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Influence of low-frequency vibrations on bubble and drop sizes formed at a single orifice

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Abstract

We have studied the influence of low-frequency vibrations of the water phase, in the 50–400 Hz range, on the size of air bubbles and oil drops formed at a single orifice. A special device, called a vibration exciter, is mounted at the bottom of the column of 0.1 m diameter, filled with water. The vibration is transmitted to the water phase by means of a piston. Both the amplitude of the vibration and its frequency can be adjusted accurately. Air, or paraffin oil, is injected through a single capillary orifice into the column at a precisely controlled flow rate. The number of bubbles, or drops, issuing from the orifice is determined accurately by video imaging techniques. Application of vibrations to the water phase is seen to reduce the size of the air bubbles by 40–50% and that of the oil drops by 70–80%. It is concluded that application of low-frequency vibration has the potential of improving contacting in fluid–fluid dispersions.

Keywords: Low frequency vibrations; Vibration exciter; Fluid–fluid dispersions

1. Introduction

There is some evidence in the published literature to show that the application of vibrations to the liquid phase, at frequencies of the order of 100 Hz, can (a) influence bubble rise in gas–liquid dispersions [1,2], (b) reduce the bubble size [3,4] and (c) improve gas–liquid mass transfer [5–8]. There is some indication from the patent literature [9] of the use of vibration devices in high pressure reactors, presumably to intensify gas–liquid reactor operation. Pulsations and periodic operations [10–14] have been shown to improve mass transfer between solids and liquids. In a recent paper, Maucci et al. [15] studied the influence of low-frequency liquid phase vibrations on gas–liquid and liquid–solid mass transfer. For pulsation frequencies below 1 Hz, they concluded that no significant mass transfer enhancement is achieved.

In this paper we study the influence of low-frequency vibrations of the water phase on the size of air bubbles and oil drops in air–water and oil–water dispersions. The objective is to show that, provided the frequency and amplitude of the vibrations are properly tuned, a significant reduction in bubble and drop sizes can be achieved.

2. Experimental set-up

The experimental set-up consists of a column filled with water, a vibration exciter, a power amplifier, a vibration controller and a personal computer. A schematic diagram of the experimental set-up is given in Fig. 1. The column, made of polyacrylate, has an inner diameter (i.d.) of 0.10 m and a height of 1.2 m. The bottom of the column is sealed by a silicon rubber membrane of 0.4 mm thickness and clamped between

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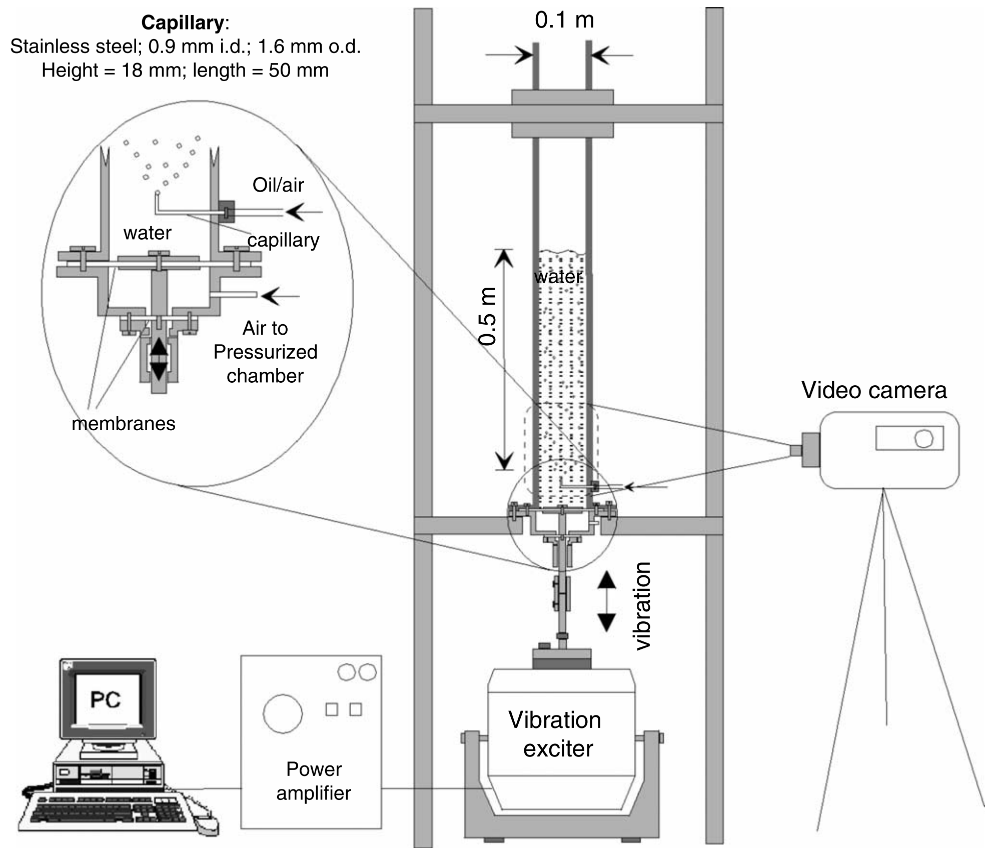

