

Intensification of flotation treatment by exposure to vibration

M. V. Ivanov and B. S. Ksenofontov

ABSTRACT

In this paper, an intensification of wastewater flotation treatment by exposure to vibration is studied. Exposure to vibration results in the decrease of air bubble size, increase of air flow through the aerator and more even dispersion of air bubbles in water. This intensifies the aeration process, thus significantly improving the treatment efficiency. A multistage model of flotation kinetics has been applied in order to take into consideration the effects of vibration. The model gives a thorough explanation of the flotation process with consideration of 'air bubble – contaminant particle' aggregate formation. A large series of experiments was conducted with paint and varnish industry wastewaters. It is shown that vibroflotation results in an increase of treatment efficiency by up to three times. A comparison of the experimental data with the results of mathematical modeling is presented, showing a good correlation of theoretical and experimental results.

Key words | flotation, vibration, vibroflotation, wastewater treatment

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INTRODUCTION

Today there are several common flotation methods in use. Dissolved air flotation is most used and is very efficient as far as bubbles reaching 0.1 mm in diameter (Matsui *et al.* 1998). However, smaller bubble size results in the decrease of their rising velocity. Another highly efficient method is electroflotation. However, it is considered to be one of the most expensive (Rubio *et al.* 2002). Often induced air flotation is used. It has acceptable efficiency but the equipment is very complicated and not reliable. Pneumatic flotation has a large set of advantages: high performance, reliable equipment and low power consumption; however, treatment efficiency does not exceed 50%. Thus, this method would become very useful if its efficiency could be increased.

Basically all intensification methods may be divided into two classes: chemical and physical. Chemical methods include the adding of flocculants, coagulants and surface-active materials, etc. Physical methods include mechanical intensification, induced electromagnetic fields, laser and ion emission, etc. Last but not least are the vibration and acoustical methods of intensification, which may be classified as follows:

- Exposure to ultrasound
- Exposure to vibration
- Exposure to sound.

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Exposure to ultrasound has been widely studied. The physics of the process and apparatus design are well known (Doinikov Zavtrak 1996; Emre Altun *et al.* 2009). Therefore, ultrasound will not be in the scope of this paper.

The effects of sound and vibration are of the most interest for flotation intensification. Nicol & Engel (1986) concluded that the superimposition of an acoustic field on a fine-particle flotation process could be helpful in improving recovery in the low size range (less than 20 μm). Another approach is given by Anderson *et al.* (2009) which describes an oscillatory baffled column. Results indicate that the flotation rate may be improved by 60% for particles finer than 30 μm and by 30–40% for coarser particles. It was also shown that energy consumption was lower compared to the impeller flotation tanks of the same performance. An improvement of mineral processing by the effect of vibration was obtained by Djednova & Mehadjiski (1992). Ellenberger & Krishna (2007) reported 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).

Most of this research relates to mineral processing. However, it may be reasonable to apply these results to wastewater treatment. This paper introduces a method of vibroflotation, with the consideration of levels, frequencies and methods of vibration.

MATERIALS AND METHODS

There are several models describing the flotation process (Fukushi *et al.* (1995); Liu & Schwarz (2009) and others). However, most of them are either very simple and do not consider various factors that can influence the treatment process, or too complicated to be used.

The vibroflotation model presented here is a derivation of the multistage kinetic model (Ksenofontov 2011) for flotation treatment described by Ksenofontov & Ivanov (2013).

The scheme of the model is shown in Figure 1. At the initial stage, contaminant particles and air bubbles are completely separate from each other in water (stage A). Under exposure to vibration, bubbles split into several smaller bubbles (Leighton 1994; Allen *et al.* 2003; Ilinskii *et al.* 2009). We consider the splitting of a larger bubble into two smaller ones as the most probable process compared to splitting into three or four etc. bubbles at once. As bubbles rise they collide with suspended particles of the contaminant. After the collision, they attach to each other and form 'air bubble – contaminant particle' aggregates (stages B and C). Afterwards, aggregates rise up and settle on the surface in a froth layer (stage D). Kinetic constants K_i represent a probability of transition from one stage to another.

