Technical Physics Letters, 2023, Vol. 49, No. 9

03.1

Effect of the surfactant concentration on the dynamics of bubble cluster rising

© V.A. Arkhipov, S.A. Basalaev, A.S. Usanina, R.A. Churkin

Tomsk State University, Tomsk, Russia
E-mail: usaninaanna@mail.ru

Received May 29, 2023
Revised July 21, 2023
Accepted July 24, 2023

The results of an experimental study of the stationary velocity of ascent of a spherical cluster of monodispersed air bubbles in glycerin at various concentrations of a surfactant in the range of Reynolds numbers $\Re < 0.1$ are presented. New method for obtaining the cluster of monodispersed bubbles to study the process of ascent of a consolidated system of bubbles is proposed.

Keywords: cluster of monodispersed bubbles, surfactant, surfactant concentration, stationary rising velocity, experimental study.

DOI: 10.61011/TPL.2023.09.56715.19642

The dynamics of bubble flows plays a significant part in solving several applied problems in industry and technological processes [1] and in laboratory research into, e.g., the processes of ignition of an electric discharge in liquids by specially produced cavitation bubbles [2,3] or the influence of acoustic waves on bubble cluster propagation [4,5]. In a number of processes, a surfactant is introduced into a liquid in order to alter the physical and chemical properties of the liquid–gas phase boundary. The introduction of a surfactant into a liquid causes a change in the velocity of bubble ascent [6] and a reduction in the probability of coalescence of rising bubbles [7] and the intensity of mass transfer along the interface between two media [8]. Most studies [6,9–12] were focused on the influence of surfactants on the ascent of individual bubbles. The motion of a bubble cluster in the presence of a surfactant has been examined only in a limited number of studies focused on bubble flows in certain technological processes. Specifically, the investigation of dynamics of a bubble cluster in a viscous liquid with a surfactant is needed in fabrication of polymer composite materials [13] and analysis of the behavior of a bubble group in a nonlinear-viscous liquid in relation to the production of foamed bitumen [14].

The examination of effect of the surfactant concentration on the stationary velocity of bubble ascent is an important part of research into physical and chemical processes in bubble media. It has been demonstrated in experiments on ascent of a single air bubble in an aqueous non-ionic surfactant solution [9] that the bubble motion velocity is independent of the surfactant concentration. However, this result contradicts the experimental data from [10], where the velocity of bubble ascent was found to decrease with increasing surfactant concentration at the phase boundary.

The aim of the present study is to examine experimentally the stationary velocity of ascent of a cluster of bubbles at different concentrations of a surfactant in liquid. A method for production of a cluster of a given configuration with a uniform distribution of monodispersed bubbles throughout its volume [15] was developed for this purpose. The method involves pulsed gas feeding through equal-diameter tubes and was implemented using the experimental setup shown in Fig. 1.

A cluster is produced from N groups of bubbles, which form horizontal layer *12*, supplied in series in equal time intervals through tubes *6* of the same height mounted at a distance of 12 mm from each other. Each tube is connected to collector *3* via a separate electropneumatic valve *10*. Replaceable medical needles (with an outer diameter of 0.2 and 0.3 mm) mounted onto tubes were used to adjust the size of bubbles in a cluster. Rubber plugs were used to block certain collector tubes in different series of experiments in order to adjust the cluster diameter and the number and the initial volume fraction of bubbles in a cluster.

For gas bubbles to be injected through a tube into liquid, one needs to maintain collector pressure p_k at a level above hydrostatic liquid pressure p_l in the lower part of tank *1*: $p_k > p_l = p_{atm} + gH\rho_l$ (p_{atm} is the atmospheric pressure, ρ_l is the liquid density, g is the gravitational acceleration, and H is the height of the liquid column in the tank above the top collector cover). Tests were performed on the actual unit to determine a more accurate relation for pressure p_k at which an individual bubble is produced reliably under pulsed gas feeding through a tube:

$$p_k = p_{atm.} + 1.25gH\rho_l. \tag{1}$$

Constant pressure p_k in collector *3*, which satisfied condition (1), was set using reducer *8*. Controller *11* was used to apply a 5 V voltage pulse from a power source simultaneously to all electropneumatic valves *10* from a certain group corresponding to a given set of tubes. Pulse duration t_1 was determined with account for the time

