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Dynamic model of the underwater discharge

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A dynamic model of an underwater electric discharge is presented. The method is based on a mathematical description of the dependence of the solution conductivity on its thickness during the formation of a vapor-gas bubble. The time dependences of the current and the voltage drop across the cell were calculated using expressions relating the current and voltage to the resistance (conductivity) of the solution and taking into account the periodicity of the processes. The presented model makes it possible to accurately describe the dynamic characteristics of underwater discharges based on the physicochemical properties of the solution, which makes it possible to predict the behavior of the discharge when using solutions with specified properties.

Keywords: underwater electrical discharge, dynamic model, conductivity.

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Various combinations of electrical discharge and liquid are of interest for the tasks of purifying and sterilizing aqueous media, modifying polymers, synthesizing nanostructures, which is reflected in reviews of recent years [1–3]. Introducing a plasma zone into the volume of liquid leads to acceleration of processes in the solution. This seems favorable for applied studies of this type of plasma. Theoretical studies of electrophysical characteristics of underwater plasma allowed to offer a mechanism of formation/development of underwater discharges [4–6]. A number of papers present underwater plasma models based on electrical characteristics of the discharge, which give detailed information about the formation of a vapor-gas bubble in which plasma forms [7,8]. The properties of the liquid are disregarded. In the present study, the underwater discharge model is considered, taking into account the physical and chemical properties of the solution/liquid.

It is assumed that during the time of gas bubble formation, which is determined by the chemical composition, concentration of the dissolved substance, electrical conductivity and the actual value of the applied voltage, processes develop in the solution and not in the plasma. When the plasma bubble collapses, convective flows arise in the solution caused by the acoustic and shock waves and the temperature gradient, which transport the plasmolysis products (atoms, radicals, and ions) into the main volume of the solution. This affects physicochemical properties of the solution and the properties of the entire system. The wiring diagram of the proposed model is shown in Fig. 1, *a*. The electrical circuit powered by an AC source, includes serially the ballast resistance and the discharge system resistance, the latter connecting the solution volume resistance and the plasma and solution film resistances in parallel. The discharge system included in the electrical circuit contains a cell with a solution divided into two parts by a septum/membrane with a hole (diaphragm). The

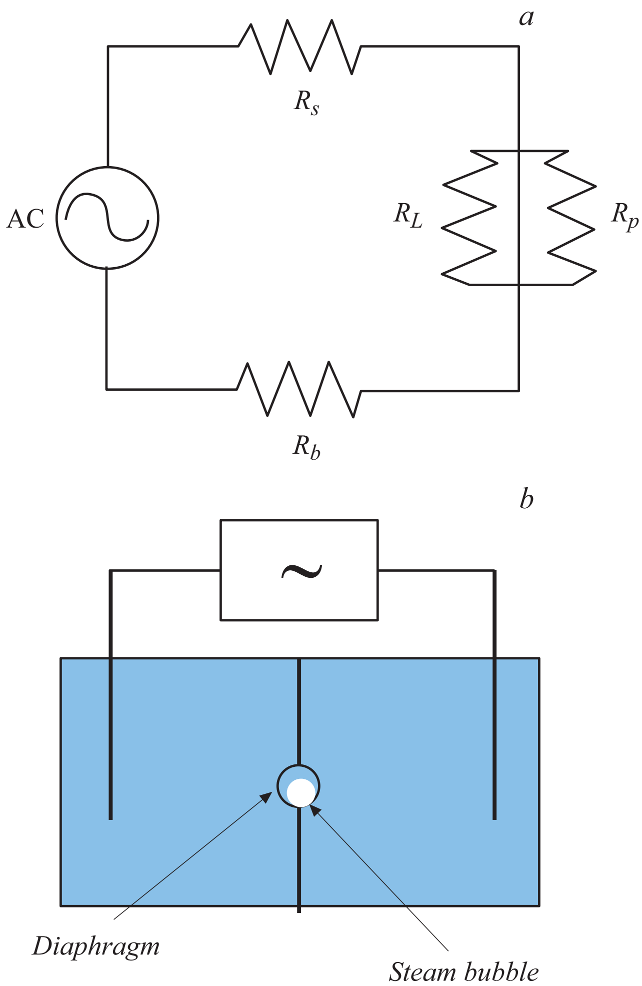

Figure 1. Wiring diagram of the model (*a*) and underwater discharge device diagram (*b*). R_b is the ballast resistance, R_s is the solution resistance, R_L is the layer resistance, R_p is the plasma resistance.