The model is described with the following system of equations:

$$\begin{cases} \frac{dC_A}{dt} = -(K_1 + K_3 + K_{10})C_A + K_2C_B + K_4C_C + K_9C_D \\ \frac{dC_B}{dt} = K_1C_A - (K_2 + K_5)C_B + K_6C_D \\ \frac{dC_C}{dt} = K_3C_A - (K_4 + K_7)C_C + K_8C_D \\ \frac{dC_D}{dt} = K_{10}C_A + K_5C_B + K_7C_C - (K_6 + K_8 + K_9)C_D \end{cases} \quad (1)$$

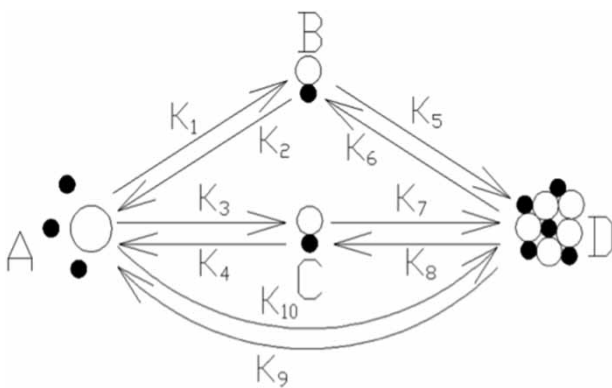


Figure 1 | A scheme for a flotation process with vibration exposure.

This system may be solved with the given transition constants K_i and known initial conditions:

$$\begin{cases} C_A(0) = C_0 \\ C_B(0) = 0 \\ C_C(0) = 0 \\ C_D(0) = 0 \\ C_A + C_B + C_C + C_D = C_0 \end{cases} \quad (2)$$

In this model, we assume that vibration parameters have been set in a way for the necessary effect of bubbles' splitting (as shown in Figure 1) to be achieved. Therefore, we do not introduce any frequency or level of acceleration into the equations.

We also assume that a larger bubble split into two of one size, and that these bubbles later behave similarly: they have same rise velocity, rupture probability and probability of an aggregate formation. Therefore, the constants K_1 and K_3 , K_5 and K_7 , K_2 and K_4 , K_6 and K_8 , will be equal.

With the given assumptions transition constants may be calculated the same way as it was described by Ksenofontov & Ivanov (2013).

Constants K_1 , K_3 stand for rate of aggregates formation:

$$K_1 = K_3 = \frac{1, 5E q}{d K_0} \quad (3)$$

where q is the barbotage rate (specific gas volume, $\text{m}^3/\text{m}^2\text{h}$); E is the efficiency of particle capture by a bubble; d is the bubbles' average diameter; and K_0 is the bubble polydispersity factor.

Rupture probability of the aggregates is described by constants K_2 and K_4 :

$$K_2 = K_4 = A \cdot C_f \cdot G_a \cdot M^2 \cdot C_p^{-1} \quad (4)$$

where A is the coefficient; C_f is the aggregates concentration; G_a is the gradient of rate in the aeration area; M is the ratio of the particle diameter to the diameter of the bubble and C_p is the concentration of air bubbles in water.

Rising of the aggregates to the froth layer is described by constants K_5 and K_7 :

$$K_5 = K_7 = \frac{v_r}{h} \quad (5)$$

where v_r is the rising velocity of the aggregates; and h is the depth of the flotation tank.

Loss of the aggregates from the froth layer is described by constants K_6 and K_8 :

$$K_6 = K_8 = F \cdot G_s \cdot C_a \cdot d_{av}^5 \quad (6)$$

where F is the coefficient; G_s is the velocity gradient in water; C_a is the bubbles concentration in the froth layer; and d_{av} is the average diameter of the air bubbles in the froth layer.

Constant K_9 stands for the loss of particles from the froth layer:

$$K_9 = \frac{v_s}{h} \quad (7)$$

where v_s is the velocity of particles sedimentation.

The probability of a direct particle rising from liquid to the froth layer without creation of the aggregate is described by a constant:

$$K_{10} = \frac{4G \cdot \alpha \cdot \varphi}{3\pi} \quad (8)$$

where α is the efficiency of aggregate formation; φ is the gas contents in the water volume; and G is the effective shear gradient of the hydrodynamic field:

$$G = \sqrt{qg/\nu} \quad (9)$$

where $g = 9.82 \text{ m/s}^2$; and ν is the water kinematic viscosity.

