Technical Physics Letters, 2022, Vol. 48, No. 7

03.1;03.4

Spreading rate of a toroidal air bubble in water

© *V.V. Nikulin, E.A. Chashnikov*

Lavrentyev Institute of Hydrodynamics, Siberian Branch, Russian Academy of Sciences, Novosibirsk, Russia
E-mail: nikulin@hydro.nsc.ru, chashnikov.e.a@gmail.com

Received April 29, 2022
Revised May 20, 2022
Accepted May 20, 2022

The rise of a toroidal bubble in water obtained by injecting a pulsed jet of air into the water through a nozzle vertically upwards has been experimentally investigated. It was found that, despite the decrease in the cross−section of the toroidal bubble during the ascent, its radius grows linearly depending on the distance traveled, as in the case of self−similar vortex rings. The coefficient of expansion of the bubble at different volumes of injected air is determined. A comparison was made with toroidal bubbles obtained when balloons burst under water. A qualitative explanation of the observed differences is given.

Keywords: vortex ring, toroidal bubble.

DOI: 10.21883/TPL.2022.07.54036.19241

Toroidal bubbles are a species of vortex rings [1] buoyant in liquid, in which gas is used as the buoyant matter [2–6]. Their characteristic feature is that the gas concentrates under the centrifugal force in the vicinity of the vortex ring core axis over the entire period of motion. Thus, the observed object is a two−phase toroidal vortex whose core contains gas while the atmosphere contains liquid. A number of papers suggest that the vortex core coincides with the bubble [3–5]. Then the bubble volume and, hence, the vortex core volume, will remain almost invariant in the case of a slight variation in the pressure relative to the atmospheric one. Due to an increase in the toroidal bubble radius, this will result in a decrease in the bubble cross−section radius and, hence, in the core radius [3–6]. In this case a question on self−similarity arises, since, in case of the self−similar motion, the toroidal core radii and cross−section are to vary as shown in [1]. At the same time, in the presence of self−similarity the core radius should increase linearly with the traveled distance. No specific−purpose studies of such a dependence for toroidal bubbles have been performed; however, experimental values of the bubble radii at different heights obtained in [4] may be approximated by linear functions. If this dependence is linear, the motion is either self−similar regardless of an increase in the ratio between radii of the toroidal bubble and its cross−section, or is more complicated than in the case of single−phase buoyant vortex rings. Therefore, the question on the toroidal bubble radius dependence on the rise height is of the fundamental character in view of modelling the bubble motion. The toroidal bubble radius R variation with traveled distance z is characterized by parameter $\alpha = dR/dz$ referred to as spreading rate or expansion coefficient [7,8]. In work [9] it was found out that the expansion coefficient of single−phase buoyant vortex rings containing a lighter gas remains invariant during motion. For the toroidal bubbles, no measurements of expansion coefficients were performed.

In this study, the toroidal bubble radius was measured experimentally versus the rise height. The bubbles are formed when a pulsed air jet is injected through a nozzle into water vertically upwards. The injected air volume is variable. A conclusion about the dependence character is made, the expansion coefficients are calculated. The results are compared with the expansion coefficients of bubbles arising when balloons burst under water. A qualitative explanation for the observed differences is given.

The experiments have been conducted in a transparent Plexiglas vessel 20 × 20 mm in cross−section and 1200 mm in height; the vessel was filled with water. Compressed air is fed to a solenoid valve through a pressure regulator. The solenoid valve is driven via a controller. The controller opens the valve for a short time interval, compressed air flow vertically upwards through the nozzle mounted at 100 mm from the chamber bottom into water where the toroidal bubble gets formed. The nozzle outlet diameter is 4 mm. The nozzle is fabricated from a non-wettable material in order to prevent water leakage into the nozzle. The bubble motion is detected by a rapid video camera MotionXtraHG-100k with the frequency of 125 fps and exposure time of 125 μs. Shadow video recording is performed in the transmission mode perpendicular to the motion direction. Images are processed in the Matlab medium using Image Processing ToolBox and basic elements; the outer lateral size R' of the shadow image has been determined. To determine the bubble air volume V, the bubble is caught with a funnel−shaped device mounted in the vessel top part. This method for the volume determination is significantly more accurate than that based on video images, since the toroidal bubble shape is not strictly circular and identical in different cross−sections. In the experiments, the compressed air pressure is varied from 2 to 6 bar, while the duration of opening the solenoid valve is varied from 10 to 25 ms. The bubble volume changes respectively from 12 to 43 cm^3. The typical bubble diameter is 50−70 mm, its path is 600 mm

