The formation method and velocity rise of bubble cluster

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Abstract. The results of an experimental study of the ascent of a compact cluster of monodispersed air bubbles in a viscous liquid are presented. To form a compact cluster of monodisperse air bubbles with given values of diameter and volume concentration, a special experimental setup has been developed. It is shown that the ascent velocity of a cluster of monodispersed air bubbles depends on their number, diameter, distance between bubbles and exceeds the ascent velocity of a single bubble. An empirical dependence for the drag coefficient of the cluster of air bubbles rising in glycerin has been obtained.

1. Introduction

Studies of the regularities of the ascent of monodispersed bubble cluster are of interest at solving the number of problems of technics and technology. The behavior of the liquid containing bubbles significantly differs from the behavior of homogeneous liquids at various physical and physical-chemical effects. These differences are actively used in industry - boiling, two-phase heat transfer, cavitation, foaming, flotation. In a number of problems, the question of forming the bubble cluster of specified sizes, in particular, at studying the ignition of an electric discharge in liquids by means of the specially created cavitation bubbles [1], effect of surfactants and acoustic waves on the bubble clusters dynamics [2-4].

Theoretical study of the problem of the motion of the solid particles group was carried out in works [5, 6]. A number of experimental and theoretical works are devoted to the dynamics of the ascent of a single bubble, the review of which is given in [7]. An experimental study of the dynamics of the ascent of a set of bubbles was carried out only for a chain of bubbles [8, 9], which is connected with the complexity of obtaining a compact spherical cluster of bubbles.

In this paper we present the results of an experimental study of the ascent of a compact cluster of monodispersed air bubbles in a viscous liquid. To form a compact cluster of monodisperse bubbles, a special experimental setup has been developed [10].

2. Diagram of an experimental setup

The experimental setup for studying the dynamics of the ascent of the monodispersed bubbles cluster is shown in figure 1. The device for generating the bubbles of an air 2 located at the bottom of the tank 1 filled with liquid is connected by the tube 4 with reservoir of a compressed air 5. The pressure from the reservoir of a compressed air 5 is supplied to the device 2 by means of micro gear 6 with a control manometer 7 and reducer 8. In addition there is a separate container 9 connected to the tube 4 by means of reducer 10 and tee-bend 11. The container 9 is used for generation of a positive pressure preventing the flow of working liquid into the device 2.
Figure 1. Diagram of an experimental setup for formation of a compact cluster of monodispersed bubbles.

The tank 1 is made in the form of a cuvette with plane-parallel walls from optical glass of $0.3 \times 0.3 \times 0.6$ m in size to allow the visualization of the process of the bubbles cluster rise. To visualize the dynamics of the scent of the bubble cluster 3 in liquid medium the two high-speed video cameras 12 located with the possibility of recording of the bubble cluster in perpendicular planes [10] are used.

The device for creating the monodispersed cluster of bubbles 2 is made in the form of the collector with perforations in the upper lid starting from the center and along equidistant concentric circles. This allow obtaining the axisymmetric bubble cluster. The use of tubes of the same diameter 13 installed in the perforations provides the formation of monodispersed bubbles. Tubes of an equal height located in each of the concentric circles provide the simultaneous formation of the "ring" of bubbles for each of the circles. The linear decrease in the height of the tubes located on the circles and increase in the radius of the circle provide the sequential formation of each "ring" of the bubbles with the same delay in time with distance from the center of the collector cover. This allows obtaining the compact cluster with uniform spatial distribution of the bubbles.

The device operates as follows. The positive pressure preventing the flow of working liquid through the micro tubes 13 into the device 2 is established by means of the reducer 10. By adjusting the pressure by means of redactor 8 from the pressure-air reservoir 5 the pressure is designated depending on the viscosity of initial liquid. Impulsive usage of the micro gear 6 (by means of electropneumatic valve, not shown in figure 1) the pressure in the system is raised. After separation of the bubbles from the tubes 13 the rising compact cluster of bubbles of spherical shape is formed in the liquid 2. The ascent of the bubbles from the micro tubes 13 over the entire working area (filled with liquid) of the reservoir 1 is recorded by two high-speed video cameras 12 arranged with possibility to record the bubble cluster 3 in perpendicular planes.

3. The results of experimental study

The number of bubbles $n = (1\div23)$ and their diameters $D = (3\div7)$ mm in a monodispersed cluster as well as the spatial arrangement of the bubbles among themselves are varied during the experimental study. Distilled water and glycerin were used as a liquid (table 1).

An experimental study of the process of ascent of the bubbles group in the contact interaction regime showed that at coagulation of the bubbles with subsequent their merging into larger bubbles or coalescence, collision without coagulation the movement of compact cluster of the bubbles does not observed and creation of separate numerous clusters or separately moving bubbles appear.
Table 1. Physical characteristics of air and glycerin at the temperature 20°C.

| Parameter | Air  | Glycerin |
|-----------|------|----------|
| $\rho$ (kg/m$^3$) | 1.205 | 1260 |
| $P_{atm}$ (Pa) | 101308 | – |
| $\sigma$ (N/m) | – | $63 \times 10^{-3}$ |

So it is not possible experimentally to analyze the dynamics and regularities of the motion of the bubbles system. Therefore, the experimental studies of the ascent of the bubbles system in the liquid were carried out for the regime of non-contact ascent of bubbles – the regime of "blown" and "partially blown" cloud.

