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Electrohydrodynamic self-synchronization of self-oscillations on two diaphragm current concentrators in electrolyte

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ABSTRACT

This work presents the result of experimental studying the mechanisms of self-synchronization of electrohydrodynamic self-oscillation processes in electrolyte for two current concentrators of different size performed in the form of holes in dielectric diaphragms.

When an inductance coil is connected to a discharge circuit, a phase synchronization of self-oscillations occurs and is realized as a result of energy accumulation in the coil at the stage of current rise and energy release during the overlapping the current channel by a bubble. The difference in self-synchronization mechanisms is due to small and great spread in concentrator sizes. When having small spread in concentrator sizes, the energy released before the overlapping the concentrators by bubbles is sufficient to provide a synchronization, and when having great spread in concentrator sizes, the energy is required to be released after the overlapping the concentrators due to gas ionization in bubbles.

1. Introduction

In [1], we considered the effect found. This was the effect of self-synchronization of current self-oscillations for multispark discharges in electrolytes on N current concentrators ($N = 2–32$) under the condition of connecting an inductance coil to a discharge circuit. We suggested a hypothesis of possible mechanism of developing the phase synchronization. In this work, we present the results of experimental studies of electrohydrodynamic processes arising on two current concentrators in the form of holes in dielectric diaphragms.

In [2,3], we considered the results of investigating the initial stage of bubble forming on one current concentrator for conditions of developing self-oscillations. It was shown that self-oscillations were provided by pulsations of vapor-gas bubbles on current concentrators. The bubbles were formed under a rapid electrolyte heating due to high current density. The bubble formation occurs at the concentrator edge due to the fact that the current density and the energy released are maximal here [4]. In experiments, we observe a formation of the multitude of small bubbles for threshold values of voltage. When increasing, bubbles merge and grow in the form of one torus-like bubble. The bubble increases and fully overlaps the current concentrator. Then it grows to a maximal size and collapses dividing into two parts. This process is repeated again for the next bubble. Stable pulsations of the current and bubbles take place during the whole period of supply of constant voltage U.

If the additional inductance is not connected to the discharge circuit, then self-oscillations on each concentrator occur independently of each other. If concentrators are of different size, then the total current has a character of complex multimode oscillations due to difference in undamped frequencies of oscillations, i.e., the phase synchronization of self-oscillations does not occur.

To obtain coherent self-oscillations in holes of dielectric diaphragms is difficult due to technological problem of producing holes of the same diameter. Using concentrators in the form of cuts of identical wires in dielectric plate [5], we decrease the diameter spread. In such setup we can obtain a synchronism of self-oscillations for no more than ~10 pulses of current. As a result, the spread in concentrator sizes leads to an essential shift of oscillation phases as the period of self-oscillations increases while sizes of current concentrators rise.

To provide a mutual synchronization of self-oscillations, it is necessary to make a connection between oscillations on separate concentrators, which could provide the phase synchronization. Such connection takes place if there is the additional inductance $L > 0$ in the discharge circuit [1].

The connection of the additional inductance coil qualitatively changes the character of processes occurring on the multitude of concentrators. Due to the fact that there is always some spread in

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concentrator sizes the current break (current channels are overlapped by growing bubbles) occurs firstly on concentrators of smaller size. Here the inductance coil L generates an overvoltage pulse due to self-induction processes. Thus, at the moment of current breaking there is an additional voltage on concentrators, which may cause gas ionization in bubbles. Such voltage leads to acceleration of bubble growing and current break on the other concentrators.

To find mechanisms of developing a self-synchronization with discharge circuit having additional inductance coils, we performed a complex investigation of electrohydrodynamic processes arising on two current concentrators in the form of holes in dielectric diaphragms.

