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Calculations of pulsation period of a toroidal bubble during diaphragm discharge in electrolyte

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ABSTRACT

Numerical calculations of pulsation period of a toroidal bubble on the edge of a round diaphragm current concentrator during electric discharge in electrolyte were performed for the self-oscillations mode. It was shown both theoretically and experimentally that the dependence of the period of the pulsations on the applied voltage has a minimum. This minimum corresponds to the conditions of the change in the leading mechanism of the bubble growth. The derived formula for the bubble pulsation period is in a good agreement with experimental data on discharges with the round diaphragms of the radii from 0.025 to 0.75 mm.

1. Introduction

The self-oscillating mode of electric discharge near the current concentrator of the shape of a round diaphragm in an electrolyte was described in [1,2]. This is one of the possible modes of the low-voltage (up to 1000 V) discharge in conducting liquids. It was shown that the self-oscillations are the processes of generation and pulsation of a toroidal bubble which develops because of electrolyte heating by the electric current. They are featured by a pulse current at the constant applied voltage that is governed with generation and pulsation of bubbles on the current concentrators (such as diaphragm). The toroidal shape of the pulsating bubble is determined by distributions of the current density and the temperature in the experimental cell that are strongly non-uniform and reach their maximum values near the edge of the round diaphragm [3]. This self-oscillation mode is important both from the fundamental point of view (study of the mechanisms of interaction of complex self-oscillating systems) and for applications (mainly for the design of generators of acoustic waves of specified geometry and frequency). The self-oscillating mode, discovered more than a hundred years ago, was not described theoretically because of the complex nature of physical processes of this mode.

The period of self-oscillation and region of the parameters where these oscillations occur are significant for the development of apparatuses (experimental and industrial equipment/devices/setups). So far there are no theoretical formulas, even approximate, describing the dependence of self-oscillation period on the parameters of discharge conditions (the size of current concentrator, voltage applied, electrolyte properties etc.). The known empirical dependencies take into consideration a change in only one parameter, for example, voltage, temperature or size of the current concentrator, and they change significantly when other parameters are varied. Therefore, there is a need of comprehensive experimental and theoretical studies of electrohydrodynamic self-oscillation process using basic principles of electrodynamics, hydrodynamics, and thermal physics to derive the dependence of the oscillation period on the parameters of the system.

Applications of low-voltage discharge in electrolytes at the current concentrators were described in several papers. For example, emission spectral analysis of low-voltage diaphragm discharge was applied to measure the concentrations of ions of metals in a liquid [4,5]. The possibility of producing carbon nanotubes with electric discharge in liquid hydrocarbons was shown in [6]. The authors of this work gained up to 3 grams per minute in their experiments. Metallic nanoparticles were produced from the initially coarse-grained mineral with the discharge in liquid in [7]. The low-voltage discharge could be used for sterilization of liquids [8,9].

Thus, the study of low-voltage discharges on the current concentrators in electrolyte is of a big importance for their industrial applications.

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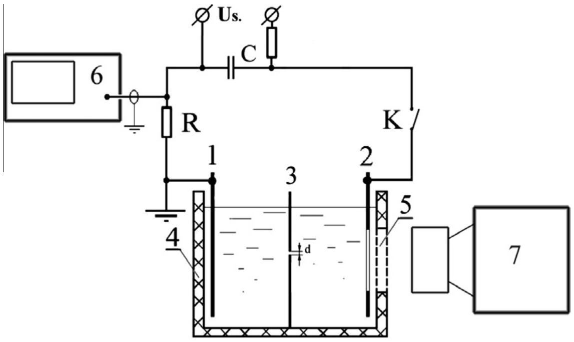

Fig. 1. The scheme of the experimental setup.

There were many studies of the process of thermal growth of a spherical bubble in overheated liquid [3,10–17]. It was shown in [17] that the radius of a vapor bubble grows proportionally to the square root of time in uniformly overheated liquid. The growth of the bubble continues until it detaches from the surface under the action of buoyancy force.

Hydrodynamics of toroidal bubbles was studied in [18,19]. In [18] the approximate equation of adiabatic bubble pulsations was obtained. In [19] the same was calculated taking into account the vortical motion of bubble and surface tension. We will use the equation obtained in [18] to solve our hydrodynamic problem.

2. Experimental setup

The used experimental setup is shown in Fig. 1. Plane electrodes 1 and 2 were placed on the opposite sides of the diaphragm with aperture 3 in plexiglass cell 4 filled with electrolyte. The distances from the diaphragm to the electrodes were ~50 mm. The electrode plates were made of stainless steel. The electric current was measured with the oscilloscope Tektronix TDS-210 (6) that was connected to the shunt of $R = 0.2$ Ohm. Another input of oscilloscope 6 was connected to electrodes 1 and 2 through a voltage divider to measure the voltage. The high-speed camera REDLAKE HG-LE (7) was used to register hydrodynamic processes through plexiglass window 5 in the cell and the round aperture in electrode 2.