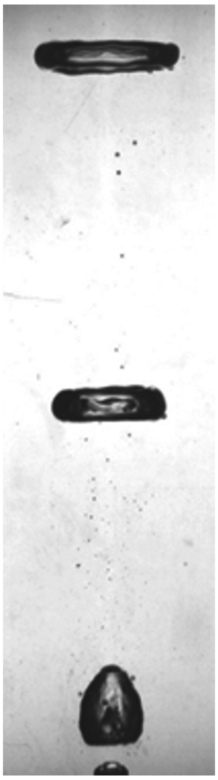

Figure 1. Shadow photos of different stages of the bubble evolution.

long. At this distance, the hydrostatic pressure variation is low as compared with the atmospheric one; therefore, the bubble volume remains constant during the motion. Only bubbles that have passed the entire path to the catching device are detected. 30 observations have been accomplished.

The shadow photos (Fig. 1) present different bubble−evolution stages corresponding to time moments 34, 276, 590 ms after the onset of the pulsed air jet injection: bubble separation from the nozzle, toroidal bubble formation, increase in radius during the ascent. One can see that the torus gets formed during of a singly linked air volume rather than due to the vortex sheet rollup as in case of vortices in a homogeneous liquid [8]. Thus, the torus is formed according to the baroclinic mechanism associated with the density gradient. During formation, a circulation takes place around the torus [2]. The toroidal bubble radius R equal to the torus axial line radius will be determined based on R' and V via two equations:

$$2\pi^2 R a^2 = V, \qquad R + a = R',$$

where a is the torus cross−section radius. From these equations there will be derived a cubic equation in R that has only one solution in the physically correct area $R \in (\sqrt[3]{V/2\pi^2}, R')$. The radius determination error does not exceed 8%. In Fig. 2, points represent the R/r_0 dependences on z/r_0 for different expansion coefficients, which correspond to the bubble volumes of 26, 23.9 and 43.4 cm^3. Here r_0 is the radius of a sphere whose volume is equal to the bubble volume. Coordinate $z = 0$ is assumed to be at 150 mm from the nozzle where the toroidal bubble has been already formed. Solid lines represent approximations of experimental points by linear regressions. Validity of the linear approximation is assessed using the determination factor [10]. The determination factors appeared to range from 0.94 to 0.99 in all the experiments. Herefrom it follows that deviations from linearity caused by unaccounted factors do not exceed 6%. Among the unaccounted factors there are radius measurement errors and the bubble shape deviations from torus associated with perturbations on its surface. Thus, the Turner's conclusion made for buoyant single−phase vortices about the fact that the law of linear increase in the vortex size with increasing traveled path remains effective during the major part of vortex travel is valid also for toroidal bubbles.

Expansion coefficients α will be determined from the linear regression plots. The α values for different volumes of injected air are given in Fig. 3. This figure shows that there is no any remarkable dependence of α on the injected air volume, i. e. on the buoyancy force. The same situation is observed also for vortices obtained in bursting in air of soap bubbles filled with lightweight gas [9]. The mean value and dispersion are $\alpha = 0.037 \pm 0.005$. The linear regressions presented in Fig. 9 of paper [4] show that $\alpha = 0.07$, 0.09, 0.1, 0.11. Authors of [9] obtained $\alpha = 0.09 \pm 0.02$. Notice that data of [4] also fit this dependence. Thus, expansion coefficients of toroidal bubbles obtained in bursting of balloons under water or of soap bubbles in air appear to be higher than in the case of air jet injection into water. This difference may be qualitatively explained as follows. Circulation arises during bursting of balloons and soap bubbles due to baroclinic

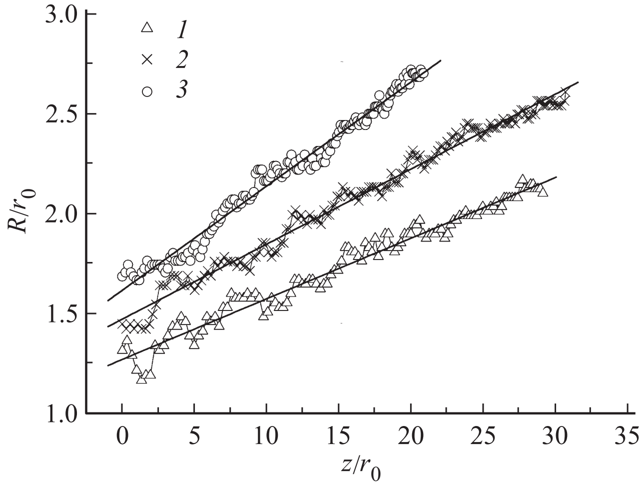

Figure 2. Experimental dependences (points) of the dimensionless toroidal bubble radius on the dimensionless rise height for the bubble volumes of 26 (*1*), 23.9 (*2*) and 43.4 cm^3 (*3*). Lines represent the points approximation by linear regressions.

