Electrophysical parameters of AC plasma system

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Abstract. Experimental results related to main characteristics of an underwater discharge with a frequency of 50 Hz and various types of electrodes were reported. The data on 1) discharge geometry; 2) current-voltage characteristics; 3) gas temperature and reduced electric field strength; 4) plasma emission spectra were obtained. Based on these data, the plasma modeling provided the information on densities of plasma active species.

1. Introduction
Investigations of interaction processes between non-equilibrium plasmas and a liquid phase are becoming important for a large number of science and technology applications. Several decades ago, research attention in this field was mainly attracted to both electrolysis and breakdown phenomena in dielectric liquids [1, 2, 3]. Recently, the field of plasma-liquid interaction studies has been expanded significantly and already covers analytical chemistry, water purification and disinfection, material processing, chemical synthesis and some others [4, 5, 6].

Similarly to gas-phase plasmas, there are some classifications of plasma-liquid systems according to the generation method or equipment configuration. At the same time, an important issue is also the type of interaction with a liquid which strongly affects the properties of plasma itself. Generally, all the variety of interactions between the gas discharge and a liquid phase can be divided into three main groups. These are gas-phase plasmas which are in the contact with a liquid, multiphase plasma discharges and plasmas directly excited in the liquid phase. Systems from the third group allow one to use various liquids, both conductive and non-conductive (for example, liquid nitrogen, ethanol or deionized water) as electrolytes. In this case, both the electrode material and ions from the solution may be the sources of solid particles generated in a liquid phase. In particular, when the electrode provides the material for nanoparticles, the corresponding process is called as the "plasma sputtering in solution" [7]. It is known also that plasma discharges in a liquid can be excited using pulsed power sources, direct current (DC) sources as well as alternate current (AC) sources [8].

Though some investigations of plasmas excited in the liquid phase have been made, there many unclear points that need additional research efforts. In particular, at the moment it is not clear how breakdowns are formed in a liquid medium. Obviously, details of the breakdown mechanism depend on both characteristics of the excitation wave and properties of the liquid. At the same time, the excitation by direct or alternate currents may lead to the Joule heating and thus, to the formation of a vapor phase through which a breakdown can occur. As such, it is believed that liquid phase discharges generated by microsecond pulses are initiated due to either gas bubbles which originally present in the liquid or bubbles formed after applying the voltage. At the same time, the ignition of a discharge seems to be possible without bubbles [9], since nanosecond high-voltage pulses are too short to form bubbles.
The purpose of this work was to determine principal characteristics of an underwater discharge with using the 50 Hz power supply as well as various types of electrodes.

2. Experimental

Experimental setup is shown in Figure 1. The discharge was excited between two metallic electrodes in ceramic cases immersed in the liquid phase in a form of the distilled water. Each electrode has a thickness of 1 mm while tested electrode materials were molybdenum, copper and steel (St3sp). The angle between electrodes was 45° with a possibility of adjustment. The discharge current (i) was 50-450 mA, and the interelectrode distance (L) was 0.1-5 mm.

The discharge power supply system included a step-up transformer (maximum output voltage of 10 kV) and an adjustable laboratory autotransformer. The GWinstek GDS-71022 oscilloscope was used to determine the voltage-current characteristics of the discharge. The geometric dimensions of the discharge (bubbles) were determined using photographs made by a digital high-speed camera. Plasma emission spectra were recorded using an AvaSpec-2048L-2-USB2 spectrophotometer. The spectrophotometer is equipped with diffraction gratings of 600 strokes/mm and an operating wavelength range of 200-900 nm. The radiation was collected on a collimating lens of a fiber light guide, through which it fell into the entrance slit (25 microns wide and 100 microns high).

Optical plasma diagnostics methods are commonly used to determine rotational and vibrational temperatures of excited electronic states as well as densities of both excited and ground-state particles [10, 11]. In this work, in order to obtain rotational and vibrational temperatures of OH⁺ radicals, we used the Cyber Wit Diatomic program. For the OH(A2Σ, V′ → X2Π, V´´) bands the values of the rotational and temperature of OH(A2Σ) molecules were adjusted to achieve the minimum deviation of the calculated band profiles from the experimentally measured ones. The arc discharge temperature was determined by analyzing the slope of the continuum on the recorded spectra. As it follows from Planck's formula, the angle tangent of inclination of the radiation spectrum constructed in certain coordinates characterizes the temperature of the emitting object.