All the main parameters such as the density $\rho$, and the dynamic viscosity $\mu$, of the liquid, the bubble diameter $D$, the rising velocity of the bubble cluster $U$, the surface tension coefficient at the liquid-gas boundary $\sigma$ were measured during the experiments. The physical properties of the studied liquids were determined before and after each experiment.

The video frames of the ascent of compact cluster of the monodispersed bubbles obtained in two perpendicular planes are shown in figure 2. The experimentally obtained diameter of the bubbles is $D \approx 5$ mm.

The typical view of the spatial arrangement of the bubbles at different times of the ascent is shown in figure 3 ($n = 7; D \approx 5.5$ mm; $\mu = 1.67$ Pa·s; liquid–glycerin).

Figure 2. Video frames of the ascent of compact cluster of the monodispersed bubbles.

Figure 3. Coordinates of the bubbles arrangement at different times from the beginning of the ascent ($t = 1.3$ s; 15 s).
The density of the studied liquids was measured by areometer with a relative error $\delta \rho_l = 0.1\%$. The coefficient $\mu_l$ was determined from the measured velocity of stationary settling $u_p$ of a steel ball of diameter $D_p$ in the Stokes regime [3].

$$\mu_l = \frac{gD_p^2(\rho_p - \rho_l)}{18u_p},$$

where $\rho_p$ is the density of the ball material.

The experimental value of the drag coefficient of the bubble cluster was determined from the equation of motion in the stationary regime (at $du/dt = 0$) by the formula:

$$C_D = \frac{4}{3}g(\rho_l - \rho)\frac{D_{bc}}{\rho_p U^2},$$

where $g$ is the acceleration of gravity; $D_{bc}$ is the diameter of the bubble cluster.

The relative error of determination $C_D$ was calculated by formula

$$\delta C_D = \sqrt{(\delta D_{bc})^2 + 4(\delta U)^2},$$

where the values for $\delta D_{bc}$ and $\delta U$ are shown in table 2. This formula does not take into account the errors of measurement of $\rho$ and $\rho_l$ because of their smallness.

**Table 2.** The error in determining the parameters of the experiment.

| $\delta \rho_l$, % | $\delta \mu_l$, % | $\delta D$, % | $\delta D_{bc}$, % | $\delta U$, % |
|-------------------|------------------|--------------|-------------------|--------------|
| 0.1               | 0.2              | 0.2          | 3                 | 0.2          |

Analysis of the experimental data on the rising velocity of the bubble cluster showed that the velocity increases as the number of the bubbles in cluster increases. The rising velocity of the bubble cluster depends on the number of bubbles, their diameter, and distance between the bubbles. In view of the insufficiently high reproducibility of the shape of the cluster in the experiments for each condition the 10–15 duplicating experiments were carried out. However, the correlation coefficient of the dependence $U(n)$ did not exceed 0.8 even at this number of experiments (figure 4).

The results of measuring the drag coefficient of the bubble cluster in dependence of the Reynolds number are shown in figure 5. An empirical dependence for the drag coefficient of the cluster of bubbles moving in glycerin at $Re < 1$ has been experimentally obtained (curve 1 in figure 5)

![Figure 4](image-url)

*Figure 4.* Dependence of the rising velocity of the bubble cluster on number of the bubbles ($D \approx 5.5$ mm; $\mu_l = 1.67$ Pa·s; initial distance between bubbles $r_i \approx 4D$; liquid – glycerin).
\[ C_D = \frac{11.3}{\text{Re}} , \]

where \( \text{Re} = \frac{\rho U D_c}{\mu} \). For the comparison, the drag coefficient of a spherical bubble moving in a homogeneous viscous liquid at \( \text{Re} < 1 \) by the Hadamard-Rybczynski formula is showed in figure 5 (the curve 2)

\[ C_D = \frac{16}{\text{Re}} . \]

Attempt to compare the results obtained in the present work with calculations by the method of works \([6, 11]\) has shown a significant difference between the calculation and experimental data. The experimental conditions \([8, 9]\) (the chain of bubbles) significantly differ from those given in the present work (the cluster of bubbles is close to spherical).

4. Conclusion
- The diagram of experimental setup that allows obtaining the compact bubble cluster of monodispersed bubbles of a given diameter has been presented.
- The qualitative picture of the ascent of the bubble cluster has been studied by the visualization method and the dependence of the rising velocity on the Reynolds number has been determined.
- For the first time, an increase in the velocity of the ascent of a cluster of air bubbles of millimeter size in a highly viscous liquid (glycerine) was found experimentally as compared with the ascent velocity of a single bubble.
- The ascent velocity of a bubble cluster depends on the number of bubbles in the cluster, their diameter and the distance between the bubbles.
- An empirical dependence for the drag coefficient of the cluster of air bubbles rising in glycerin has been obtained.

Acknowledgments
This study was supported by the Russian Science Foundation (Project No. 15-19-10014).
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