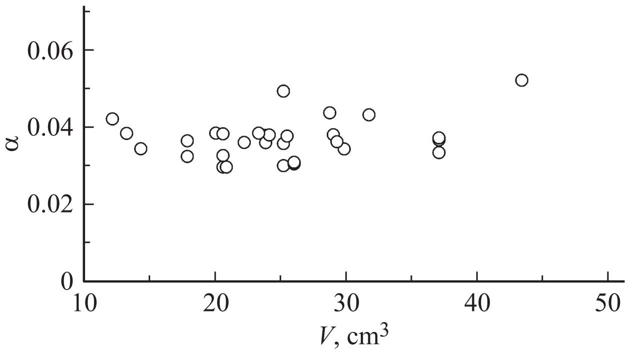

Figure 3. The toroidal bubble expansion coefficients α for different volumes of injected air.

force moments acting upon a bubble formed after the burst. Let us designate the circulation as Γ_0. When an air jet is injected into water, circulation Γ_0 is summed with circulation Γ_1 appearing due to a shear layer at the air jet – water interface. Therefore, similarly to [7], in this case it is possible to represent the total circulation as the following sum: $\Gamma = \Gamma_0 + \Gamma_1$. Since the toroidal bubble radii increase linearly with height, i. e. the expansion coefficients are constant, they may be analytically represented by the Turnerś formula [1]: $\alpha = F/(2\pi c\Gamma^2)$, where F is the buoyancy force per unit mass, c is constant. Then during bubble bursting $\alpha = \alpha_0 = F/(2\pi c\Gamma_0^2)$; parameter Γ_0^2 is proportional to F [7]. In the case of jet injection into water, $\alpha = F/\big(2\pi c(\Gamma_1 + \Gamma_0)^2\big) = \alpha_0/(1 + \Gamma_1/\Gamma_0)^2$. Hence, $\alpha < \alpha_0$.

Thus, it has been established that, regardless of the absence of self–similar interrelation between the toroidal bubble radii and cross–section, toroidal bubbles expand linearly with the ascent height. The paper shows that toroidal bubbles obtained due to the air jet injection into water possess a lower expansion coefficient than that in case of balloon bursting. This is associated with additional circulation occurring when air is injected.

Conflict of interests

The authors declare that they have no conflict of interests.

References

[1] J.S. Turner, Proc. Roy. Soc. A, **239**, 61 (1957). DOI: 10.1098/rspa.1957.0022
[2] J.K. Walters, J.F. Davidson, J. Fluid Mech., **17**, 321 (1963). DOI: 10.1017/S0022112063001373
[3] T. Pedley, J. Fluid Mech., **32**, 97 (1968). DOI: 10.1017/S0022112068000601
[4] A.R. Vasel-Be-Hagh, R. Carriveau, D.S.-K. Ting, J. Fluid Mech., **769**, 522 (2015). DOI: 10.1017/jfm.2015.126
[5] A.R. Vasel-Be-Hagh, R. Carriveau, D.S.-K. Ting, J.S. Turner, Phys. Rev. E, **92**, 043024 (2015). DOI: 10.1103/PhysRevE.92.043024
[6] X. Yan, R. Carriveau, D.S.-K. Ting, J. Fluids Eng., **140**, 054502 (2018). DOI: 10.1115/1.4038661
[7] D. Bond, H. Johari, Exp. Fluids, **48**, 737 (2010). DOI: 10.1007/s00348-009-0761-z
[8] D.G. Akhmetov, Vortex Rings (Springer, Berlin, 2009).
[9] B.I. Zaslavskii, L.M. Sotnikov, J. Appl. Mech. Tech. Phys., **24**, 16 (1983). DOI: 10.1007/bf00914471.
[10] E. Forster, B. Ronz, *Methoden der correlations und regressions analyse* (Wirtschaft, Berlin, 1979).