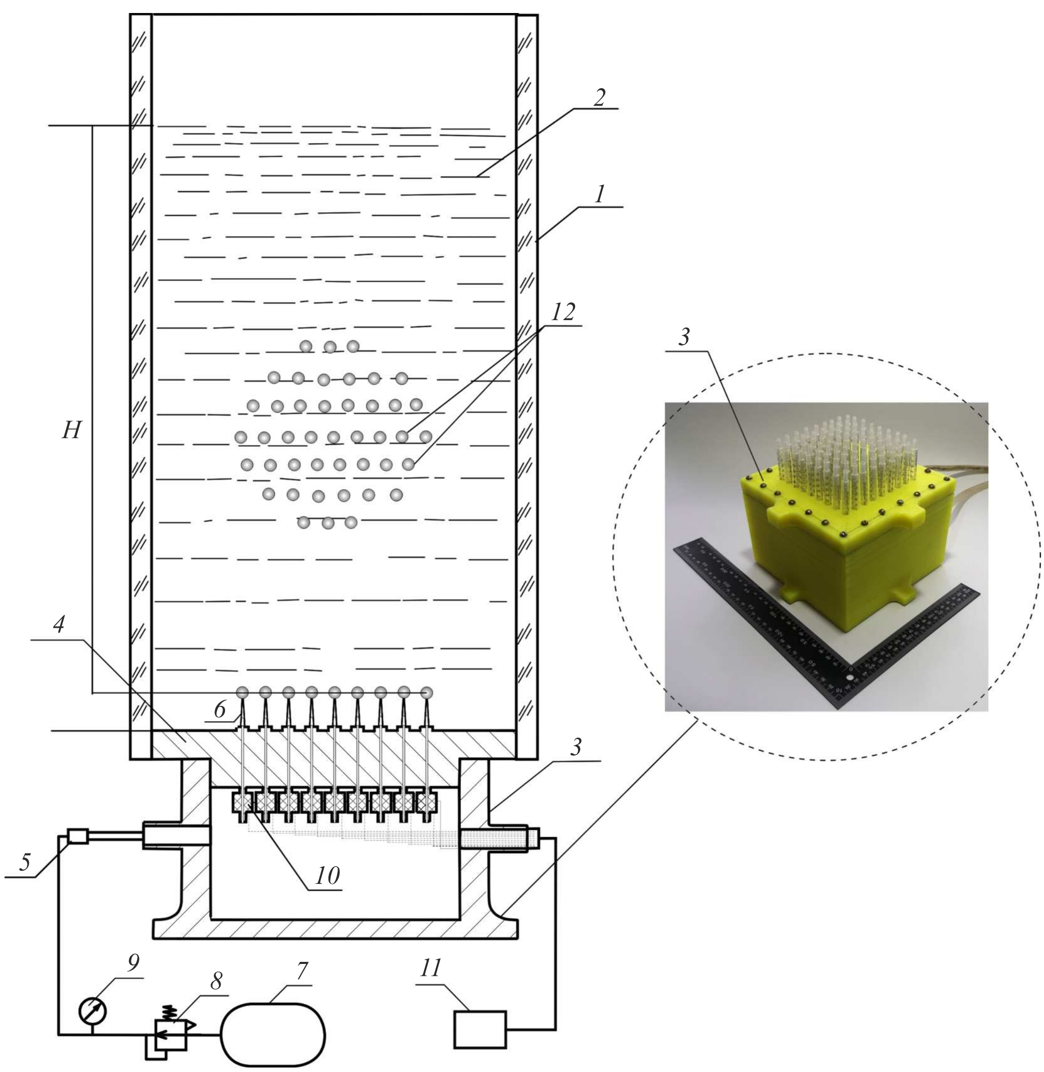

Figure 1. Diagram of the experimental setup for examination of the process of ascent of a bubble cluster. *1* — Tank, *2* — liquid, *3* — collector, *4* — collector cover, *5* — reducing pipe, *6* — tubes, *7* — compressed gas cylinder, *8* — reducer, *9* — pressure gage, *10* — electropneumatic valve, *11* — controller, and *12* — bubble layer.

