Measurement of Bubble Size Distribution by Passive Acoustic Method

Stepan A. Gavrilev and Mikhail V. Ivanov and Evgeny A. Yusupov

Abstract— **Biphasic bubble flows are widely used in the energy industry. One of the key parameters of such flows is the bubble size distribution. To solve such problems, acoustic methods are used. These methods are of two types: active and passive. The passive method is considered in this paper. Unlike active methods, it does not affect the process, what can be considered as significant advantage. The mathematical model described in the paper of recalculating the noise spectrum of bubbles into a bubble size distribution was tested on an experimental setup with various operating modes with median radii of bubbles from 1.3 to 3 mm.**

Index Terms— **acoustic bubble sizing, bubble size distribution, bubble dynamics, process monitoring**

I. Introduction

With the development of technical systems of the energy industry, in which two-phase gas-liquid flows are used, there is a need for accurate monitoring of the parameters of the processes occurring in such systems. One of the key parameters to which special attention is paid in many papers [1]–[3] is the distribution of gas bubbles by size in a liquid medium. To solve such problems using optical, photometric and acoustic methods.

Optical and photometric methods are most common [4]–[9], but they have one major drawback - they are applicable only in optically transparent media, i.e. they are not suitable for measuring the size distribution of air bubbles in turbid liquid media. Therefore, acoustic methods are considered more versatile.

Most modern acoustic methods for determining the distribution of bubbles in size are based on measurements of the attenuation and velocity of an acoustic wave passing through a layer of a bubble cloud. These methods are called active and are well described in [10]–[12]. However, this approach has one minor drawback. An acoustic wave generated to irradiate a bubble cloud can have an effect on the bubbles. This phenomenon can be seen in the results of [13]. The authors of this work conducted a series of experiments while changing the intensity of the emitted acoustic wave and in each of the experiments received different results. Thus, in a number of cases, where the maintenance of regimes with a certain bubble size is especially important, the use of active methods is unacceptable. Therefore, it is preferable to use passive methods that do not affect the dynamics of the studied processes.

Passive methods are based on the fact that air bubbles in water are sources of acoustic signals. They emit an acoustic signal due to the alternating pressure of the gas inside the bubble. In 1933, Minnaert showed that under adiabatic conditions (heat exchange between the bubble gas and the liquid is insignificant) the frequency of the acoustic signal f, a gas emitted by a bubble depends on its size as follows:

$$f = \frac{1}{2\pi R}\sqrt{\frac{3\gamma P}{\rho}}. \qquad (1)$$

where f – sound wave frequency emitted by a bubble; P – absolute fluid pressure; γ – specific heat coefficient of gas, ρ – fluid density; R – bubble radius.

This expression is valid for spherical bubbles. The shape of the bubbles usually changes during the ascent. Depending on the size, they may take the form of a sphere, an oblate spheroid of a spherical segment, or a mushroom cap. In [14], a characteristic is presented, according to which the bubbles can be considered approximately spherical, if the condition:

$$R < \delta_\sigma. \qquad (2)$$

where R – bubble radius; δ_σ – fluid capillary constant.

According to this criterion, bubbles in water are shaped as spheres, if their radius is $R < 2{,}7$ mm.

Leighton (1994) gave the most complete description of bubble acoustics. According to [15], the spectrum of sound emitted by bubbles can be used to determine their size. Later this idea was developed in [16]–[20].

II. Theoretical Part

Let's g*(r)* – the density distribution of bubbles along the radius.

Accept that *g(r)* – Gaussian distribution. It is defined by two parameters: median size R_0 and mean-square deviation (SD) *s*.

$$g(r) = \left(s\sqrt{2\pi}\right)^{-1} exp(-(r-R_0)^2 / 2s^2). \qquad (3)$$

We assume that the acoustic pressure *p(r)* created by the bubble is proportional to its size (the larger the bubble, the more it rustles). Write this as:

$$p(r) \sim r. \qquad (4)$$

Taking into account that we know the initial distribution of bubbles in size:

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$$p(r) \sim r \cdot \sqrt{g(r)} = = r\sqrt{\left(s\sqrt{2\pi}\right)^{-1} exp(-(r-R_0)^2/2s^2)}. \quad (5)$$

Now let's move to the frequency domain. To do this, we use the ratio of Minnaert:

$$f \approx M[m \cdot s^{-1}]/r. \quad (6)$$

For air bubble in water:

$$M \approx 3[m \cdot s^{-1}]. \quad (7)$$

Rewrite expression for 3 with expression for 4:

$$\frac{M}{f}\sqrt{\left(s\sqrt{2\pi}\right)^{-1} exp(-(\frac{M}{f}-R_0)^2/2s^2)}. \quad (8)$$

