

Improving Gas-Liquid Mass Transfer in Bubble Columns by Applying Low-Frequency Vibrations

By R. Krishna* and J. Ellenberger

We show that application of low-frequency vibrations, in the 50–200 Hz range, to the liquid phase of an air-water bubble column causes significantly smaller bubbles to be generated at the distributor plate. For bubble column operation in the homogeneous flow regime, measurements of the volumetric mass transfer coefficient using the oxygen absorption technique show that the increase in the $k_L a$ values ranges from 50–100 % depending on the flow rate. It is concluded that application of low-frequency vibration has the potential of improving the performance of bubble columns.

1 Introduction

A bubble column reactor is a commonly used reactor type (see Fig. 1a). Increase in the gas-liquid mass transfer coefficient often has a beneficial effect on the reactor performance. One common method for improving the mass transfer is by carrying out the reaction in a stirred vessel (see Fig. 1b). The energy input from the stirrer device serves to break up the bubbles, leading to an increased contact area between gas and liquid. There are two important disadvantages of stirred vessels. The first disadvantage relates to the large energy inputs required to achieve the desired improvement in interfacial transfer rates. The second disadvantage stems from the fact that stirring causes the gas bubbles to be recirculated in the vessel (see Fig. 1b).

Bubble recirculation is undesirable because the overall driving force for mass transfer is reduced. It is preferable to have piston flow of gas bubbles up through the liquid column, with little or no backmixing of the gas bubbles. Many aerobic fermentation processes (e.g. in beer manufacture) are carried out in stirred vessels. Some bacterial cells suffer death when the agitation is too severe. There is therefore a need to improve contacting without intense agitation.

There is some evidence in the published literature to show that the application of vibrations to the liquid phase (cf. Fig. 1c), at frequencies of the order of 100 Hz, can influence bubble rise [1,2], reduce the bubble size [3,4] and improve gas-liquid mass transfer [5–7]. There is some indication from the patent literature [8] of the use of vibration devices in high-pressure reactors, presumably to improve reactor conversion.

The advantage of using low-frequency vibrations over mechanical agitation is that the plug flow character of the bubbles is maintained and no additional large-scale backmixing of the liquid phase is induced. Our objective in this paper is to study the influence of vibrations on both bubble size and mass transfer with a view to confirm the scattered information available in the published literature. We also aim to demonstrate that the improvement in mass transfer is entirely attributable to the reduction in the bubble size.

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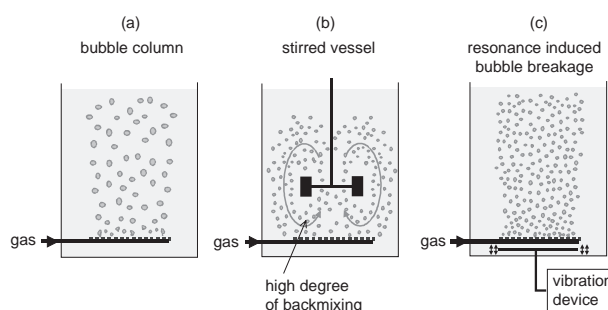


Figure 1. a) Typical aeration device, a bubble column reactor. b) Stirred gas-liquid dispersion. c) Liquid phase subjected to vibrations.

2 Influence of Vibrations on Bubble Size

In order to study the influence of vibrations on bubble size, we first carried out a series of experiments in a cylindrical polyacrylate column of 1050 mm height and 51 mm inner diameter. A loudspeaker is mounted at the bottom of the column (see Fig. 2a). The outer diameter of the loudspeaker is 0.18 m and the vibrating diaphragm has a diameter of 0.12 m. The loudspeaker is connected to a frequency generator. The

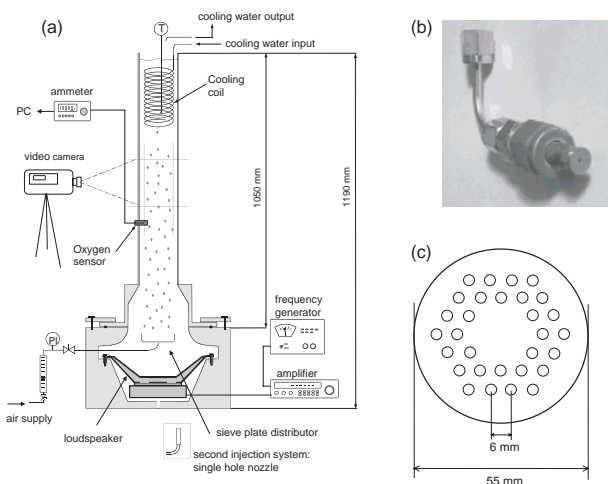


Figure 2. a) Experimental setup. b) Single nozzle gas distribution. c) Sieve plate distributor used in mass transfer experiments.