Solution of the system of equations (1) with calculated transition constants K_i gives, for each respective stage, a concentration of contaminant that changes with time.

One can see that, using this model, vibroflotation may be considered as a complex, multistage process. Vibration may be used to intensify different stages of the flotation. Particularly, it results in more intense aeration and splitting of large bubbles into smaller ones. As a result, bubbles disperse more equally in water. Furthermore, vibration stimulates the stirring of bubbles and contaminants in water. This results in an increased probability of contaminants and bubbles colliding and, hence, in better aggregate formation. These features are considered in the transition constants K_1 and K_3 .

This model of vibroflotation has been approved in a large set of experiments on wastewater from the paint and varnish industry. The total concentration of contaminants varied from 100 to 800 mg/l.

An experimental test stand is presented in Figure 2. The flotation column (4) is filled in with water up to a certain

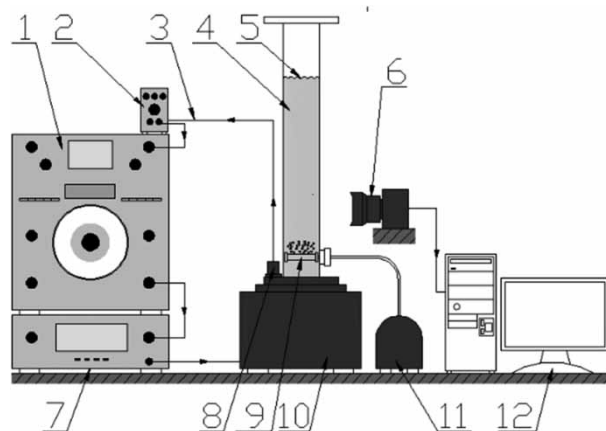


Figure 2 | An experimental test stand for the research of vibroflotation. 1 – generator, 2 – preamplifier, 3 – closed loop circuit, 4 – flotation column, 5 – wastewater level, 6 – photo-video camera, 7 – amplifier, 8 – accelerometer, 9 – aerator, 10 – shaker, 11 – air pump, 12 – computer.

level (5). Air is supplied with an air pump (11) to a ceramic aerator (9), which is fixed in the column. Airflow may be adjusted. The column assembly is installed on the shaker (10). A sine signal is supplied from the generator (1) via power amplifier (7) and may vary by amplitude and frequency. The accelerometer (8) measures the vibration level and controls the signal. A camera (6) controls the processes and performs photo and video capturing.

Liquid height in the column was 500 mm. Froth was removed and collected in the froth tank.

Experiments were carried out in several steps:

1. Flotation of the given wastewater in the flotation column (see (4) in Figure 2) without vibration exposure.
2. Adjustment of the necessary vibration parameters (frequency and acceleration).
3. Flotation of the given wastewater in the flotation column with the vibration exposure.

The efficiency of the treatment was evaluated by a turbidity meter (HACH 2100 AN). Results of experiments were captured by a camera with a macro lens. To define bubble size in water in front of the camera a graduated ruler was dipped with a minimum scale of 0.1 mm.

Based on previous studies and the experiments conducted, an assumption has been made that the eigen frequency of the flotation column should be used for vibroflotation treatment. It was found, that for the given test stand they varied from 90 to 200 Hz depending on the initial contamination concentration in wastewater and on the column water level. Figure 3 shows the distribution of the number of bubbles depending on the frequency for the

