HIGH-FREQUENCY DISCHARGES FROM PLASMA UNDER PRESSURE

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A whole series of scientific and technical investigations requires a study of electrodeless high-frequency discharges in nitrogen and in dry* and humid air, including measurement of intense microwave radiation characteristics [1], modeling of long-lived plasma formations [2], creation in a real atmosphere which is opaque to radio waves [3], research in plasma chemistry [4, 5], etc. This study investigates spatial changes in a plasma high-frequency discharge as a function of pressure and atmospheric humidity, determines the state for which the plasma occupies the smallest volume, and calculates several parameters of the discharge.

Experiments were conducted at frequencies of 5 and 37 MHz and 10 GHz in quartz pipes with internal diameters of 0.010, 0.013, 0.019, 0.080, and 0.090 m. Discharges were created in dry air and in nitrogen for pressures from 60-3000 Pa using a magnetron generator with maximum power output of $\sim$200 W at a frequency of 2.4 GHz. The system was operated in the pulse mode (τ = 1.50-1.75 μsec, F = 300 Hz). The discharge pipe ($d = 1.3\cdot10^{-2}$ m, l = 1.5-2.0 m) was positioned at the maximum of the standing wave H_{10} of a rectangular waveguide. Monitoring of the plasma outside the waveguide was done using resonator methods [6] at frequencies of 2.6-2.8 GHz. A K24 klystron generator was utilized. The measurement resonator, operating with E_{010} oscillations, was $1.5\cdot10^{-2}$ m in height and had an aperture diameter of $1.6\cdot10^{-2}$ m. The resonator was moved along the discharge pipe for measuring the spatial distribution of the electron density. A change in frequency $\Delta\omega$ was detected by a resonance wavemeter with an oscilloscope. Measurement of the electron density was done using a simple interferometer (λ = 8 mm) which functioned at a wavelength determined from the condition $\nu \ll \omega$, where ν is the electron collision frequency and ω is the frequency of the sounding signal. The measurement arm of the interferometer was connected across the narrow walls of the rectangular waveguide so that the plasma formed between horn antennas with dielectric lenses.

Curves for the electron density distribution along the discharge pipe are given in Fig. 1. The measurements begin at the center of the narrow wall of the waveguide. For all practical purposes, the boundaries of the high-frequency plasma discharge and the emission coincide. It is evident in Fig. 1 that the form and dimension of the emission of long pipes strongly depends on the gas pressure. For p $\simeq$ 319 Pa, the pipe contains only those electrons obtained from ionization of the gas (nitrogen) in the high-frequency waveguide field. As one moves away from the wide wall of the waveguide to a distance of $(2\text{-}3)\cdot10^{-2}$ m, the density of these electrons goes almost to zero. When the pressure is increased, the primary electrons cause additional ionization of the neutral gas in the pipe at a distance of $l \simeq 0.35$ m from the center of the waveguide and lead to the formation of a secondary electron zone which can easily be observed by the gas emission in the pipe. The region occupied by the primary electrons is virtually independent of the gas pressure in the pipe.

The maximum density of secondary electrons is $3\cdot10^{8}$ and $5\cdot10^{8}$ cm^{-3}, respectively, for pressures of 704 and 2077 Pa. When the pressure is further increased to $\sim$3000 Pa, the emission is uniform along the entire length of the pipe, and both regions overlap. The electron collision frequency ν is determined from the relation [7]

$$\nu = \frac{\Delta\left(\frac{1}{Q}\right)\omega_0^2}{2\Delta\omega_0},$$

where $\Delta(1/Q) = 1/Q - 1/Q_0$, and Q and Q_0 are the Q-factors for the measurement resonator with the plasma and without the plasma, respectively. For p = 2077 Pa, near the point of maximum secondary electron density (l = 0.35 m) $\nu \simeq (1.12\text{-}1.35)\cdot10^{10}$ sec^{-1}.

*Dry air is *assumed* to be air with a molecular concentration less than 0.1%.

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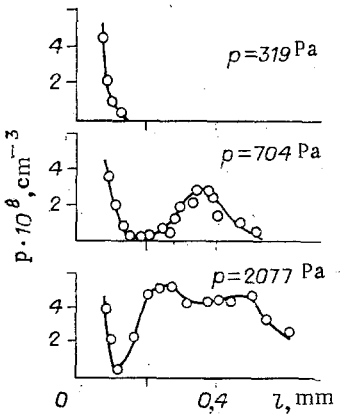

Fig. 1

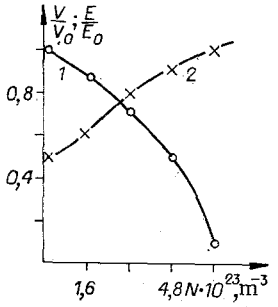

Fig. 2

Direct calculation of n_e for a phase shift φ is done using the equation [7]

$$\varphi = \frac{\omega}{2c} \frac{dn_e}{n_c},$$

where c is the velocity of light, d is the diameter of the plasma column, n_e is the average density of electrons, and n_c is the critical electron density.