2. Setup of experiments

Fig. 1 shows experimental setup to study self-synchronization mechanisms of electrohydrodynamic self-oscillations on the multitude of current concentrators. Electrodes 1, 2 were placed into a nonconductive cuvette 4 with electrolyte on both sides of diaphragm 3 with holes. The distance from the diaphragm to electrodes was ∼50 mm. As electrodes we used plates of stainless steel, whose area was >10 cm^2. To measure current in the discharge circuit, we used the oscillograph Tektronix TDS-210 (6), which was connected to the shunt ($R = 0.2\ \Omega$). The second input of the oscillograph was connected to the voltage divider, which in its turn was connected to electrodes 1, 2. Filming hydrodynamic processes was performed with the help of high-speed video camera MotionXtra HG-LE (7) through a Plexiglass window 5 in the cuvette and a round hole in the electrode 2. The electric circuit of the setup consisted of capacitor of $C = 100$ µF, which was charged from the external source up to the voltage $U_C = 100$–400 V, the inductance coil L, controlled electromagnetic switch K. The self-inductance of the setup was 3 µH.

In all experiments presented, the active resistance of electrolyte cell R_{cell} was in the region $R_{\text{cell}} > 2\sqrt{L/C}$. For such parameters, natural oscillations of the $R_{\text{cell}}LC$ circuit are not excited.

In all experiments, we used additional inductance coils $L =$ 0.8–42 mH. As electrolyte we used NaCl solution of weight concentration 5% in distilled water. A Teflon film 20 µm thick was used as a diaphragm.

The experiments were performed in the following setups:

1. The diaphragm with holes $d_1 = 0.25$ mm and $d_2 = 0.26$ mm was in the cuvette. The distance between the holes was 3 mm.
2. The diaphragm with holes $d_1 = 0.45$ mm and $d_2 = 0.25$ mm was in the cuvette. The distance between the holes was 2.5 mm.
3. Two diaphragms with holes $d_1 = 0.45$ mm and $d_2 = 0.25$ mm (each diaphragm has one hole) were in two separate cuvettes.

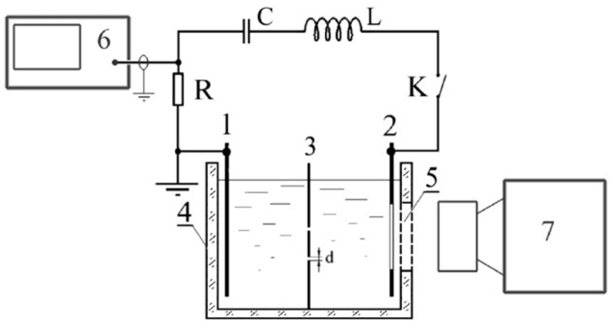

Fig. 1. Principal scheme of the experimental setup for the study of self-oscillations on two current concentrators in the form of holes in a dielectric film.

The cuvettes were connected in parallel. Moreover, a separate registration of current on concentrators was performed.

If current concentrators are made as holes in diaphragms, we can divide the electrolyte cell into two parts: the first part is an electrolyte layer in the diaphragm hole, the second one is an electrolyte layer between the diaphragm and the electrodes. The resistance of the first part far exceeds that of the second one. Therefore, we consider that voltage on the electrodes coincides with that on current concentrators.

3. Results

Fig. 2 shows the high-speed recording of bubble pulsations and oscillograms of total current I, voltage U, released power $P = UI$, and dependence of outer diameter of bubbles on concentrators on time according to results of filming for the self-oscillation process in setup 1 ($d_1 = 0.25$ mm, $d_2 = 0.26$ mm) for $L = 2.3$ mH, $U_C =$ 200 V. The exposure of filming was 10 µs, and the rate was 30 000 frames per second.

The first frame corresponds to the moment of unmatched collapse of bubbles. The second frame shows that in the left hole a new bubble begins appearing while in the right hole the previous bubble has not collapsed yet. The third frame presents that on the left concentrator the bubble has almost overlapped the hole while on the left one the bubble begins forming. It corresponds to current drop and voltage rise on the electrodes. The forth frame shows that both concentrators are overlapped by bubbles of almost the same size. Then, in the fifth frame, they grow synchronously.