needed to fill a bubble with volume V with gas:

$$t_1 = \frac{V}{Q} = \frac{2}{3}\frac{D^3}{d^2}\sqrt{\frac{p_g}{05\rho_l g H}}. \tag{2}$$

The gas volume flow rate is given by

$$Q = S\sqrt{\frac{2\Delta p}{\rho_g}},$$

where S is the passage area of a tube for gas supply into the tank and $\Delta p = p_k - p_l$ is the pressure differential across a tube. The first layer of rising bubbles $(n = 1)$ was thus formed in the liquid.

Controller *11* was then used to produce subsequent bubble layers $(n = 2, 3, \ldots, N)$, which form a cluster, by applying voltage pulses to electropneumatic valves *10* in equal time intervals

$$t_2 = \frac{l}{u(D, \rho_l, \mu_l)}, \tag{3}$$

where l is the distance between tube axes and $u(D, \rho_l, \mu_l)$ is the velocity of ascent of a gas bubble with diameter D in the liquid with density ρ_l and dynamic viscosity coefficient μ_l. A preset program code for the controller enabled the formation of a cluster with a given configuration. Conditions (1) and (2) ensured that the distribution of bubbles in a cluster was uniform. A photographic image of a spherical cluster of monodispersed air bubbles rising in glycerin is shown as an example in Fig. 2.

The discussed setup was used to examine the process of ascent of an initially spherical cluster of monodispersed air bubbles in pure glycerin and in a glycerin–dilamide (non-ionic surfactant) solution. The contactless type of ascent of a bubble cluster [16] was studied (i.e., moving bubbles did

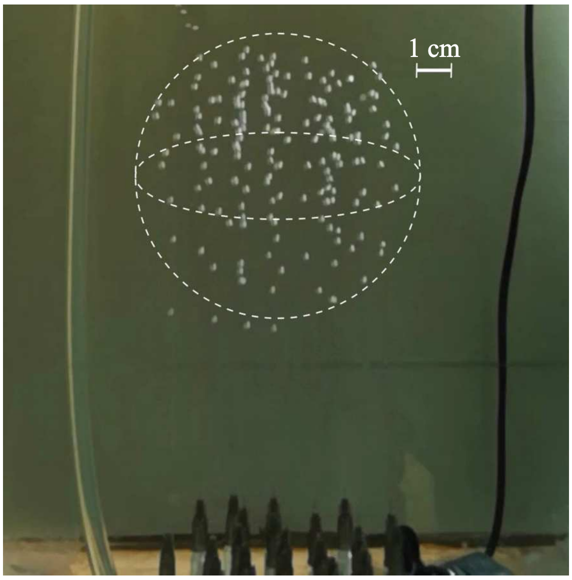

Figure 2. Photographic image of a spherical cluster of monodispersed air bubbles in glycerin.

Surface tension coefficient of the studied liquids

Parameter	Surfactant concentration, g/l			
	0	$2.87 \cdot 10^{-2}$	$2.87 \cdot 10^{-1}$	2.87
σ, mN/m	64.9	56.4	44.3	36.2
μ_l, Pa·s	1.27	1.27	1.22	1.15

not come into contact with each other at the initial time and throughout the entire process of ascent). The values of surface tension coefficient σ of liquids used in experiments are listed in the table. Bubble diameter D in a cluster was varied from 2.3 to 3.9 mm by mounting different replaceable medical needles onto tubes *6*. The error of determination of bubble diameter D in a cluster is defined by the resolving capacity of the video camera and the quality of footage and reached $\delta D = 3\%$. The initial diameter of a bubble cluster was varied within the range of $D_c = 4.8{-}8.5$ cm. The error of determination of diameter D_c is attributable to fluctuations of the cluster shape in the course of ascent and did not exceed $\delta D_c = 3\%$. The initial volume fraction of bubble clusters in experiments was

$$C_V \sim \pi(D/l)^3/6 = 0.005.$$

The velocity of ascent of a bubble cluster was determined within the stationary section of its motion (in the given experimental conditions, the origin of this section was at an average distance of 5 cm from the point of separation of bubbles). The velocity of ascent of the center of mass of a bubble cluster was determined in experiments using the following formula: $u_c = L/t$, where L is the distance traveled by the center of mass of a bubble cluster prior to the onset of noticeable deformation within time t and t is the time within which a cluster travels a distance of L. The governing error of u_c calculation is associated with the determination of the center of mass of a cluster. The percentage error of u_c identification was $\delta u_c = 4\%$.