Fig. 1. Experimental set-up of the bubble column with vibration excitement device. Further details of the experimental set-up including photographs of the rig are to be found on our website: http://ct-cr4.chem.uva.nl/vibrationexciter.

two metal disks of 0.096 m in diameter; see inset to Fig. 1. At a distance of 0.1 m above the membrane, air or paraffin oil (density 795 kg/m^3; dynamic viscosity = 2.9 mPa s; surface tension = 0.028 N/m) is fed to the column through a stainless steel capillary of 0.9 mm i.d. and 1.6 mm outer diameter (o.d.) as shown in the inset to Fig. 1. The air or oil flow is controlled by means of a calibrated flowmeter (*Brooks*). In order to hold the membrane at constant vertical position after filling the column with the liquid phase, a chamber for pressure compensation is mounted below the membrane. The membrane is connected to an air-cooled vibration-exciter (*TIRAvib 5220*, Germany). The amplifier of this vibration-exciter is controlled by the *SignalCalc* 550 *Vibration-controller* in a PC environment. The frequency range is 10–5000 Hz. Depending on the frequency, the amplitude can be varied between 0 and 25 mm. The vibrations follow a sinusoidal motion. The maximum acceleration under unloaded conditions is 700 m/s^2. Further details of the experimental set-up including photographs of the rig are to be found on our website: http://ct-cr4.chem.uva.nl/vibrationexciter.

For all the sets of experiments reported in this paper, the height of the water phase in the bubble column was maintained constant at 0.5 m. The pressure at the top of the column is atmospheric. All experiments were carried out at ambient temperature of 290–293 K.

In the experiments the range of frequencies was varied in steps between 0 and 400 Hz and the range of amplitudes used in the experiments varied from 0.0025 to 0.32 mm. However, due to limitations of the TIRA vibration-exciter, there is a limit to the maximum frequency for amplitudes exceeding 0.04 mm. For example, at an amplitude of 0.04 mm, the frequency is limited to 400 Hz, and at an amplitude of 0.16 mm, the maximum frequency is limited to 200 Hz.

At each vibration frequency, video recordings, using a Panasonic DSP colour CCD camera, of the air–water or oil–water dispersion were made at 25 frames per second for a period of 5 s. Frame-by-frame analysis of the video images, gives accurate information on the number of bubbles passing through the observation window (sketched in Fig. 1) in the time interval of the observation (5 s). The video imaging technique is the same as that described in an earlier publication [16]. For the set volumetric flow rate of the dispersed phase, the average air bubble or oil drop diameter of the dispersion can be calculated.

Additionally, we used a FASTCAM Ultima-high-speed camera 40K (Roper Scientific MASD, Inc., San Diego, CA, USA) at a frame rate of 2250 frames per second to examine the influence of vibrations on bubble and drop formation in some more detail. The video recording using FASTCAM have been placed on our website: http://ct-cr4.chem.uva.nl/vibrationvideo.

