Steam-gaseous discharges with jet fluid electrodes at the decreased pressure

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Abstract. In this work the experimental research of low temperature plasma of frequency capacitive discharge and constant currents discharge with jet fluid electrodes in pressure range of $p = 10^5 - 10^2 \text{Pa}$ are presented. The area where the field gradient exceeds the threshold value necessary for temporary use of the steam-gaseous discharges is presented. The plasma radiation spectrum is presented. Estimates on composition of plasma, an electron concentration and temperature of a heavy component are presented.

1. Introduction

The steam-gaseous discharge is a kind of the discharge which generated by direct or alternating current in an interelectrode spacing where one or both electrodes are liquid. As a liquid electrode, as a rule, a salt solution is used in technical distilled or tap water. Type and form of steam-gas discharges depends from active voltage, pressure, a configuration and type of electrodes, speed and character of flowing medium. For this type of discharge is characterized by nonstationarity. For a given type of discharge, the dependence of the parameters of the fluid on the formation of the discharge plasma in the expanding vapor-gas shell is characteristic. From an analysis of previously published works it follows that this branch of science has been studied for a long time. A number of scientific papers have been devoted to this direction of science [1-4], however, the number of "white spots" in this field is still high. For example, high-frequency (HF) vapor-gas discharges of a capacitive type with liquid electrodes are still practically unexplored, whereas the scientific foundations of the high-frequency discharge with solid electrodes are described in detail in well-known works by Yu.P.Ryiser, M.N. Shneydera, N. A.Yatsenko, and others [5].

2. Experiment

The experimental studies of RF and DC vapor-gas discharges with jet liquid electrodes between the jet and liquid electrodes as the pressure decreases were carried out using an experimental plant (Figure 1A) with gas discharge chamber (Figure 1B). On the block diagram (Figure 1): 1 - source of power, 2 - vacuum chamber, 3 - vacuum gauge, 4 - air injection valve; 5 - working area with gas discharge chamber, 6 - rotary vane pump of "2NVR-5DM" brand, 6 - jet of liquid, 8 - metal plate for potential supply to the electrolyte; 9 - tube of flow of a liquid jet. The DC generator
ensuring an adjustable DC voltage of up to 4000 V at a nominal current of up to 10 A or RF generator of "RFG8-60/13" brand tuned to frequency $f = 13.56 \text{ MHz}$ were used as power sources. Researches were carried out in the range of the set parameters: pressure $p = 10^5 - 10^3 \text{ Pa}$, jet length $l_c = 10 - 25 \text{ mm}$, jet diameter $d_c = 3 - 5 \text{ mm}$, jet velocity $v_c = 0.05 - 0.6 \text{ m/s}$, and voltage $U = 0.1 - 5 \text{ kV}$.

Figure 1. Functional diagram of the experimental setup (a) and gas discharge chamber (b).

To solve the set tasks, a modern complex of diagnostic equipment and techniques has been applied:
1. Emission spectrum of the vapor-gas discharge plasma was determined by PLASUS EC 150201 MC Fiber-Optic Spectrometer with a Collimator for fixing light beams within the wavelength range of 195 – 1105nm. The slit function was assessed by SIRSH 6 – 100 calibration lamp. The minimum width of single, optically thin and the narrowest lines is $\Delta \lambda_g = 1 \text{ nm}$, which is taken as a slit width. The studied emission was collected from the discharge, the plasma composition and components were evaluated without reference to a specific area. Spectrum identification was performed through line identification by comparing the test spectrum with the database of The National Institute of Standards and Technologies (NIST).
2. The amplitude distribution of the electric field strength of the RF vapor-gas discharge between two parallel jets was calculated using pdetool tool in the MATLAB environment.
3. An estimation of the vibrational and rotational temperature of molecules in the plasma of high-frequency discharges of high-frequency and direct currents with liquid electrodes was carried out by comparing the experimentally recorded molecular spectrum with the calculated model in the "LIFBASE" program and in the program "Specair 2.2.0.0."

The authors calculated distribution of the amplitude of the electric field strength of the RF vapor-gas discharge between the two parallel jets and identified the area where the field strength amplitude exceeds the threshold value necessary for maintaining the discharge. At frequencies of RF voltage $f \leq 13.56 \text{ MHz}$, an E-type discharge occurs, where ionization of gas occurs as a result of collisions of electrons (accelerated by an alternating electric field) with gas particles. The determining parameter for maintaining the discharge in this case is the electric field strength vector amplitude. The discharge occurs when the field strength amplitude exceeds the threshold value which depends on pressure and frequency of the RF voltage. The magnetic field and the bias current is irrelevant in this mode. The radio-frequency discharge at low pressures is close by its properties to the positive glow discharge in a constant field.