Fig. 3 presents a high-speed recording of the bubble growing stage with corresponding oscillograms of current, voltage, released power, and dependence of the outer bubble diameter on time for the experiment in setup 2 ($d_1 = 0.45$ mm, $d_2 = 0.25$ mm), for $L = 30$ mH, $U_C = 200$ V. The parameters of filming are like those in the previous setup. The first frame shows the bubble growth on both concentrators. In the second frame, the left torus-like bubble does not overlap the concentrator completely (white space in the center) while the right one has already overlapped the concentrator. In the third frame, we observe a luminescence of both bubbles. In the smaller bubble, the luminescence is brighter and the region of luminescence is more, which is an indirect evidence of higher brightness temperature of gas in the smaller bubble. It corresponds to the moment when all concentrators are overlapped by bubbles, and the voltage is near to maximum. Then the bubbles D_1 and D_2 grow synchronously, which can be seen in the forth frame, and collapse at the same time.

In the plot of the dependence of the bubble boundary on time, it is shown that during one oscillation of the bubble D_1 on big concentrator, the bubble D_2 on smaller one, in some cases, has time to perform two oscillations (for example, between 1 and 1.3 ms). The first overlapping the concentrator d_2 by a bubble is attested by low overvoltage pulse corresponding to time about 1.1 ms. At the moment of overlapping the concentrator d_1 by a bubble, the overvoltage pulse generated by an inductive circuit causes the appearance of luminescence in both bubbles, which are equalized rapidly by size. Then they collapse synchronously.

Breaks in curves of $D_1(t)$ and $D_2(t)$ are corresponded to bubble disintegrated processes.

For the setup 1 the synchronization has occurred with inductance L no less than ∼ 2 mH, while for setup 2 this threshold value was ∼15–20 mH.

Fig. 4 shows oscillograms of separate registration of currents (I_1, I_2) and voltage U on the electrodes, and released power on the concentrators (P_1, P_2) in setup 3, where I_1 and P_1 are the current and the released power in the hole $d_1 = 0.45$ mm, respectively, and I_2 and P_2 are the current and the released power in the hole $d_2 = 0.25$ mm, respectively.

4. Analysis of results

It follows from the data of experimental results that the connection of the inductance coil qualitatively changes the character of processes occurring on current concentrators connected in parallel. Due to the fact that current channels are overlapped by growing bubbles, the current break occurs firstly on concentrators of smaller size. Here, due to self-induction processes, there is an overvoltage pulse on the electrodes. Thus, at the moment of current break on concentrators, an additional voltage, which may cause gas ionization in bubbles, arises. This voltage leads to acceleration of bubble growth and current break on the other concentrators.

The voltage on current concentrators is described by a formula

$$U = U_C + U_L = U_C \pm L \sum_i \left| \frac{\mathrm{d}I_i}{\mathrm{d}t} \right|, \qquad (1)$$

where U_C is the voltage across the capacitor C, U_L is the voltage across the inductance coil L, I_i is the current flowing through the ith concentrator. At the stage of current increase, we have sign "−", and at the stage of current drop, we have sign "+".

In the experiments described above, each current pulse can be conditionally divided into two main stages:

(1) At the stage of current rise (bubble collapse), the inductance coil L accumulates energy from the capacitor. In this case, on the electrodes (Figs. 1–3), there is a voltage drop proportional to the magnitude L. The velocity of energy release on the current concen-