3. Influence of vibration excitement in air–water system

In the first set of experiments, the air flow rate through the single capillary was maintained at 5.3 × 10^{-7} m^3/s which corresponds to a hole velocity in the capillary of 0.83 m/s and the amplitude λ was set at a constant value and the vibration frequency was varied in steps. The results are shown in Fig. 2. Let us consider the experiments at $\lambda = 0.0025$ mm. There is a significant reduction in the bubble diameter from 3.7 mm (at 0 Hz) to 2.3 mm when the frequency f is reduced to 125 Hz. Increasing the frequency beyond 125 Hz does not reduce the bubble diameter further and it appears that there is an optimum at 125 Hz. There is another minimum

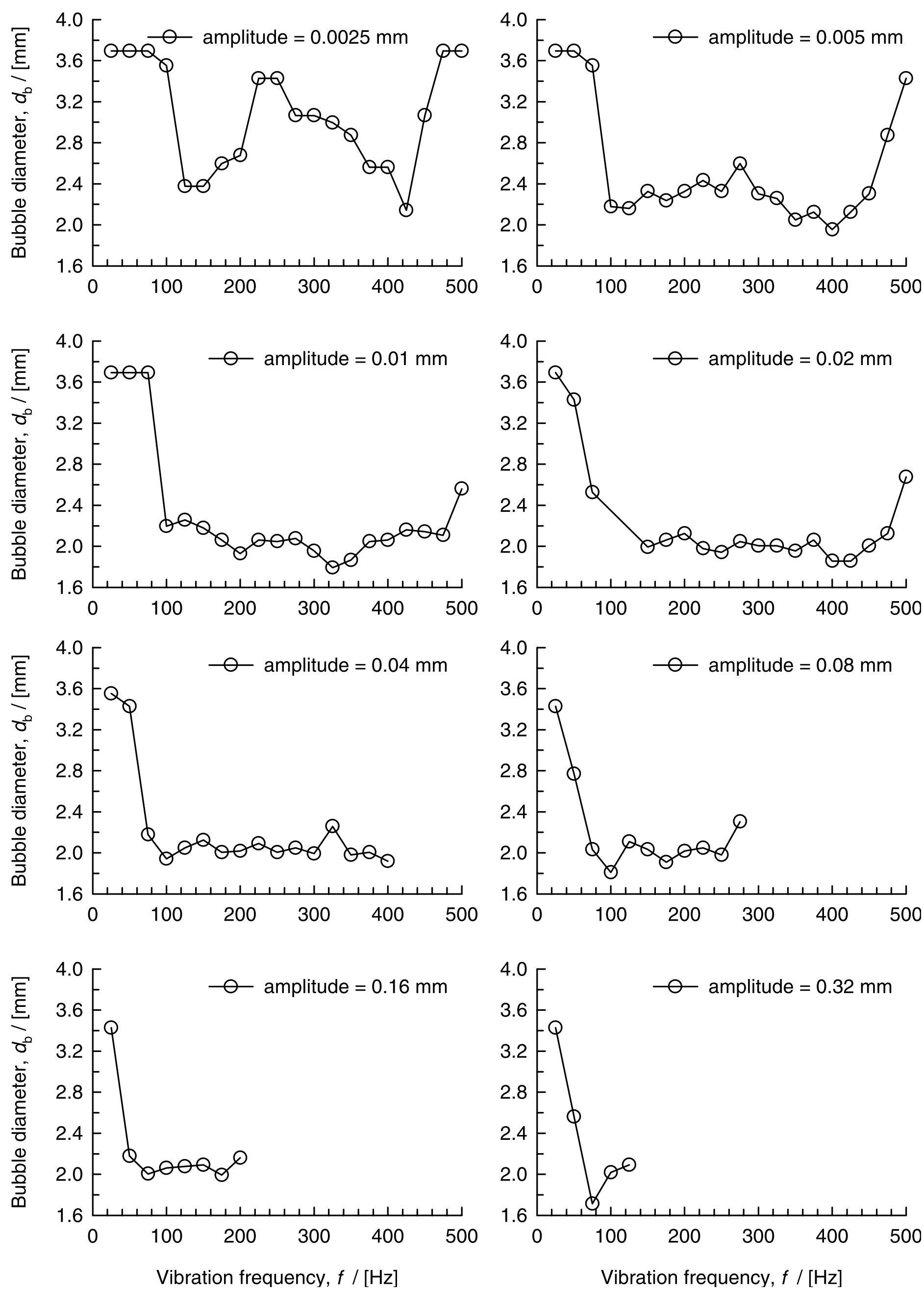

Fig. 2. Influence of variation in vibration and amplitude on the average bubble diameter in air–water system. The velocity of air through the hole, $U_h = 0.83$ m/s.