The electric circuit of set included the capacitor of $C = 10 \div 100\ \mu\text{F}$ charged from external DC power supply U_s up to $U_C = 10 \div 1000\ \text{V}$, solenoid switch K governed with an external trigger generator. The trigger generator was used also for switching the camera and oscilloscope on. The setup self-inductance was 3 μH. The solution of $1 \div 5\%$ (weight concentration) of NaCl in distilled water was used as the electrolyte. Teflon films of the thickness of 20 μm and polyester films of the thicknesses of 50 μm and 100 μm were used as the diaphragms. Aperture radius a was varied from 0.025 to 0.75 mm from one experiment to another.

The video record of toroidal bubble generation at the current concentrator is shown in Fig. 2 ($a = 0.1$ mm, $U = 100$ V, electrolyte was 5% solution of NaCl in distilled water). The initial bubbles arose at the edge of the concentrator where the surface was non-uniform.

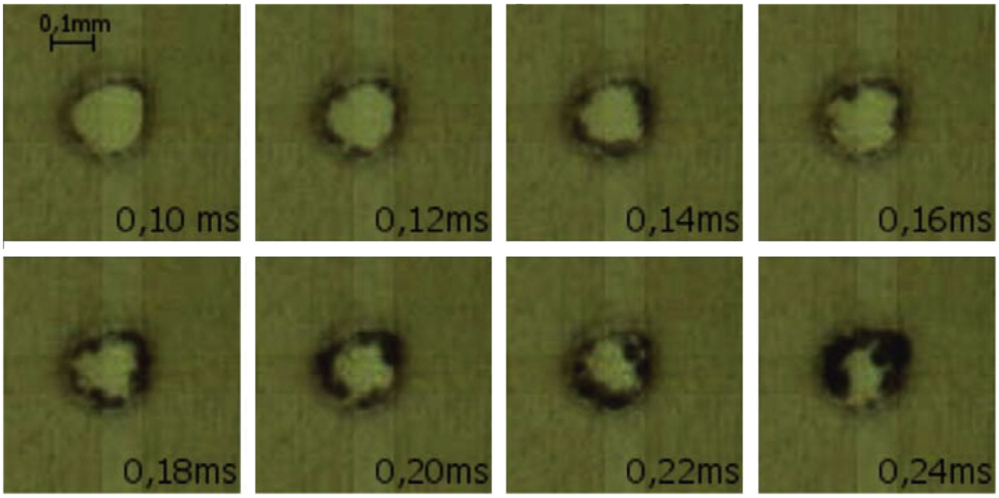

Fig. 2. Dynamics of the bubble formation at the edge of the concentrator after application of the voltage, $a = 0.1$ mm, $U = 100$ V, 5% solution of NaCl in distilled water.

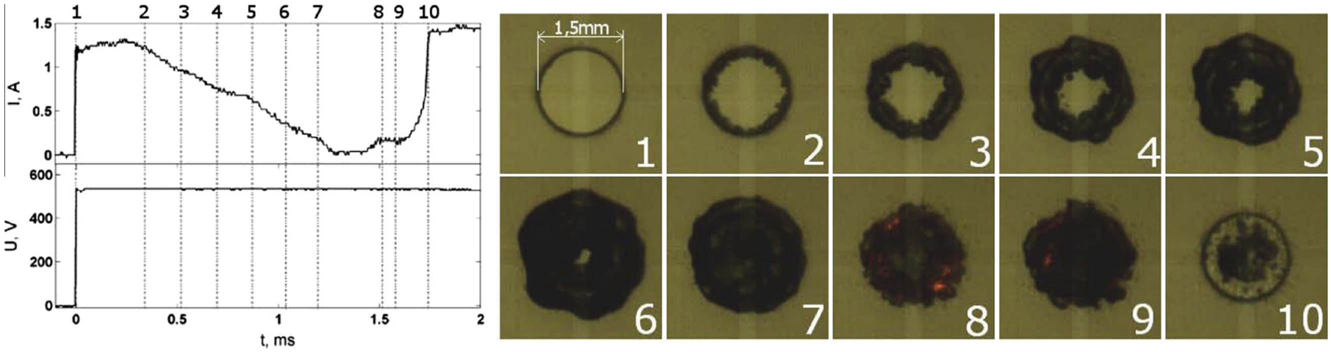

Fig. 3. The frames of the video record of bubble pulsation on round aperture in a diaphragm ($a = 0.75$ mm) with the oscillograms of the current and voltage.