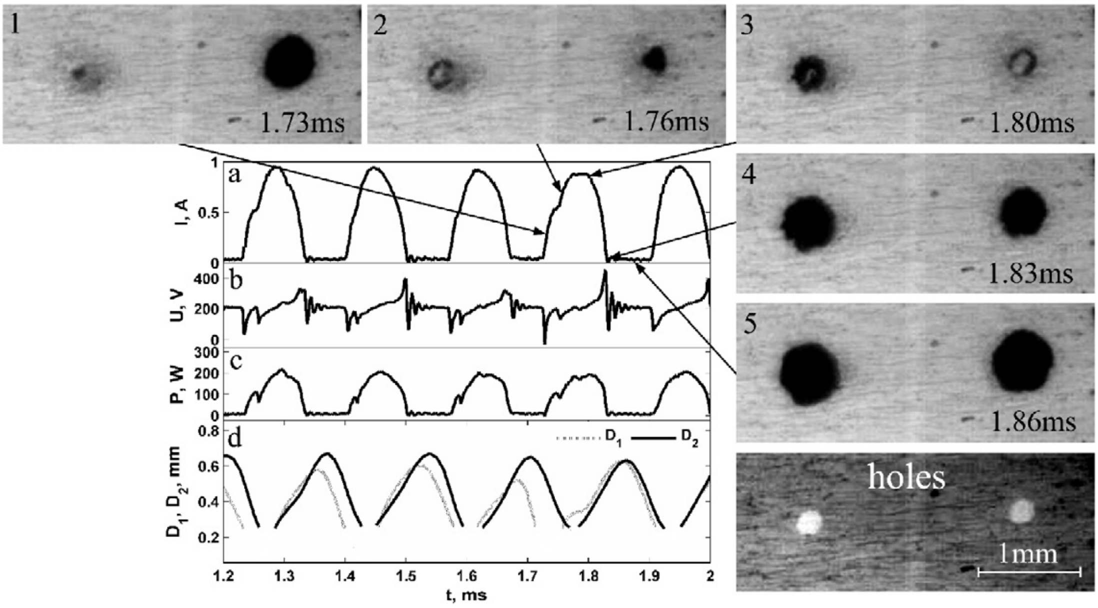

Fig. 2. Frames of high-speed recording and corresponding oscillograms of current (a), electrode voltage (b), released power (c), and plot of bubble edge motion (d) for self-oscillations on concentrators of setup 1 ($d_1 = 0.25$ mm, $d_2 = 0.26$ mm). $L = 2.3$ mH, $U_C = 200$ V.

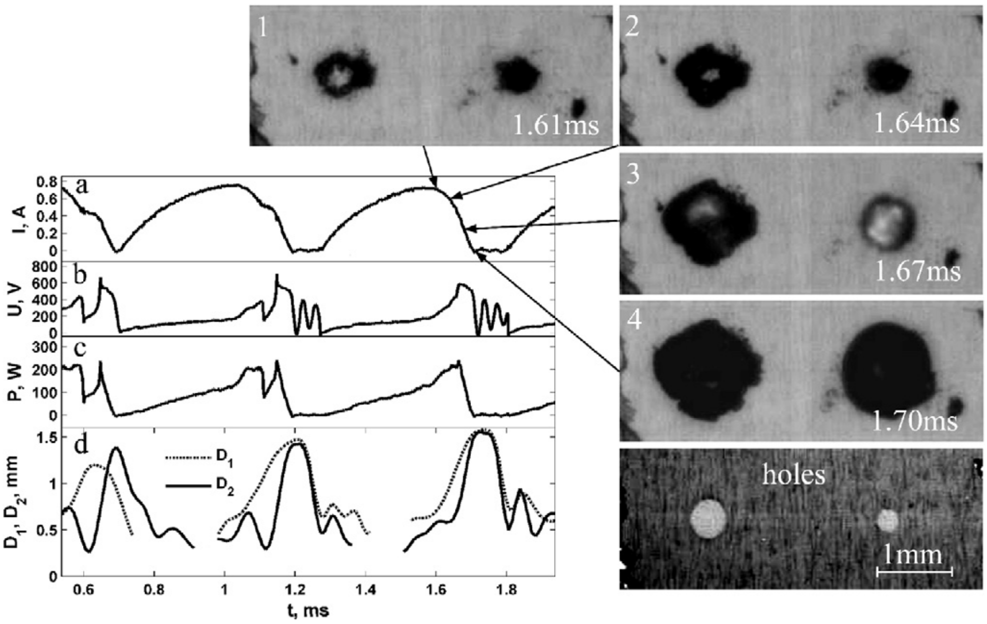

Fig. 3. Frames of high-speed recording and corresponding oscillograms of current (a), electrode voltage (b), released power (c), and plot of bubble edge motion (d) for self-oscillations on concentrators of setup 2 ($d_1 = 0.45$ mm, $d_2 = 0.25$ mm). $L = 30$ mH, $U_C = 200$ V.