Note that $p(f)$ is an analog of the bubble noise spectrum. It is erroneous to assume that in the spectrum we will see a peak at the frequency $f_0=M/R_0$ corresponding to bubbles with a radius R_0. In fact, the peak will be shifted to the left. Find this peak. By simple calculations (taking the derivative and equating it to zero), we find out that the maximum is reached at:

$$f_{\max} = 2M(M/f_0 + \sqrt{(M/f_0)^2 + 8s^2})^{-1}. \quad (9)$$

Thus, if we measure the spectrum of the noise of bubbles, we will see a peak at a frequency f_{max}, which will correspond to bubbles with a radius:

$$r_{\max} = M/f_{\max} = = \frac{1}{2}(M/f_0 + \sqrt{(M/f_0)^2 + 8s^2}) = = \frac{1}{2}(R_0 + \sqrt{R_0{}^2 + 8s^2}). \quad (10)$$

As can be seen from the resulting expression, the offset size depends on the magnitude of the SD s. Now we need to understand how to determine f_0 from the measured spectrum, knowing f_{max}.

Looking again at expression for 5, it becomes clear that the peak is shifted due to the *1/f* multiplier. Those, if we divide the graph of the measured spectrum by *(1/f)*, then we get a curve with a maximum at $f=f_0$:

$$p(f)/(1/f) \sim \sqrt{g(r)}. \quad (11)$$

Recalling that in the case of spectra it is easier to work in logarithmic quantities, we prologize the resulting expression:

$$20\log(p(f)/(1/f)) = = 20\log(p(f)) - 20\log(1/f). \quad (12)$$

Those, if we subtract 20log(1/f) from the measured spectrum mapped in (dB), we get a curve with a maximum at the point f_0. Thus, it became clear how to calculate the median bubble radius $R_0=M/f_0$.

It remains only to determine *SD* s. To do this, from the expression for 9 through r_{max} and R_0 express *s*:

$$s = \sqrt{\frac{(2r_{\max} - R_0)^2 - R_0^2}{8}}. \quad (13)$$

Thus, we found the initial distribution of bubbles *g(r)*with the median size R_0 and *SD s*.

III. Experimental Part

To confirm the theory, a series of experiments were conducted to determine the distribution of air bubbles by size in water. The experiments were carried out in a cubic tank (1) with dimensions of 0.3x0.3x0.3 m (see Fig. 1). The tank was filled with water. Through the injection needle 23G (2), the air was passed from the accumulation tank (5) and thus bubbles were generated. The size of the bubbles was controlled by the flow rate of the supplied air. The higher the flow rate, the larger the bubbles.

Acoustic noise emitted by bubbles was recorded with VK type 8103 (3) hydrophone connected to Pulse LAN-XI (4) spectral analyzer. Next, the recorded signal was processed by fast Fourier transform (FFT) and the noise spectrum was calculated. The hydrophone was located in the center of the tank next to the stream of bubbles.

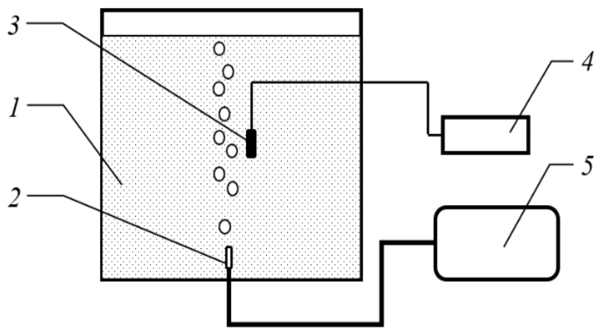

Fig. 1. Experimental setup scheme. 1 – cubic tank filled with water; 2 – injection needle 23G; 3 – Bruel & Kjaer type 8103 hydrophone; 4 –Pulse LAN-XI spectral analyzer; 5 – storage tank with air.

4 experiments were conducted. The first experiment was carried out with a maximum flow rate of air supplied. In subsequent experiments, the airflow was reduced.

IV. Results

Processing of the results was carried out as follows. From the measured spectrum of the noise of the bubbles was the frequency f_{max} − corresponding to the peak. Further, the spectrum was adjusted according to expression (12). Then, the frequency f_0 was determined, corresponding to the peak on the corrected spectrum. After that, the radii of the bubbles R_0 and r_{max} were calculated from the relation of Minnaert (6). Finally, according to formula (13), the deviation from SD *s*.

By finding the parameters R_0 and *s*, graphs of the distribution of air bubbles in size *g(r)* were plotted. The obtained distributions were compared with the distributions calculated from relation (11). The results are shown in Fig. 2-5.