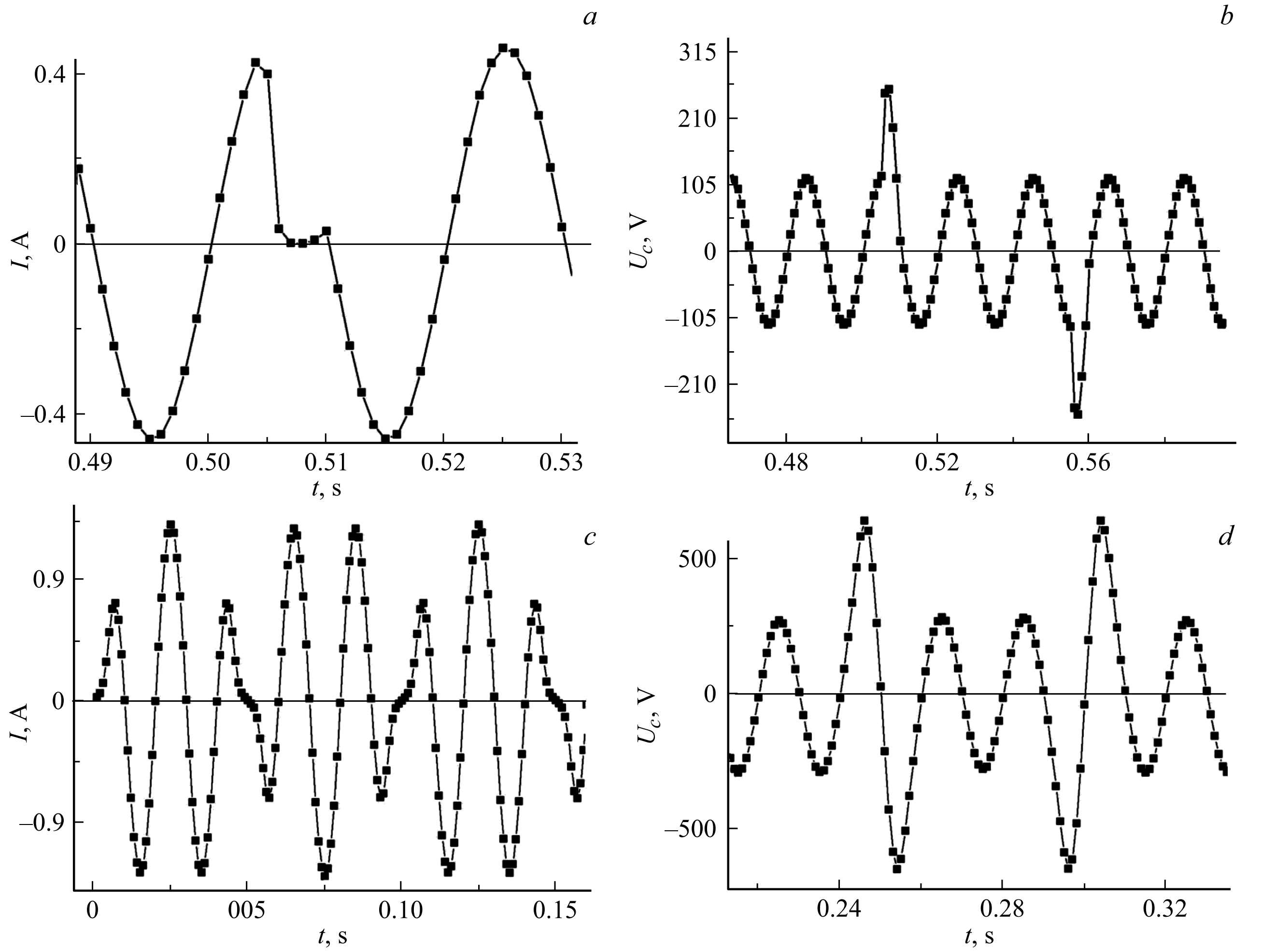

Figure 2. Temporal changes in discharge current $((a, c)$ and cell voltage drop (b, d) obtained using the sigmoidal (a, b) and hyperbolic (c, d) functions.

electrolysis current flows through the diaphragm and a gas bubble is formed in the diaphragm (Fig. 1, b).

Voltage is applied to the load, which consists of the ballast resistance and the complex resistance of the cell (series connection of the solution resistance and the discharge gap). The ballast resistance is a constant, as is the actual value of the applied voltage. However, the value of the complex resistance of the cell will change. This is evidenced by the experimental data for the ratio I/U [5]. The current in this circuit will be determined by the ratio

$$I = \frac{\varepsilon_{total}}{R_b + R_c}. \quad (1)$$

Here ε_{total} is the applied voltage, R_b is the ballast resistance, R_c is the cell resistance.

The voltage applied to the discharge gap will be determined by the difference between the applied voltage and the voltage drop across the ballast resistor

$$U_c = \varepsilon_{total} - IR_b. \quad (2)$$

Suppose that the thickness of the conducting layer δ in the diaphragm can vary within certain limits $0 < \delta < d$, where d is diaphragm diameter. Thus, at the moment when there is no bubble, the orifice (diaphragm) is filled with electrolyte solution, the conductivity is maximum and is determined by the conductivity of the solution. In the case when the bubble size reaches a maximum, the thickness of the conductive layer will be zero in the limit. Based on this, we can specify the dependence of conductivity on the thickness of the conductive layer $\lambda = f(\delta)$. For mathematical description of the model, nonlinear approximations of the Origin application SW were chosen. The iteration method was used to select functions that give a saturation curve for the dependence $\lambda(\delta)$ and dependence $I(t)$ and $U(t)$, consistent with experimental oscillograms. Only two functions meet such conditions: the sigmoidal