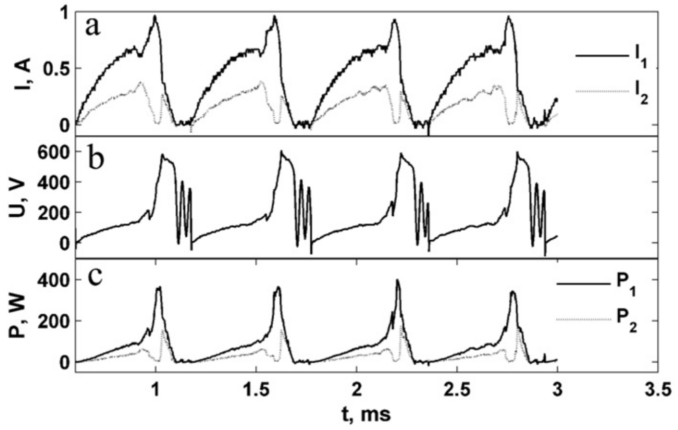

Fig. 4. Current oscillograms on concentrators (a), electrode voltage U (b), and released power (c) for the experiment of setup 3 ($d_1 = 0.45$ mm, $d_2 = 0.25$ mm). $L = 30$ mH, $U_C = 200$ V.

trator depends on the magnitude L, i.e., the presence of inductance causes the prolongation of the current pulse (Figs. 1–3).

(2) At the stage of current drop (bubble growing) occurring due to overlapping the cross-section of the current concentrator by a growing bubble, the generation of additional voltage occurs on electrodes due to the effect of self-induction. For maximal values $|dI/dt|$, the voltage is maximal. In this work, we obtained $U_{max} \leqslant 5U_C$. Here, the energy accumulated in the inductance coil is released in growing bubbles, which facilitates the equalization of bubbles by size.

Separate registration of current on the concentrators allows us to elicit stages of synchronizing interaction of self-oscillations on current concentrators of different size in detail. From the analysis of oscillograms (Fig. 3), it follows that the maximum of the power released P_2 coincides with that of the voltage on the electrodes U. The maximum of the power P_1 corresponds to the moment between the maximum of the current I_1 and that of the voltage U. Here, the maximum of voltage corresponds to initiating the ionization processes of gas in bubbles, which is shown in Fig. 2. Thus, as current on the concentrator d_2 drops (an overlapping the concentrator by a bubble), the energy flow to the non-overlapped concentrator d_1 increases that causes the acceleration of bubble growth on the concentrator. This stage takes place for current concentrators both of different and of the "same" size.

In setups 2, 3, at the moment of overlapping the concentrator d_1 by a bubble, the current I_2 rises sharply that corresponds to resistance decrease on the concentrator d_2. Here, the current curve I_1 has a characteristic bend. From this moment until the voltage drops below a threshold value for the discharge in bubbles, an additional energy has been supplied into the bubbles on the concentrators due to gas ionization inside the bubbles.

According to above oscillograms and high-speed recordings, we can evaluate the electric field intensity in a bubble at the moment of developing ionization processes. If we assume that at this moment the bubble has a spherical form, then the field will have the maximal value at the bubble edge adjacent to the diaphragm, and the field will have the minimal value at the hole centerline. The assumption of the bubble sphericity is justified for the bubble on the smaller concentrator, as there is sufficient time (∼3 µs) from the moment of overlapping the concentrator till the breakdown in the bubble. The minimal value of the electric field at the moment of registering the beginning of luminescence (beginning of ionization) in the bubble is $E \approx U_{max}/D$, where D is the bubble diameter. In setup 2, for the bubble in a smaller hole ($d_2 = 0.25$ mm), we have $E \approx 8$ kV/cm. According to [6], during the discharge between liquid electrodes in water vapor, the field is 0.8–3 kV/cm. In our case, the electric field intensity is higher than that in [6], which is probably to be connected with higher pressure in a growing bubble at the moment of luminescence beginning. Thus, we can conclude that the value E in the bubble is sufficient for the development of ionization processes. It is impossible to evaluate the electric field intensity in the bubble on the concentrator d_1 at the moment of discharge initiation, as the bubble shape has a geometry of torus near to closing the bubble at the hole centerline.