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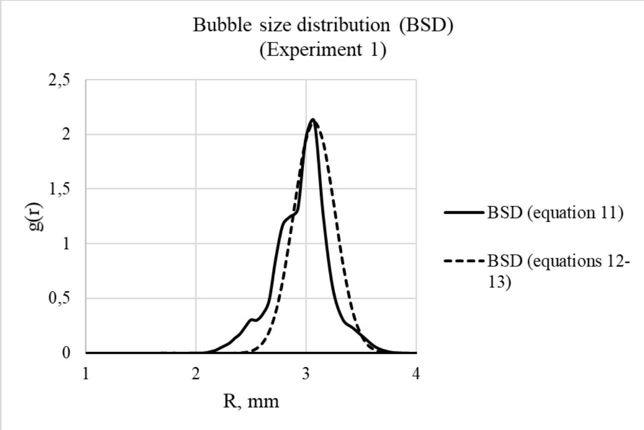

Fig. 2. First experiment's results

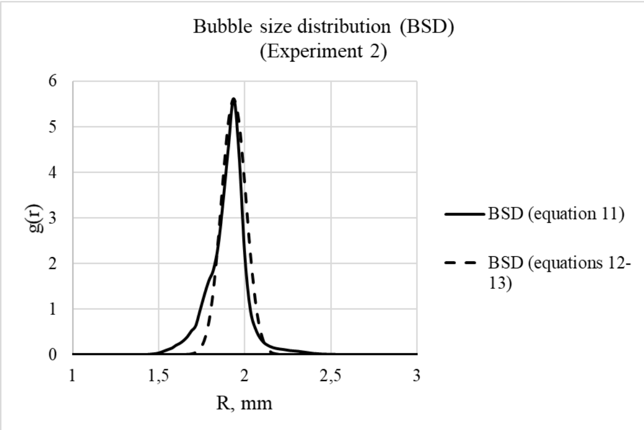

Fig. 3. Second experiment's results

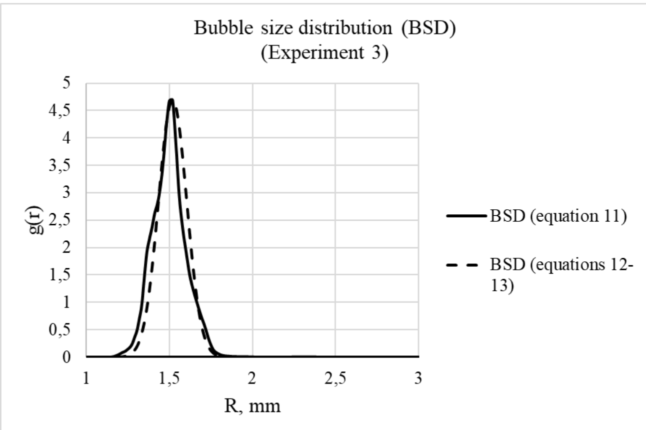

Fig. 4. Third experiment's results

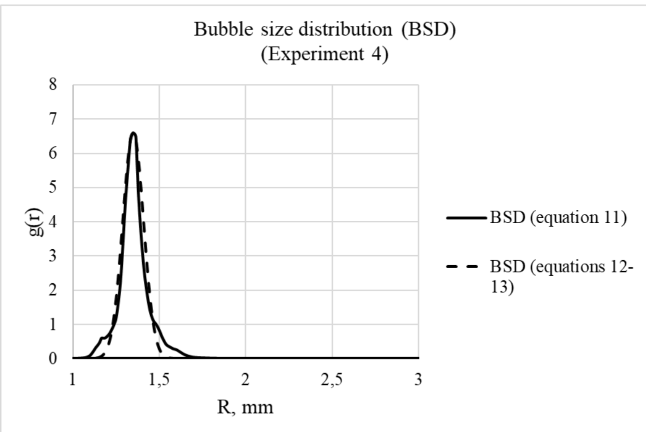

Fig. 5. Fourth experiment's results

As can be seen from the results of the experiments, the size of the bubbles depends on the flow rate of the supplied air: the greater the flow, the larger the size. The distributions calculated from the corrected spectrum using relation (11) are slightly different from the Gaussian distribution. The larger the bubble size, the greater the deviation. This may be because the frequency of an acoustic wave emitted by a bubble is inversely proportional to its size. Accordingly, as the frequency decreases, the relative error in determining the frequency difference f_{max} and f_0, which is used in calculating the parameters of the Gaussian distribution, increases. It is worth noting that for bubbles with a radius of less than 1.5 mm (Fig. 4.5), the distribution is almost identical to the Gaussian.

V. Conclusion

In this paper, the authors proposed a passive acoustic method for determining the size of air bubbles in water. The advantage of this method is that, unlike active methods, it is invasive, i.e. does not affect the gas-liquid stream under study. The mathematical model described in the second part of recalculating the noise spectrum of bubbles into a bubble distribution by size was tested on an experimental setup with different operating modes with median radii of bubbles from 1.3 to 3 mm.

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