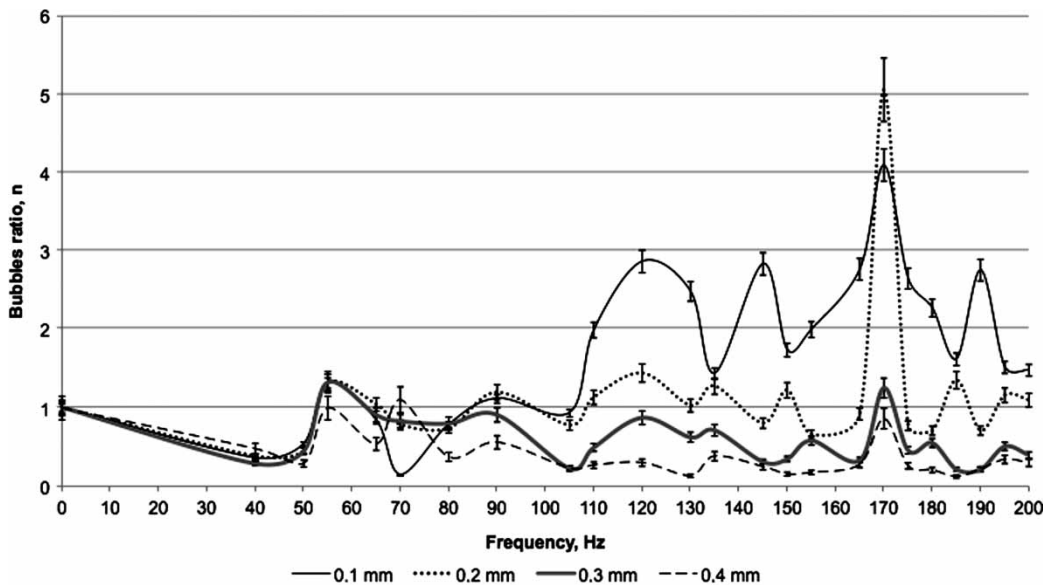


Figure 3 | Bubble size distribution depending on the frequency of the vibration.

given water level (500 mm) and given initial concentration of contaminants. The vertical axis shows the ratio (n) of number of bubbles of a certain size at the given frequency to the number of bubbles of the same size without vibration. Frequency $f=0$ Hz on the horizontal axis corresponds to the aeration mode without vibration. Thus, it may be seen, that at frequencies of 90, 120 and 170 Hz there is a significant increase in the amount of bubbles in the water. The amount is especially high at a frequency of 170 Hz, which is the main eigen frequency of the assembled flotation column when filled with water. Best air bubble dispersion was achieved at 170 Hz whilst lower sizes were achieved at a vibration level starting at 2 g and higher. This vibration mode results in the decrease of bubble size by up to five times (from 0.5–1 mm up to 0.1–0.4 mm).

RESULTS AND DISCUSSION

The experiments resulted in a significant increase of flotation efficiency under exposure to vibration. Initial turbidity of the wastewater was 1900 NTU; the average turbidity after flotation without vibration was 900 NTU, while the average turbidity of the water treated by flotation with vibration decreased to 330 NTU. So, treatment was three times more efficient. The change of turbidity with and without vibration is shown in Figure 4. These experiments were repeated several times to exclude all possible errors.

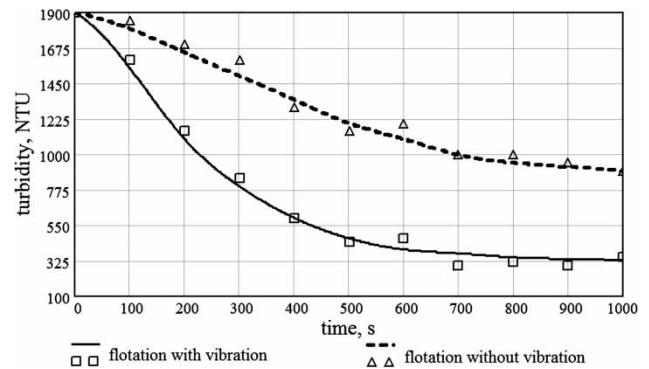


Figure 4 | Comparison of flotation results with and without vibration.

To show how the model of vibroflotation was applied, a calculation of transition kinetic constants for one of the vibroflotation treatment processes is presented below.

Constants K_1 and K_3 were defined by Equation (3). Air was fed into the aerator at the rate of 15 l/min. The diameter of the flotation column was 10 cm. Therefore, the barbotage rate will be equal $3.2 \times 10^{-2} \text{ m}^3/\text{m}^2\text{s}$.