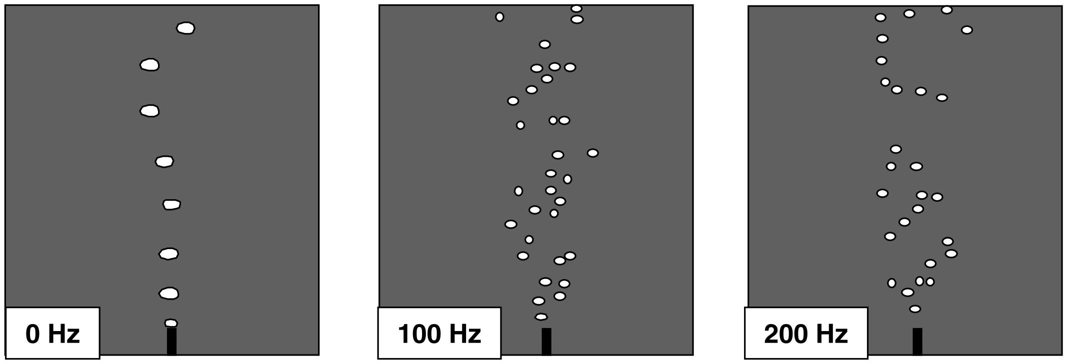

Fig. 3. Typical video snapshots taken at three different vibration frequencies for the air–water system using single nozzle injection device. The actual video images (placed on our website: http://ct-cr4.chem.uva.nl/vibrationexciter) have been retraced. The hole velocity of air, $U_h = 0.83$ m/s. The vibration amplitude is 0.005 mm.

bubble diameter at 425 Hz. Beyond 425 Hz the situation does not improve and the situation returns to the 0 Hz case. In the next series of experiments, carried out with $\lambda = 0.005$ mm, we note that the bubble breakage occurs at 100 Hz. The bubble diameter remains practically constant in the frequency range of 100–400 Hz. Increasing the frequency beyond 400 Hz, produces no improvement in comparison with the 0 Hz case. Snapshots of the bubble dispersions obtained at 0, 100 and 200 Hz and vibration amplitude of 0.005 mm are shown in Fig. 3. A similar pattern emerges for the other experiments with increasing amplitude. It is to be noted that increasing the amplitude does not seem to cause a further reduction in the bubble size to values lower than about 1 mm.

From the above series of experiments we conclude that a minimum vibration frequency of 100 Hz is required for significant bubble size reduction. Furthermore, we conclude that no further size reduction is achieved beyond 100 Hz.

In order to get a better feel for the influence of the vibration amplitude, we carried out a series of experiments in which the frequency was kept constant at 100 Hz and the amplitude was varied in the 0.0025–0.32 mm range; the results are presented in Fig. 4. We note a sharp decrease in the bubble diameter when the amplitude is increased from 0.0025 mm. Increase in the amplitude beyond 0.01 mm does not seem to have a further beneficial effect.

Fixing the vibration frequency at 100 Hz and the amplitude at 0.01 mm, we carried out a series of experiments with variation in the air flow rate through the single capillary. The experimentally determined bubble sizes, with and without vibration, are shown in Fig. 5. For the no-vibrations situations, the measured bubble sizes agree reasonably well with predictions using the model of Kumar and Kuloor [17]; see Fig. 5. We note that the reduction of 40–50% of the value for no-vibrations case persists over a wide range of hole velocities.