loudspeaker was made to vibrate at various frequencies, in the range 0–250 Hz. The amplitude vs. frequency characteristics of the speaker are shown in Fig. 3. The column is filled with demineralized water. There is a slight increase in the liquid temperature due to the energy imparted to the liquid phase by the vibrations and so the water was maintained at constant temperature by a cooling coil arrangement (see Fig. 2a).

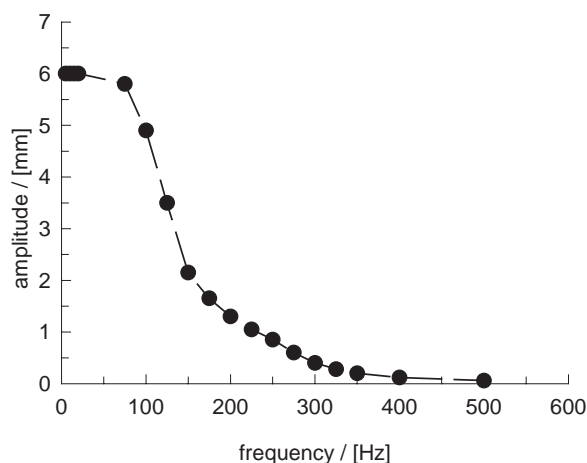


Figure 3. Amplitude vs frequency characteristics of the loudspeaker.

Firstly, experiments were carried out with a single hole nozzle of 0.5 mm as gas distributor shown in Fig. 2b. Video recordings, at 25 frames per second, were made and retraced video pictures of the column operation at 0, 150 and 250 Hz are shown in Fig. 4. These pictures were analyzed frame by frame to count the number of bubbles and to determine the bubble diameter. Fig. 5a shows the number of bubbles passing through the observation window per second, for the 0 Hz and 150 Hz cases. From information on the volumetric air flow rate, the average bubble size can be calculated; these data are shown in Fig. 5b.

For operation at a hole velocity of 0.33 m/s, for example, application of 150 Hz vibration reduces the bubble size from 3.8 mm to 2.7 mm. This represents an interfacial area increase of 40 %. The video images also showed that the reduction in the bubble size occurs during the bubble formation itself; movies can be viewed on our website: <http://ct-cr4.chem.uva.nl/vibration/>.

3 Influence of Vibrations on $k_L a$

A second series of experiments was carried out to determine the influence of vibrations on the volumetric liquid-phase mass transfer coefficient. The mass transfer measurements were carried out for the system air-demineralized water. In this experimental series the gas phase was introduced at the bottom of the column, using a sieve plate distributor, placed above the loudspeaker. The distributor has a diameter of 55 mm and contains 30 holes, each of 0.5 mm diameter; the

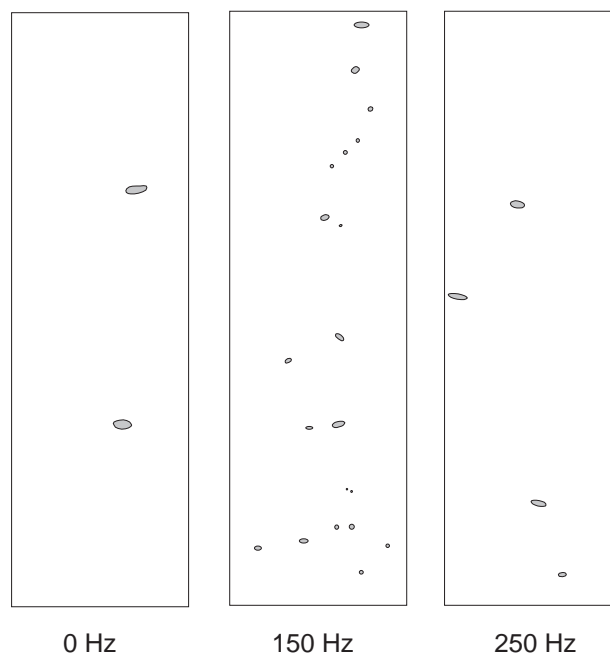


Figure 4. Typical video snapshots taken at three different vibration frequencies for the air-water system using single nozzle injection device. The actual video images (placed on our website: <http://ct-cr4.chem.uva.nl/vibration>) have been retraced. The hole velocity $U_h = 0.33$ m/s. The dotted contour lines cover the area indicated in Fig. 2a.