Efficiency of particle capture by a bubble may vary from 0.5 to 1%. We have shown above that adding vibration enhances the flotation process and, particularly, distributes bubbles in water more evenly, hence increasing the efficiency of particle capture. Therefore, we assume it to be equal 1%.

The polydispersity factor for the constant diameter of bubbles was assumed to be equal to 1 because, due to vibration, bubbles disperse very evenly. The average bubble diameter was 0.1 mm.

Therefore, the calculated constants K_1 and K_3 were equal to $3.2 \times 10^{-3} \text{ s}^{-1}$.

The terminal rise velocity of bubbles 0.1 mm in diameter is 1.8 mm/s (Parkinson *et al.* 2008). Calculation of the constants K_5 and K_7 using Equation (5) resulted in a value of $3.6 \times 10^{-3} \text{ s}^{-1}$.

The particles' sedimentation velocity has been defined experimentally. Its value is 0.1 mm/s. Therefore, according to Equation (7) K_9 constant equals $2 \times 10^{-4} \text{ s}^{-1}$.

Constants K_2 , K_4 , K_6 and K_8 turn zero as we assume that the aggregates do not rupture and once risen to the froth surface they do not sediment.

The water kinematic viscosity $\nu = 10^{-6} \text{ m}^2/\text{s}$, and barbotage rate q was defined above, so the effective shear gradient may be defined from Equation (9) and equals 560 s^{-1} . According to Rulev *et al.* (1991) the coalescence efficiency, $\alpha = 10^{-2}$; and the gas contents in water volume for the given case is $\varphi = 0.02$. So, calculating Equation (8) result in constant K_{10} , which equals $2.4 \times 10^{-3} \text{ s}^{-1}$.

After definition of all the constants, the system of equations 1 has to be solved with the initial conditions 2. The graphical solution is presented in Figure 5.

It is necessary to admit here that the C_B and C_C curves are identical as we assumed above that two smaller bubbles splitting from a larger one will be of the same size and behave identically.

The superposition of C_A , C_B and C_C is of the most interest when analyzing the solution. This line presents the actual concentration of contaminant in water, which may be present at any stage: either floating separately from air bubbles (stage A, Figure 1), or floating in water as aggregates (stages B and C). It may be seen that after 900 s (15 min) the

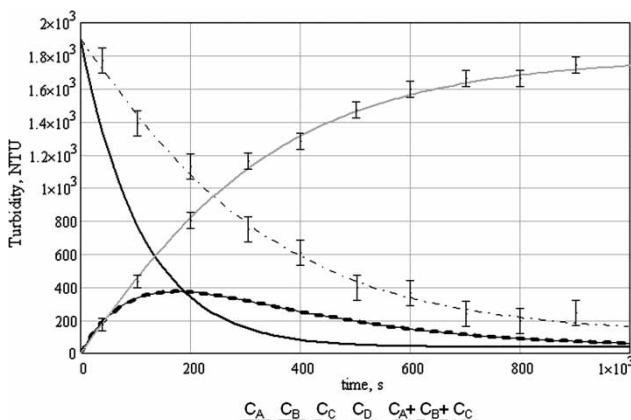


Figure 5 | Comparison of experimental data with the theoretical solution for pneumatic flotation of paints and varnish wastewater. Lines – theoretical values, dots – results of the experiments with maximum deviation.

treatment is almost over: further increase in time does not result in much further decrease of the total contaminant concentration. The measured turbidity at this point is 330 NTU. This correlates with the theoretical curves with consideration of standard error deviation.

The analysis of Figure 5 shows that the total treatment efficiency after 15 min equals 84%. However, it is necessary to admit one important feature of the multistage model. From the C_A curve it may be seen that almost all contaminant particles have already formed aggregates (shifted to B and C stages in Figure 1) after 500 s or 8 min. This means that the aeration may be turned off after this time, because all the aggregates have already been formed and will eventually rise to the surface, not in the aeration tank but in the next stages. So, treated water may flow faster in the aeration chamber.

CONCLUSIONS

This work presents a physical method for the intensification of the flotation process. This method has shown a high efficiency experimentally. A theoretical model describing the processes has been developed and numerically approved on a large series of experiments. A good correlation of theoretical and experimental data has been shown.