The physical explanation of the above observations is that application of vibrations to the liquid phase serves

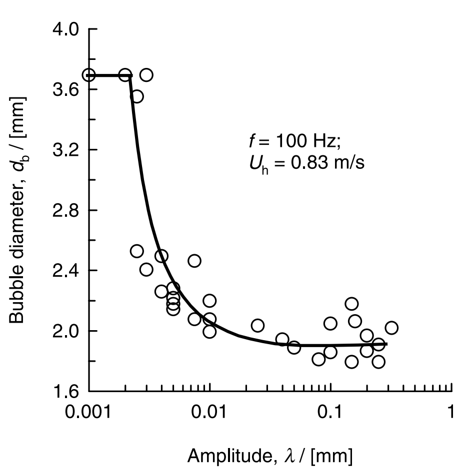

Fig. 4. Influence of vibration amplitude on the average bubble diameter for air–water operation. The vibration frequency was maintained constant at 100 Hz. The hole velocity $U_h = 0.83$ m/s.

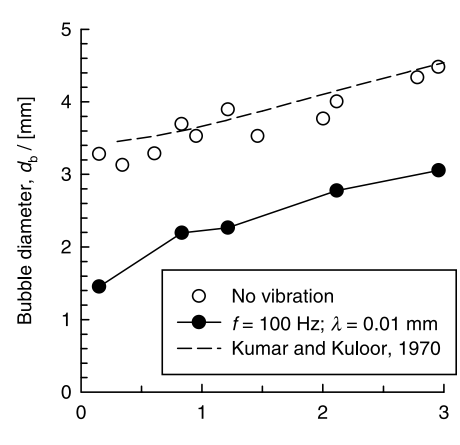

Fig. 5. Influence of hole velocity U_h through capillary nozzle on the bubble diameter d_b in air–water operation. Measurements without vibration compared with data obtained with 100 Hz vibrations and amplitude $\lambda = 0.01$ mm. The dashed line represents the calculations of the bubble diameter using the model of Kumar and Kuloor (1970).

to overcome the surface tension forces and assist the break-up of the bubbles formed at the orifice [3].

4. Influence of vibration excitement in oil–water system

Next we performed experiments in which paraffin oil was dispersed through the capillary, using exactly the same set up as in the foregoing air–water experiments. Consider operation at a hole velocity $U_h = 0.0339$ m/s. A snapshot (retraced from the recorded video images) of the drop formation for the no-vibrations case is shown in Fig. 6(a). The average diameter of the oil drop is calculated to be 5.4 mm. When the water phase is vibrated at a frequency $f = 70$ Hz, keeping the amplitude $\lambda = 0.15$ mm, much finer oil drops are formed at the orifice; see the snapshot in Fig. 6(b). The average drop diameter for this case is 0.8 mm, amounting to a size reduction by more than 80%. When the oil flow velocity through the capillary is increased to U_h 0.265 m/s, the corresponding snapshots obtained are shown in Fig. 6(c) and (d). For the no-vibrations case, the drop diameter is 5.3 mm. Application of vibrations to the water phase at a frequency $f = 70$ Hz, keeping the amplitude $\lambda = 0.15$ mm results in a oil dispersion with an average drop diameter of 1.65 mm, a size reduction of about 70%.

For a range of velocities of paraffin oil through the orifice, the measured drop diameters without vibrations and when vibrated at $f = 70$ Hz and $\lambda = 0.15$ mm are shown in Fig. 7. We note that the reduction in the drop size varies between 70 and 80%.

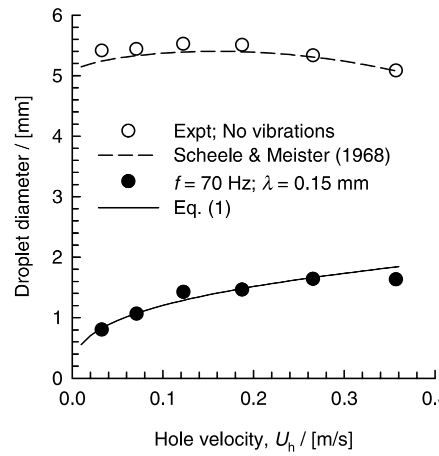

Fig. 7. Influence of vibrations on the average drop diameter for paraffin oil–water operation with varying velocity of oil through the orifice. The vibration frequency was maintained constant at $f = 70$ Hz and amplitude $\lambda = 0.15$ mm.

The drop diameters for the no-vibrations case corresponds very well with the predictions using the model of Scheele and Meister [18], provided we use the orifice diameter to correspond with the o.d. (= 1.6 mm) in view of the fact that the oil phase wets the stainless steel capillary and covers the whole of the outer surface at the point of break-up. When the water phase is vibrated at $f = 70$ Hz, we note that the frequency of disengagement of oil drops corresponds closely with this frequency.