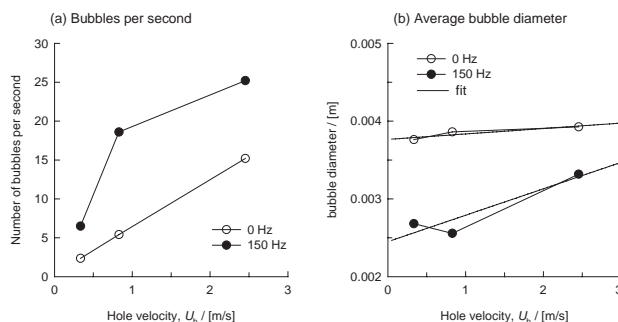


Figure 5. Influence of hole velocity and vibration frequency on a) the number of bubbles per second within observation window and b) the average diameter of the bubbles.

layout is shown in Fig. 2c. The desired air flow rate in the column was adjusted by means of a flowmeter. The volumetric mass transfer coefficient was determined by the oxygen absorption technique, described in detail in our earlier work [9]. The dissolved oxygen concentration in water was measured by means of an oxygen sensor; this sensor was placed at a position 600 mm below the clear liquid height in the column. The signals from the sensor were directly recorded on to a PC.

Firstly, the oxygen was stripped from water almost completely by injection of pure nitrogen through the distributor; this took about 15 minutes. When all the oxygen has been stripped out, air was sparged into the column and the oxygen uptake into the liquid phase was monitored continuously by means of the oxygen sensor. A total measuring time of 30 minutes was used for each experiment. This time

was chosen large enough in order to reach the oxygen saturation concentration, C^* .

Assuming the liquid phase to be perfectly mixed, the dissolved-oxygen concentration is described by the relation:

$$\frac{\partial C}{\partial t} = k_L a (C^* - C) \quad (1)$$

where $k_L a$ is the volumetric mass transfer coefficient and C is the dissolved-oxygen concentration in the liquid bulk. Eq. (1) can be integrated with the initial condition that for $t = 0$ (the starting point of the experiment), the dissolved-oxygen concentration is C_0 . This yields to:

$$C(t) = C^* - (C^* - C_0) \exp(-k_L a t) \quad (2)$$

After normalizing the data between C_0 and C^* , the dimensionless dissolved-oxygen concentration signal was fitted with the model:

$$\frac{C(t) - C_0}{C^* - C_0} = 1 - \exp(-k_L a t) \quad (3)$$

The only unknown constant in Eq. (3) is $k_L a$, which was determined using standard multiple regression solver routine in which the mean square deviation between the experiments and the model predictions is minimized. For operation at a superficial gas velocity of 1.1 mm/s, snapshots of the column operation at 0 Hz (no vibration) and 150 Hz are shown in Fig. 6. The corresponding dynamic oxygen absorption profiles are shown in Fig. 7, along with the fitted curves using Eq. (3). The fitted volumetric mass transfer coefficient $k_L a$ increases from 0.0026 s^{-1} at 0 Hz to 0.0045 s^{-1} at 150 Hz. The obtained values of $k_L a$ will be changed if the assumption of a well-mixed liquid phase would be replaced by a more detailed model taking into account the liquid phase dispersion. However, in this study we are primarily focusing on the enhancement of $k_L a$, due to vibrations; this enhancement would not be expected to depend on the details of liquid mixing, which can be expected to be approximately the same for the two cases (with and without vibrations).

The influence of vibration frequency of the loudspeaker on $k_L a$ for a constant superficial gas velocity $U = 1.1 \text{ mm/s}$ is shown in Fig. 8a. The maximum value of $k_L a$ is obtained at a vibration frequency of 150 Hz; at this frequency the energy input to the system (i.e., amplitude \times frequency) is the maximum.