Let's consider the RF current vapor-gas discharge between the two parallel jets of liquid. The jets radiuses are set to 4 mm, the distance between the jets is 2 cm and amplitude of the RF voltage is $U_m = 750 \text{ V}$. The potential amplitude on surface of the jets is equal to the amplitude of the applied RF voltage $U_m$. Field distributions $E$ and electric field potential $\varphi$ can be found by solving the electostatics equations:
\[
\text{div} \mathbf{E} = \frac{1}{\varepsilon_0} e(n_+ - n_e), \quad \mathbf{E} = -\text{grad} \varphi
\]

3. Results
The distribution of the amplitude of the electric-field-strength \(E_m\) near the jets was established (Figure 2a) and region with \(E_m > E_{\text{thr}} = 6.5 \cdot 10^4 \text{ V/m}\) where the discharge occurs was identified during the investigation (Figure 2b). Knowing the visually determined boundaries of the discharge region and the amplitude of the applied voltage, it is possible to estimate the threshold amplitude of the electric-field-strength \(E_{\text{threshold}}\), at which the RF vapor-gas discharge with jet liquid electrodes generates.

![Figure 2](image1.png)

**Figure 2.** Distribution of the field strength amplitude at equal values of the electric field strength modulus \(E_m\) near the jets (a) with a voltage amplitude exceeding the threshold value \(E_{\text{threshold}}\).

The spectrum analysis of the vapor-gas discharges plasma (Figure 3) shows that in the experimental region of plasma there are different elements, hydrogen atoms HI, sodium Na I, potassium K I, zinc ZnI, nitrogen molecules N2 (2+) and hydroxyl OH (A-X).

![Figure 3](image2.png)

**Figure 3.** The investigated spectrum with identified spectral lines: 1 - DC vapor-gas discharge between jet anode and liquid cathode; 2 - DC vapor-gas discharge between jet cathode and liquid anode; 3 - RF vapor-gas discharge between jet and liquid electrodes at atmospheric pressure; 4 - RF vapor-gas discharge between jet and liquid electrodes at atmospheric pressure.
The elemental composition for spectra 1, 2, and 3 is identical. Spectrum 4 lacks a band of the OH molecule (A-X). This is due to the fact that UV radiation with a wavelength of less than 330 nm was absorbed through the viewing window of the vacuum chamber. The estimation of the electron concentration in plasma of RF and DC gas-vapor discharge for spectra 1, 2, and 3 was carried out by analysis of the profiles of Hydrogen lines H\(_a\), H\(_b\), H\(_c\) in the Balmer series. The authors determined the width of the Voigt profile of the hydrogen line H\(_a\) which at its half-height corresponds to \(\Delta \lambda_f = 1.33\) nm (spectrum 1), \(\Delta \lambda_f = 1.5\) nm (spectrum 2), \(\Delta \lambda_f = 1.23\) nm (spectrum 3). The estimation of the electron concentration in plasma of RF gas-vapor discharge at reduced pressure for spectrum 4 was made according to the H\(_b\) line, since this is the widest observed line of the Balmer series (Table 1). Given the slit broadening under the assumption of the Voigt profile of the registered line, the Lorentz profile of the line \[\text{Fig. 22}\] is equal to \(\Delta \lambda_L = 0.56\) nm (spectrum 1) and \(\Delta \lambda_L = 0.81\) nm (spectrum 2), \(\Delta \lambda_L = 0.4\) nm (spectrum 3), \(\Delta \lambda_L = 1.78\) nm (spectrum 4). According to the reference \[\text{Fig. 23}\], the value \(\Delta \lambda_L\) conditioned upon linear Stark effect corresponds to electron concentration \(n_e = 5.5 \times 10^{16}\) cm\(^{-3}\) (spectrum 1), \(n_e = 8.49 \times 10^{16}\) cm\(^{-3}\) (spectrum 2), \(n_e = 3.47 \times 10^{16}\) cm\(^{-3}\) (spectrum 3) \(n_e = 2.02 \times 10^{16}\) cm\(^{-3}\) (spectrum 4). The methods used for estimating the electron temperature assume that plasma is in the Local Thermodynamic Equilibrium (LTE) \[\text{Fig. 22-24}\]. It is difficult to determine the electron temperature from the above spectra (Fig. 3) due to insufficient data on atomic or ionic lines, therefore it is necessary to undertake further study. The estimation of the vibrational and rotational temperature of molecules in plasma of RF and DC vapor-gas discharges with liquid electrodes was carried out by comparing the experimentally recorded molecular spectrum with the model calculated in LIFBASE program and in Specair 2.2.0.0. program. (Fig.3). The vibrational and rotational temperatures for spectra 1, 2, and 3 were determined for the molecular band OH (A-X), as for spectrum 4 the temperature values were determined for the molecular band N2 (2+) as this series of lines was the clearest one (Fig. 3). The best matching for the molecular band OH (A-X) in spectra 1, 2, and 3 was obtained at temperature ranges of \(T_v = 3500 - 3600\) K and \(T_r = 4700 - 4900\) K. For the molecular band N2 (2+) in spectrum 4, the temperature values are equal to \(T_v = 2000\) K and \(T_r = 2700\) K.

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