The application of vibration for flotation of wastewater significantly improves treatment. Exposure to vibration results in an increase of efficiency by up to three times compared to traditional pneumatic flotation. This is due to processes that intensify the aeration:

- Average airflow increases by 10% irrespective of the flow rate.
- Air bubbles disperse more equally in water.
- Bubble size diminishes up to five times (initial average bubble size was 0.5–2 mm, and with vibration the size decreases to 0.1–0.5 mm).

Exposure to vibration allows aeration to be stopped twice as early as with pneumatic flotation. It is suggested that vibro flotation may be used for the design of new flotation tanks and for the modernisation of old ones to increase their performance and efficiency.

REFERENCES

- Allen, J. S., Kruse, D. E., Dayton, P. A. & Ferrara, K. W. 2003 *Effect of coupled oscillations on microbubble behavior*. *Journal Acoustical Society of America* **114** (3), 1678–1690.

- Anderson, C. J., Harris, M. C. & Deglon, D. A. 2009 Flotation in a novel oscillatory baffled column. *Minerals Engineering* **22**, 1079–1087.
- Doinikov, A. A. & Zavtrak, S. T. 1996 Interaction force between a bubble and solid particle in a sound field. *Ultrasonics* **34**, 807–815.
- Djednova, S. & Mehadjiski, V. 1992 Study of the effects of the acoustic vibration conditioning of collector and frother on flotation of sulphide ores. *International Journal of Mineral Processing* **34**, 205–217.
- Ellenberger, J. & Krishna, R. 2007 Levitation of air bubbles and slugs in liquids under low-frequency vibration excitement. *Journal of Chemical Engineering Science* **62**, 7548–7553.
- Emre Altun, N., Hwang, J.-Y. & Hicyilmaz, C. 2009 Enhancement of flotation performance of oil shale cleaning by ultrasonic treatment. *International Journal of Mineral Processing* **91** (1–2), 1–13.
- Fukushi, K., Tambo, N. & Matsui, Y. 1995 A kinetic model for dissolved air flotation in water and wastewater treatment. *Water Science Technology* **31** (3–4), 37–47.
- Ilinskii, Y. A., Zabolotskaya, E. A. & Hamilton, M. F. 2009 Acoustic radiation force on a gas bubble in tissue. *Journal of Acoustical Society of America* **125** (4), 2552.
- Ksenofontov, B. S. 2011 *Water Systems Flotation Treatment: Wastewater and Soil Flotation Treatment*. Lap Lambert, Germany, 189 pp.
- Ksenofontov, B. S. & Ivanov, M. V. 2013 A novel multistage modeling of flotation for wastewater treatment. *Water Science and Technology* **68** (4), 807–812.
- Leighton, T. J. 1994 *The Acoustic Bubble*. Academic Press Limited, London, 613 pp.
- Liu, T. Y. & Schwarz, M. P. 2009 CFD-based multiscale modeling of bubble-particle collision efficiency in a turbulent flotation cell. *Chemical Engineering Science* **64**, 5287–5301.
- Matsui, Y., Fukushi, K. & Tambo, N. 1998 Modeling, simulation and operational parameters of dissolved-air flotation. *Journal Water SRT – AQUA* **47** (1), 9–20.
- Nicol, S. K. & Engel, M. D. 1986 Fine-particle flotation in an acoustic field. *International Journal of Mineral Processing* **17**, 143–150.
- Parkinson, L., Sedev, R., Fornasiero, D. & Ralston, J. 2008 The terminal rise velocity of 10–100 μm diameter bubbles in water. *Journal of Colloid and Interface Science* **322**, 168–172.
- Rubio, J., Souza, M. L. & Smith, R. W. 2002 Review of flotation as a wastewater treatment technique. *Minerals Engineering* **15**, 139–155.
- Rulev, N. N., Kolesnikov, V. A. & Karas, S. V. 1991 Vosdeistvie coalescencii na raspredelenie razmera puzirkov vo flotatore (Affect of coalescence on the bubble' size dispersion in the bubbles is the flotation tank). *Chemistry and Water Technology* **13** (2), 127–132 (in Russian).

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