For a range of superficial gas velocities, $k_L a$ was measured at 0 Hz and at 150 Hz; the results are shown in Fig. 8b. Let us rationalize these $k_L a$ results using the penetration theory for mass transfer, which shows that k_L is inversely proportional to the square root of the contact time between the gas bubbles and the liquid, t_c .

$$k_L \propto \sqrt{\frac{1}{t_c}}; \quad t_c = \frac{d_b}{V_b} \quad (4)$$

where the contact time can be estimated from time a bubble takes to rise a distance equal to its own diameter, d_b . For a



Figure 6. Photographs of bubble dispersion in air-water system with sieve plate distributor comparing no-vibration case with 150 Hz-vibration situation. Operation at superficial gas velocity $U = 0.0011 \text{ m/s}$.

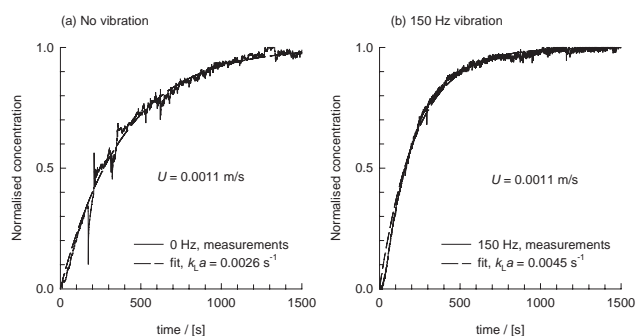


Figure 7. Typical oxygen uptake profiles for a) the no vibration case and b) at 150 Hz vibration.

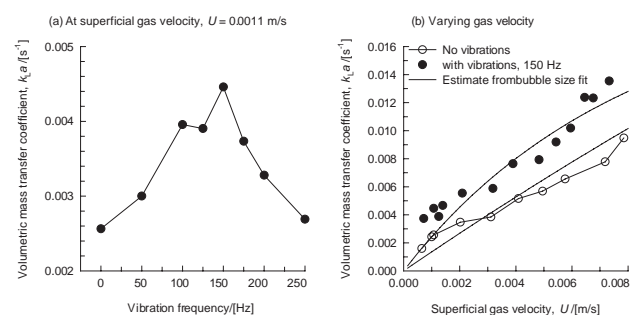


Figure 8. Data on the volumetric mass transfer coefficient $k_L a$, with and without vibrations.

given superficial gas velocity U , the interfacial area can be estimated from

$$a = \frac{6\varepsilon}{d_b}; \quad \varepsilon = \frac{U}{V_b} \quad (5)$$

Since the sieve plate distributor used for the $k_L a$ has the same hole diameter (0.5 mm) as in the single nozzle experiments, the bubble size data shown in Fig. 5 is assumed to hold. The rise

velocity V_b of the bubble swarm is practically independent of the bubble size and was determined from the video recordings to be 0.24 m/s. The continuous lines in Fig 8b have been drawn taking $k_L = 0.0002$ m/s for a bubble size of 4 mm. The increase in the volumetric mass transfer coefficient at 150 Hz is therefore to be attributed entirely to the decrease in the bubble size.

4 Concluding Remarks

We have shown that low-frequency vibrations, in the 50–250 Hz range, have the effect of reducing the bubble size in a gas-liquid dispersion to a significant extent. The maximum reduction in the bubble size occurs when the power input from the vibration device is maximum; in our experiments using a loudspeaker this occurs at a vibration frequency of 150 Hz. High-speed video recordings of the single nozzle operation show that the decrease in the bubble size occurs during bubble formation; there appears to be no further reduction to the bubble size after bubble detachment. Using a sieve plate distributor, the volumetric mass transfer coefficient was measured for a variety of superficial gas velocities. For operation at 150 Hz, the improvement in $k_L a$ ranges from 30 to 100 % depending on the operating gas velocity with the maximum improvement at lower gas velocities. Higher energy inputs (larger vibration amplitudes and higher frequencies) will result in higher increases in $k_L a$ values.

Scale-up studies are under way in our laboratories in Amsterdam using vibration exciter and a column of 0.1 m diameter.

Acknowledgement

This research was supported by a grant from the Netherlands Foundation for Scientific Research (NWO) for development of novel concepts in reactive separations technology.

Received: July 23, 2001 [CET 1459]

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