$$\lambda = \frac{1}{1 + e^{-\delta}} \quad (3)$$

and hyperbolic

$$\lambda = \frac{e^{\delta} - e^{-\delta}}{e^{\delta} + e^{-\delta}}. \quad (4)$$

The times of gas bubble formation and extinction on the order of 0.1−0.2 s were obtained on the basis of video observation data. If we assume that the processes will run continuously, they can be described by a periodic dependence with a characteristic frequency of 5−10 Hz and time dependences derived.

Expressing R through $\lambda = f(\delta)$ and substituting it in the equations for current and voltage, we calculated the functions $I = f(t)$ and $U = f(t)$ using the Origin application SW. Simulation results are presented graphically (Fig. 2).

Analysis of the obtained results shows that the sigmoidal dependence $\lambda = f(\delta)$ yields the dynamic characteristics of current and voltage vs. time, fully consistent with the experiment [9]. The hyperbolic function follows the changes in thickness of the conductive layer more smoothly. Because of this, transitions between the states of the system (discharge combustion modes) proceed more smoothly and for longer periods of time.

Thus, the model enables a clear description of dynamic properties of underwater discharge. Assumptions of this model use no empirical data for $I = f(t)$ and $U = f(t)$, but are based on experimental estimates of the formation and extinction times of the gas bubble. Consequently, the obtained model is semi-empirical and confirms the hypothesis that the dynamic features of underwater discharges are determined by the physical and chemical properties of the solution.

Conflict of interest

The author declares that she has no conflict of interest.

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