To explain the mechanism of size equalization of bubbles, we performed the evaluations of the power released per unit of volume and unit of bubble surface area. The value of power was calculated according to data from Fig. 4 at the moments of maximal voltage (the moment of overlapping all concentrators by bubbles). The diameter of bubbles at that moment was evaluated according to the high-speed recording (Fig. 3). The results show that the volume power is $P_1/v_1 \approx 250$ W/mm^3 and $P_2/v_2 \approx 750$ W/mm$^3 \approx 3P_1/v_1$. The power per unit of bubble surface area is $P_1/S_1 \approx 60$ W/mm^2 and $P_2/S_2 \approx 120$ W/mm$^2 \approx 2P_1/S_1$, where $v = (1/6)\pi D^3$ is the bubble volume and $S = \pi D^2$ is the bubble surface area.

According to plots of dependence of the outer diameter of bubbles on time for setup 2 (Fig. 2), we can evaluate a volume velocity of the bubble growth after the overlapping the concentrators. It turns out that $dv_2/dt \approx 2dv_1/dt$. Thus, we can assume that ionization and energy release occurs mainly at the bubble boundary and the mechanism of bubble growth after overlapping the current concentrator may consist not only in heating gas inside the bubble due to ionization, but in "explosive boiling" of a thin layer near the bubble surface [7,8].

Consequently, a phase equalization of self-oscillations occurs at the stage of overlapping current concentrators by bubbles, i.e., at the stage of bubble growth. At this stage, an additional energy release occurs on current concentrators having both great and small spread in sizes. When having a small spread in hole diameters, an additional energy, before the concentrators are overlapped by bubbles, is sufficient to provide synchronization.

When having a great spread in hole diameters to provide synchronization, an additional energy is necessary to be released after overlapping all concentrators by bubbles due to gas ionization processes occurring in bubbles. A determining factor is a bubble pulsation on the bigger concentrator, while bubble oscillations on the smaller concentrator "slave" to those of the bigger one. We may assume that at moments of "breakdown" the degree of gas ionization in a smaller bubble is higher than that in a bigger one. Hence, the gas temperature at the boundary of smaller bubble is higher than that at the boundary of bigger one. This can provide an accelerated growth of a smaller bubble.

The results of filming the dynamics of bubble formation on single current concentrators jointly with registration of electrical parameters showed that the beginning of forming a torus-like bubble corresponds to the moment of maximal current value. Moreover, we noted the effect of multiple synchronization (of order 2:1) for self-oscillations on concentrators of different size ($d_1/d_2 = 1.8$) in setup 2. The analysis of filming showed that in some cases, during one period of bubble oscillation in the bigger hole, the bubble in the smaller hole had time to perform two oscillations. In addition, while overlapping the bigger concentrator, the bubble sizes were equalized and collapsed synchronously independently of the initial phase of the bubble on the smaller concentrator.

Thus, the experimental results clearly show that when introducing a feedback into the system in the form of an additional inductance coil, the character of processes, occurring on current concentrators connected in parallel, qualitatively changes.

When bubbles collapse (the stage of bubble growth), the inductance coil L accumulates energy, and when bubbles grow (the stage of current drop), the inductance L releases energy. "Slaving" phases of self-oscillations occurs during the bubble growth on current concentrators that corresponds to current drop, and the connection between the concentrators is provided due self-induction processes. The size of smaller bubbles is equalized to that of bigger ones.

The inductance allows us to redistribute the electrical energy and release it selectively during the bubble growth equalizing them by size. We showed the difference in mechanisms of synchronization for current concentrators with small and great size spread. When having a small size spread, the release of additional energy occurs before the current is broken, and when having a great size spread, the release of additional energy occurs before and after the current is broken. The difference in dynamics of gas ionization processes in bubbles provides an accelerated growth of smaller bubbles due to voltage across the inductance coil.

The given effect is possible to apply for disinfection of water-biological mediums [9], monitoring of water and land resources [10], shock-waves generation and physicochemical reactions initiation in liquid.

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