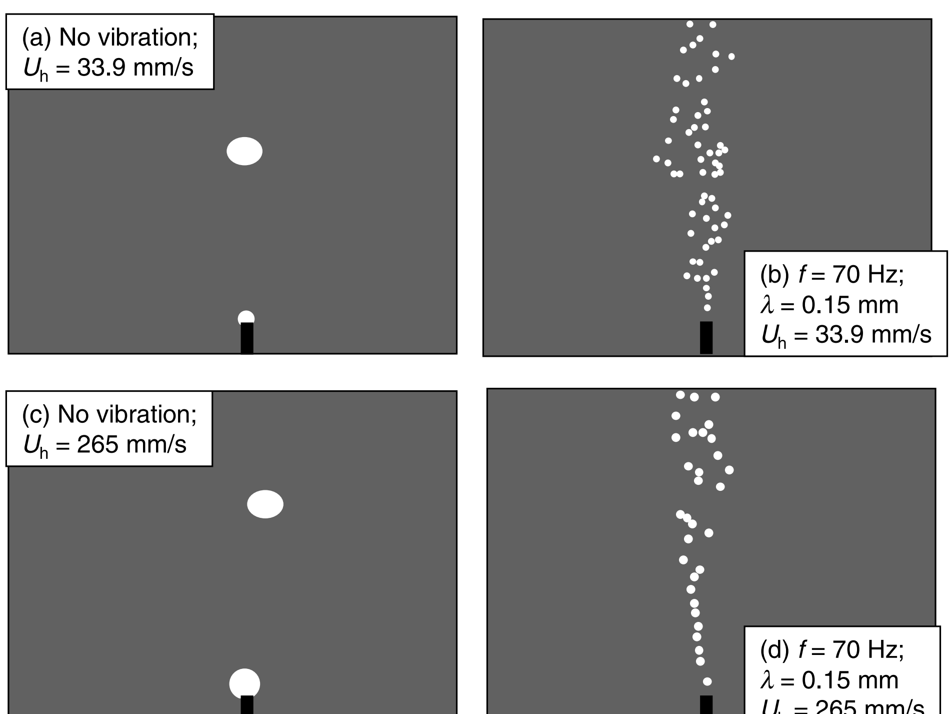

Fig. 6. Typical video snapshots of paraffin oil–water dispersion at two different oil velocities through the orifice.

This would suggest a simple model for calculation of the drop diameter:

$$d = \left(\frac{6Q_h}{f\pi}\right)^{1/3} \quad (1)$$

where Q_h is the volumetric flow rate of the oil phase through the orifice. Eq. (1) implies that the number of drops issuing from the orifice corresponds to f per second. Calculations using Eq. (1) show very good agreement with the measured drop sizes when vibrations at $f = 70$ Hz, are applied; see Fig. 7.

Following Eq. (1), for a given flow rate Q_h, increasing the vibration frequency should lead to smaller drop diameters. This is indeed found to be the case when the hole velocity U_h is maintained at 0.22 m/s and frequencies of 40, 70 and 150 Hz are applied; see the snapshots in Fig. 8(a–c). In these cases, the amplitude of the vibrations is adjusted to 0.3, 0.05 and 0.02 mm, respectively. With increasing frequency, the amplitude has to be reduced in order to prevent shattering of the drops that makes the counting of drops impossible. Increasing the vibration frequency beyond 150 Hz does not reduce the drop size because the drops issuing from the orifice are so close to each other that they coalesce, leading to an increase in the drop size. This fact is illustrated by the snapshot of the 150 Hz operation (cf. Fig. 8(c)) where we note that the drops are touching each other when leaving the orifice. The drop diameters measured at 40, 70 and 150 Hz show good correspondence with the calculations following Eq. (1); see Fig. 9.