Measurements show that in the pressure interval considered above the density of primary electrons is $n_e \sim 8 \cdot 10^{12}$–$2 \cdot 10^{13}$ cm^{-3}.

For determining a change in the form of the high-frequency discharge as a function of the atmospheric humidity, pipes were used with internal diameters of $d \simeq 1.9 \cdot 10^{-2}$ m and lengths of $l = 0.35$ m. The pipes were maintained at a constant pressure p equal to 1, 2, 3, or 4 kPa. As in [8], a pulse generator (f = 37 MHz, (f = 37 MHz, τ = 30 msec) with a maximum power output per pulse of P = 40 kW was used as a source of high-frequency radiation. The pipes were activated by capacitance or inductance discharges. Better correlation between the high-frequency generator and the pulse load was obtained with the capacitance discharge. The width of the electrode rings in this case was $2 \cdot 10^{-2}$ m at a distance of $(1.0$–$1.5) \cdot 10^{-2}$ m. A change in the electron density over time $n_e = f(t)$ at the end of a high-frequency pulse was measured using interference techniques [7]. For our experiment, the plasma was quasineutral [8].

When the H_2O molecule exists in the discharge volume, the plasma volume and the breakdown voltage of the electric field change substantially. Changes in the emission volume and the breakdown voltage as functions of atmospheric humidity (curves 1 and 2, respectively) are illustrated in Fig. 2 in relative units. The presence of H_2O in the discharge noticeably decreases the volume occupied by the plasma (by 12-15 times). If the concentration of water is higher, the output voltage of the high-frequency generator is insufficient for ensuring breakdown. The obtained values for the breakdown voltage agree with those in [9], where the breakdown voltage E for water vapor is higher than for dry air when $p \geqslant 533$ Pa.

The plasma volume decreases and the electrical strength of the mixture (air + H_2O) increases because the plasma electrons are cooled by the water molecules [5] through the reaction

$$H_2O + e^- \rightarrow H_2O^* + e^-.$$

More detailed physical processes occur in nonequilibrium discharges with water vapor, as considered in [4]. Beginning with a concentration of water molecules of $N \simeq 1.6 \cdot 10^{23}$ m^{-3}, the discharge turns crimson red due to the excitation of molecular bands pertaining to the vibrational spectrum of H_2O [10].

For considering compression of the plasma, the internal diameter of the pipe was increased to $\sim 7.2 \cdot 10^{-2}$ m, and the relative concentration of H_2O molecules was chosen so that the volume of the plasma discharge was minimal. Experiments were done for an initial pressure of 4000 Pa with sealing of the pipe.

Visual observation shows that the discharge is surrounded by a halo near the surface of the plasma formation which disappears with an increase in power ($\sim$40 kW). The plasma densities measured at wavelengths of 3 cm, 8 mm, and 4 mm are $n \gg 7.54 \cdot 10^{13}$ cm^{-3}.

This analysis has shown that the form of the discharge strongly depends on the pressure inside the discharge pipe and on the atmospheric humidity. Under certain experimental conditions, the volume occupied by the plasma was minimal due to cooling of the plasma by water vapor.

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NONMONOTONIC RELAXATION IN AN ATOMIC GAS AND THE KINETICS OF THRESHOLD PROCESSES

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Deviations from equilibrium in the high molecular energy range can have a significant effect on the kinetics of threshold processes such as thermonuclear synthesis, gas phase chemical reactions, etc. The nonequilibrium tails of energy distributions must be considered in interpreting the results of physical diagnostics employing selective excitation of a gas. In this connection the effect of nonequilibrium on relaxation properties and transport processes in gases has attracted much attention [1-7]. However, the pattern of global evolution of the distribution function of gas molecules has been studied little, even for the simple case of homogeneous relaxation of an atomic gas. This is due to the complexity of the kinetic equation in Boltzmann's theory of gases [8].

Individual results obtained with asymptotic estimates [4, 5, 8] and on the basis of simple exactly soluble models [7, 9] are basically of a qualitative nature and have limited applicability. In particular, for the hydrodynamic moments of the distribution function we have Maxwell's estimate, according to which their evolution to local equilibrium is monotonic and completed in two or three mean free molecular path times [8]. This property of transition to equilibrium in the region of the "dome" of the distribution function is the basis of the hydrodynamic expansions of the Chapman–Enskog method. But extrapolation of this estimate to the process of relaxation of the distribution function as a whole, often found in the literature (see, for example, [10]), is in general erroneous. Krook's kinetic model with a single relaxation time for the entire energy spectrum also distorts the pattern of evolution of the distribution function tail significantly [11]. For example, for finite distributions, in which a tail is completely absent at the initial moment, the time required for

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