The spectrum of thermal radiation of a real object with an arbitrary emissivity ε(λ,T) ≤ 1 is described by the formula: I(λ,T) = ε·C1·λ⁻⁵[exp(C2/λT)]⁻¹, where C1 and C2 are the first and second pyrometric constants (C1 = 2πhc² = 37418 W·µm⁴·cm⁻²; C2 = h·c/k = 14388 µm·K), h is Planck’s constant, k is Boltzmann's constant, c – the speed of light in a vacuum, λ is the wavelength. For the Wine region, the formula takes the form ln(εC1) - C2/(λT) = ln(λ³I). For a gray body (ε = const), this expression is the equation of a straight line in coordinates x=λ¹I and y=ln(λ³I) (T<3000K) or x=ln(1+C1/λ¹I) (T>4500K), while the slope of the straight line is determined by temperature [12].

![Figure 1](image)

**Figure 1.** Experimental setup diagram (not to scale): 1 - adjustable laboratory autotransformer, 2 - step-up transformer, 3 - ceramic casings and electrodes, 4 - spectrophotometer lens, 5 - quartz cuvette with a volume of 50 ml, 6 - plasma formation zone, R - ballast resistance.

3. Results and Discussion

The approximate power density of heat sources was determined by analyzing the heating area (dT/dt)Heating and cooling area (dT/dt)Cooling of the liquid phase temperature from time to time (Figure 2).
The calculation of the power density of thermal effluents and sources was carried out according to the formula \( cm(dT/dt) = \Sigma Pi - \Sigma Pj \). In this case, \( \Sigma Pi \) represents the total power of all heat sources heating the system, and \( \Sigma Pj \) the power of thermal effluents in the system. The power put into the system by a discharge at a current strength of 100 mA and an interelectrode distance of 5 mm \( \Sigma Pi \approx 141 \text{ W} \), and \( \Sigma Pj \approx 18 \text{ W} \).

![Figure 2](image1.png)

**Figure 2.** Change in the temperature of the liquid phase at the discharge between two electrodes made of copper (1), steel (2) and molybdenum (3); current 100 mA; interelectrode distance 5 mm.

Bands of hydroxyl radicals and hydrogen molecules, emission lines of iron, copper, molybdenum, hydrogen and oxygen atoms were detected in the discharge emission spectra (Figure 3). The arc temperature did not depend on the types of electrodes and the interelectrode distance, amounting to 5800 ± 500 K. The effective rotational (Tr) and vibrational (Tv) temperatures of OH(\( \Sigma^2 \Sigma \)) are weakly dependent on external conditions \( \text{Tr} \approx 3300\pm100 \text{ K} \), and \( \text{Tv} \approx 7800\pm200 \text{ K} \).

![Figure 3](image2.png)

**Figure 3.** The emission spectrum of discharge in the form of a spark (1) and arc (2).

Based on the registered volt-ampere characteristics of the discharge (Figure 4), the duration of a single discharge was determined, which was 1.22 milliseconds. This value does not depend on the electrode material and the interelectrode distance. The voltage and current of the micro-discharge are determined mainly by the interelectrode distance. The frequency of initiation of single discharges in the vast majority of cases coincides with the frequency of the current. Under the same conditions, individual micro-discharges are almost completely identical, but are accompanied by stochastic current fluctuations. In the interval of several seconds, we can talk about the existence of a stable path along which the bulk of the discharges pass. The initially formed discharge passage area shifts to the surface of the liquid phase, which leads to the elongation of the discharge channel and subsequently its rupture.
In the overwhelming majority of cases (≈ 70%), it can be said that the length of the discharge channel is ~ 10-20% longer than the interelectrode distance for all types of electrodes. Table 1 shows plasma electro physical parameters.

Table 1. Plasma electro physical parameters.

| Electrodes | U, V | i, A | E, V/cm | N, cm⁻³ | E/N, V·cm⁻² | D, cm | J, A/cm² | W, W/cm³ |
|------------|------|------|---------|---------|-------------|-------|----------|----------|
| Mo–Mo      | 228  | 0.276| 114     | 2.1·10¹⁸ | 0.5·10⁻¹⁶  | 0.010 | 3.3      | 374      |
| Cu–Cu      | 246  | 0.257| 366     | 2.2·10¹⁸ | 1.7·10⁻¹⁶  | 0.015 | 1.4      | 511      |
| Fe–Fe      | 311  | 0.633| 239     | 2.5·10¹⁸ | 1.1·10⁻¹⁶  | 0.014 | 4.4      | 1042     |

* Interelectrode distance 3 mm

4. Conclusion

The results of the study of the parameters of an electric discharge in the liquid phase when using an alternating power source with a frequency of 50 Hz are presented. The digital photos, radiation spectra and volt-ampere characteristics of the discharge were recorded, the thermal sources of heating of the liquid phase and the geometric parameters of the discharge were evaluated.

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