It has been demonstrated experimentally that the presence of a surfactant at the liquid–gas phase boundary leads to a reduction in the velocity of ascent of a bubble cluster [17]. As the surfactant concentration increases, the velocity of ascent of a bubble cluster decreases (and the drag coefficient increases accordingly). Experimentally determined velocities of ascent of the center of mass of a spherical cluster of monodispersed air bubbles in a glycerin–surfactant solution are presented in Fig. 3 as functions of Reynolds number $\mathrm{Re} = \rho_l u_c D/\mu_l$ for different surfactant concentrations. The dependences of velocities of ascent of an individual bubble determined with account for Hadamard–Rybczynski $C_D = 16/\mathrm{Re}$ (curve *2*, filled circles — experimental data [18]) and Stokes $C_D = 24/\mathrm{Re}$ relations (curve *3*, filled squares — experimental data [6]) for the drag coefficient at $\mathrm{Re} < 1$ [19] are shown in the same figure for comparison. It was demonstrated in [6,18] that curves *2* and *3* in Fig. 3 correspond to the ascent of a bubble in a liquid with no surfactant and in a liquid–surfactant solution, respectively.

Thus, a new method to form a cluster of a given configuration from monodisperse bubbles distributed uniformly throughout its volume was proposed. Notably, the process

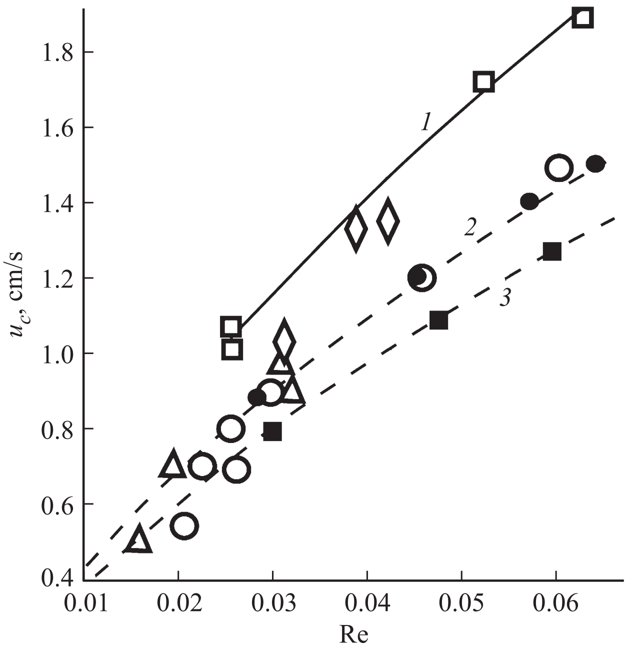

Figure 3. Dependences of the stationary velocity of ascent of an air bubble cluster in a glycerin–surfactant solution on the Reynolds number at different surfactant concentrations. Curve *1* (approximation of experimental data): open squares — $C = 0$ g/l, diamonds — $C = 2.87 \cdot 10^{-2}$ g/l, triangles — $C = 2.87 \cdot 10^{-1}$ g/l, and open circles — $C = 2.87$ g/l; curve *2* (Hadamard–Rybczynski dependence): filled circles — experimental data [18]); curve *3* (Stokes dependence): filled squares — experimental data [6]).

of formation of a bubble cluster shares a similarity with the technique for item fabrication by 3D printing.

