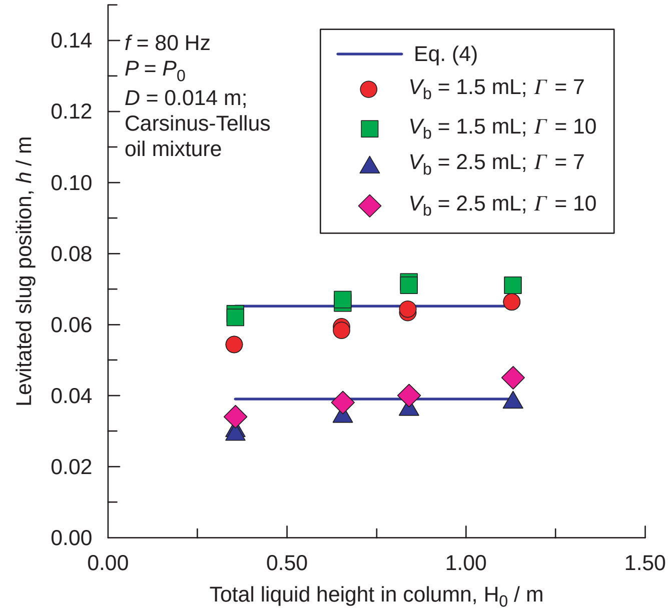

Fig. 6. Dependence of the levitated bubble height h on the clear liquid height H_0 in the 0.014 m diameter column filled with Carsinus oil–Tellus oil mixture. Experiments at $f = 80$ Hz for two different bubble volumes V_b and two different values of the vibration intensity Γ. The continuous solid lines represent calculations using Eq. (4).

values of the vibration intensity Γ carried out with varying H_0 show a slight increase in h with increasing H_0; see Fig. 6; Eq. (4) does not anticipate any influence of H_0 on the levitation height.

4. Conclusions

A study on the levitation of single air bubbles and slugs in three different liquids of varying density and viscosity in two different columns, under the influence of low-frequency vibration excitement was carried out. The following major conclusions can be drawn.

1. The levitation height h is strongly influenced by the bubble volume V_b. Increasing V_b has the effect of increasing the buoyancy and causes a bubble or slug to be levitated closer to the top of the liquid surface.
2. The levitation height h is strongly dictated by the frequency of the vibration exciter f. Increasing the frequency causes a bubble or slug of a given volume to be levitated closer to the top of the liquid surface.
3. The levitation height h is also dependent on the absolute pressure above the liquid P. Increased P tends to counteract the buoyancy effect.
4. The vibration amplitude λ has a significant effect on the levitation height.
5. The levitation height h shows a slight increase with the clear liquid height H_0.

Except for the influence of the vibration amplitude, λ, Eq. (3) or (4) provides a reasonably good *quantitative* prediction of levitation height.

Notation

f	vibration frequency, Hz
g	acceleration due to gravity, 9.81 m s^{-2}
G	height of slug, m
h	height below liquid surface at which gas bubble is levitated, m
H_0	clear liquid height, m
P	pressure above the liquid, Pa
r_0	equilibrium bubble radius, m
R_c	column radius, m
V_b	bubble or slug 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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