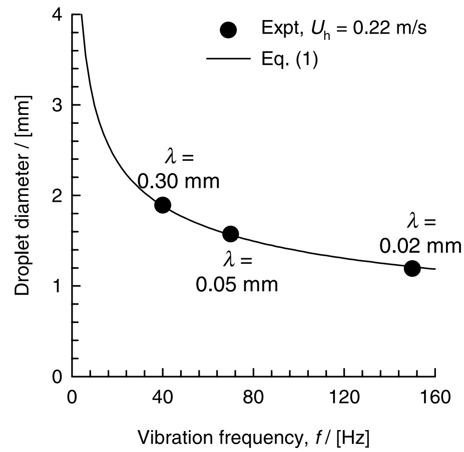

Fig. 9. Influence of vibration frequency on the average drop diameter for paraffin oil–water operation for constant velocity of oil through the orifice $U_h = 0.22$ m/s.

5. Concluding remarks

We have shown that low-frequency vibrations, in the 50–400 Hz range, are capable of causing a significant reduction in the bubble and drop sizes in air–water and oil–water dispersions formed from a single orifice. For the air–water system, a 40–50% reduction in the bubble size is obtained. For the oil–water system, the drop size reduction is 70–80% depending on the oil flow rate through the orifice.

Our study shows that the frequency and amplitude of the vibrations have to be carefully tuned to obtain the maximum reduction in bubble or drop size. The reason

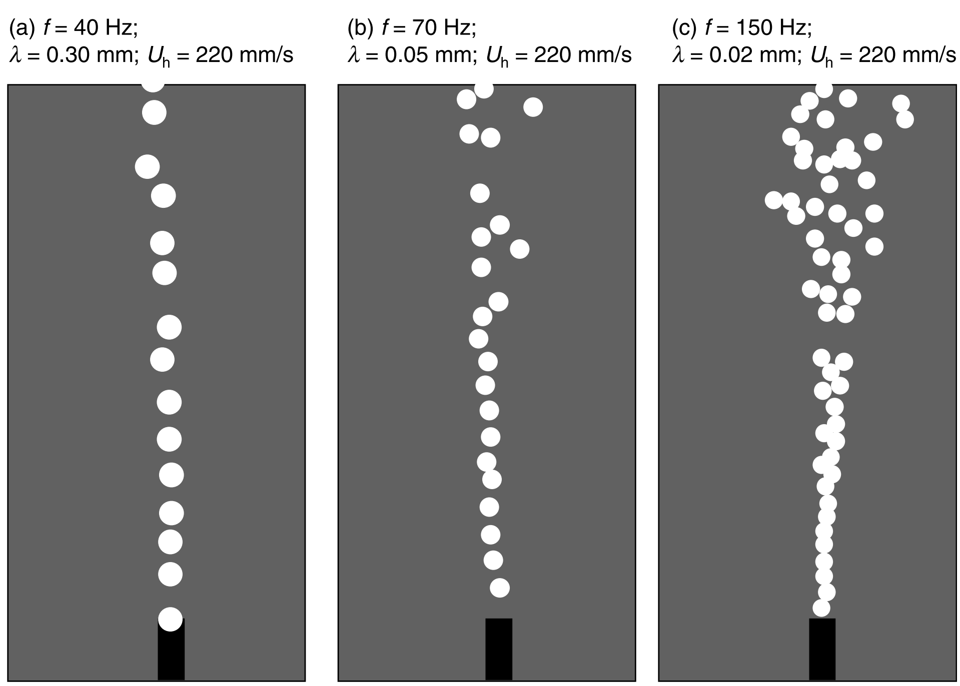

Fig. 8. Typical video snapshots of paraffin oil–water dispersion at three different vibration frequencies. The hole velocity $U_h = 0.22$ m/s.

for the pessimistic result obtained by Maucci et al. [15] on the influence of vibrations on gas–liquid dispersion is due to the fact that the vibration frequency used (1 Hz) is too low to engender a significant effect.

We are currently carrying out experimental work with a multi-capillary gas distribution device. Preliminary results show that the gas hold-up and volumetric mass transfer coefficients can be improved by more than 100% by application of low frequency vibrations. Further effort is being expended in obtaining a fundamental model to simulate the influence of vibrations on bubble and drop formation at a single orifice; some preliminary results obtained using Computational Fluid Dynamics (CFD) are available on our website: http://ct-cr4.chem.uva.nl/sonicsim.

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