It was demonstrated that the stationary velocity of ascent of a cluster in a liquid with no surfactant exceeds the corresponding velocity for an individual bubble by $\sim 30\%$ at equal Reynolds numbers. This agrees with the results reported in [6] and is attributable to the influence of neighboring bubbles on the velocity of ascent. The difference between the above velocities decreases with increasing surfactant concentration (Fig. 3). The velocity of a bubble cluster was found to decrease by 20–30% within the examined range of surface tension coefficients at the phase boundary ($\sigma = 36.2-64.9\,\mathrm{mN/m}$).

Funding

This study was supported by grant No. 22-79-10028 from the Russian Science Foundation (https://rscf.ru/project/22-79-10028/).

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] B.V. Boshenyatov, *Mikropuzyr'kovye gazozhidkostnye sredy i perspektivy ikh ispol'zovaniya* (LAP LAMBERT, Saarbrücken, 2016) (in Russian).
[2] A.P. Drozhzhin, S.M. Korobeinikov, V.S. Teslenko, Nauchn. Vestn. Novosib. Gos. Tekh. Univ., No. 2, 1 (2003) (in Russian).
[3] V.V. Skorykh, Zh. Tekh. Fiz., **56** (8), 1569 (1986) (in Russian).
[4] A.O. Maksimov, E.V. Sosedko, Tech. Phys. Lett., **29** (2), 102 (2003). DOI: 10.1134/1.1558738.
[5] O.B. Gus'kov, J. Appl. Math. Mech., **78** (2), 126 (2014). DOI: 10.1016/j.jappmathmech.2014.07.004.
[6] V.A. Arkhipov, I.M. Vasenin, A.S. Usanina, Fluid Dyn., **51** (2), 266 (2016). DOI: 10.1134/S0015462816020137.
[7] J. Lu, C.M. Corvalan, Y.M.J. Chew, J.Y. Huang, Chem. Eng. Sci., **196**, 493 (2019). DOI: 10.1016/j.ces.2018.11.002
[8] K.A. Bushueva, M.O. Denisova, A.L. Zuev, K.G. Kostarev, Konvekt. Techeniya, No. 3, 139 (2007) (in Russian).
[9] Y. Zhang, J.A. Finch, J. Fluid Mech., **429**, 63 (2001). DOI: 10.1017/S0022112000002755
[10] R. Bel Fdhila, P.C. Duineveld, Phys. Fluids, **8** (2), 310 (1996). DOI: 10.1063/1.868787
[11] F. Takemura, Phys. Fluids, **17** (4), 048104 (2005). DOI: 10.1063/1.1879712
[12] Y. Tagawa, S. Takagi, Y. Matsumoto, J. Fluid Mech., **738**, 124 (2014). DOI: 10.1017/jfm.2013.571
[13] V. Michaud, Transp. Porous Med., **115** (3), 581 (2016). DOI: 10.1007/s11242-016-0629-7
[14] O.V. Matvienko, V.P. Bazuev, M.V. Agafontseva, Vestn. Tomsk. Gos. Arkhit.-Stroit. Univ., No. 4 (37), 144 (2012) (in Russian).
[15] V.A. Arkhipov, A.S. Usanina, K.G. Perfil'eva, S.A. Basalaev, S.N. Polenchuk, K.V. Kostyushin, *Sposob polucheniya puzyr'kovogo klastera zadannoi konfiguratsii*, RF Patent No. 2796910 (published May 29, 2023) (in Russian).
[16] V.A. Arkhipov, S.A. Basalaev, K.G. Perfil'eva, A.S. Usanina, J. Eng. Phys. Thermophys., **93** (5), 1200 (2020). DOI: 10.1007/s10891-020-02222-4.
[17] V.A. Arkhipov, A.S. Usanina, S.A. Basalaev, L.E. Kalichkina, V.S. Mal'kov, Fluid Dyn., **55** (1), 103 (2020). DOI: 10.1134/S0015462820010024.
[18] V.A. Arkhipov, I.M. Vasenin, A.S. Usanina, J. Eng. Phys. Thermophys., **86** (5), 1171 (2013). DOI: 10.1007/s10891-013-0939-3.
[19] R.I. Nigmatulin. *Dinamika mnogofaznykh sred* (Nauka, M., 1987) (in Russian).

Translated by Ego Translating