EFFECT OF GAS HEATING ON DEVELOPMENT OF AN INDEPENDENT HIGH-PRESSURE GLOW DISCHARGE IN INERT GASES

V. M. Fomin, V. A. Shveigert,
and I. V. Shveigert

UDC 537.523

In high-pressure gas discharge systems Joulean heating of the gas changes integral properties of the discharge such as current density and cathode voltage drop. In the cathode dark space (cds) of an independent glow discharge the electric field intensity is several orders of magnitude higher than in the positive column, so that by discharging to atoms fast ions heat the gas mainly in a thin layer adjacent to the cathode. In gas discharge tubes the nonuniform energy contribution over the discharge gap produces a longitudinal motion of the gas and formation of shock waves, the intensity of which determines the rate of energy introduction. In the low-field range the gas heats weakly, since the ion temperature is close to the gas temperature and transfer of energy from electrons to atoms is hindered by the great difference in their masses. An analytical treatment of perturbations in a laser medium was performed in [1] in the acoustic approximation. The interferograms obtained in [2] clearly show shock-wave propagation from the cathode through the active laser medium. Gas heating was also estimated from the measured velocity of wave propagation. A dependent glow discharge was described in [3] by numerical solution of the gasdynamic equations in the steady-state case and in the isobaric approximation. The present study will carry out a self-consistent calculation of the nonsteady-state system of gasdynamic equations for a thermally conductive gas and the equations describing a gas discharge in the drift approximation. Evolution of a glow discharge in neon, heating of the gas, shock-wave formation and propagation, and changes in cathode voltage U_C and discharge current j are traced.

The processes of ionization, recombination, and secondary electron emission at the cathode due to ion-electron emission and photoemission were considered in describing a high-pressure gas discharge. The system of equations includes the transport equation for electrons and ions and the Poisson equation for the electric field

$$\frac{\partial n_e}{\partial t} + \frac{\partial}{\partial z}(v_e + v)\,n_e = \alpha v_e n_e - \beta n_i n_e, \quad v_e = \mu_e E,$$

$$\frac{\partial n_i}{\partial t} + \frac{\partial}{\partial z}(-v_i + v)\,n_i = \alpha v_e n_e - \beta n_i n_e, \quad v_i = \mu_i E,$$

$$\frac{\partial^2 \varphi}{\partial z^2} = 4\pi e\,(n_e - n_i), \quad E = \frac{\partial \varphi}{\partial z}, \quad U_\text{p} = U_0 - jR, \quad j = \sigma E$$

with initial and boundary conditions

$$n_e(z,\,0) = n_i(z,\,0) = n_0, \quad U_\text{p}\,(t = 0) = U_0,$$

$$v_e n_e(0,\,t) = \gamma_i n_i v_i + \gamma_\text{ph} \int\limits_0^d \alpha v_e n_e\,dz, \quad n_i(d,t) = 0, \quad \varphi(0,t) = 0, \quad \varphi(d,t) = U_\text{p}.$$

Here and below the cathode coordinate z = 0, while at the anode z = d; d_C is the width of the cathode dark space, v is the velocity of gas motion, n_e and n_i are the electron and ion concentrations, μ_e and μ_i are the electron and ion mobilities, β is the recombination coefficient; φ is the potential, U_0 is the initial voltage, γ_i, γ_{ph} are the ion-electron emission and photoemission coefficients, n_0 is the initial plasma concentration created by preionization, U_p is the voltage on the electrodes. For the power source we consider a line with internal resistance R and electrode area 1 cm². Analytical approximations of the shock ionization coefficient α and the electron and ion drift velocites v_e and v_i were taken from [4]. We assume a local dependence of α, v_e, v_i on electric field intensity. We write the system of gasdynamic equations in the form

---

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 5, pp. 15-18, September-October, 1988. Original article submitted July 10, 1987.

0021-8944/88/2905-0614$12.50

$$\frac{\partial v}{\partial t} + v\frac{\partial v}{vz} = -\frac{1}{\rho}\frac{\partial g}{\partial z}, \quad g = p + \frac{\partial v}{\partial z}, \quad \frac{\partial \rho}{\partial t} + \frac{\partial}{\partial z}\rho v = 0,$$

$$\frac{d}{dt}\left(\varepsilon + \frac{v^2}{2}\right) = \frac{1}{\rho}\frac{\partial}{\partial z}(pv) + \frac{1}{\rho}\frac{\partial}{\partial z}\varkappa\frac{\partial T}{\partial z} + \sigma E^2, \quad p = \rho\varepsilon(\gamma - 1)$$

with initial and boundary conditions

$$\rho(z, 0) = \rho_0, \ T(z, 0) = T_0, \ v(z, 0) = 0,$$
$$v(0, t) = v(d, t) = 0, \ T(0, t) = T(d, t) = T_0,$$

where σ is the conductivity; ε is the internal energy of the gas, $\varkappa$ is the thermal conductivity coefficient; ρ, T are the gas density and temperature.

Calculations were performed of gas discharges burning in anomalous regimes in neon. Figures 1-5 show calculation results for $j_0 = 200$ A/cm², $R = 8.56\ \Omega$, a highly anomalous regime, and $j_0 = 10$ A/cm², $R = 260\ \Omega$, a weakly anomalous regime for $T_0 = 300$ K, $p = 10^5$ Pa, $n_0 = 10^8$ cm^{-3}, $\gamma_i = 0.1$, $\gamma_{ph} = 0.001$, $U_0 = 3.1$ kV, $p_0 d = 10^4$ Pa·cm.

It is known [5, 6] that the assumption of local dependence of the shock ionization coefficient electron drift velocity on electric field intensity is a coarse one for the purpose of discharge description. The drift approximation used for description of electrons in an anomalous glow discharge does not produce a qualitative picture of the cathode region. Since at high current densities the width of the cathode dark space becomes comparable to the electron free path length, the maximum rate of gas ionization by electron collision is located in the range of low electric fields. To describe motion of electrons with an energy greater than the energy of the lowest excited state a kinetic approach is necessary [6].

In the present study an independent high-pressure glow discharge was modeled by the drift approximation since that approach is simpler than the kinetic one. To analyze the applicability of the drift approximation for describing dynamics of integral quantities related to Joulean heating of the gas, profiles of the quantities E and n_i, which define the rate of energy introduction, were calculated by two approaches: kinetic (based on a Monte Carlo method) and drift. Figure 1 shows the ion concentration distribution and the dimensionless electric field for the highly anomalous case without consideration of gas heating (dashed lines, kinetic model; solid lines, drift). For $z > d_c$ ion concentrations differ greatly. This is explained by the fact that in the drift approximation ionization occurs only in the cathode dark space. In fact, the maximum ionization rate in the anomalous regime occurs in the negative glow region. But in that area the electrical energy of the ions is low, since the field E is low and the gas does not heat up. Therefore the temperature fields are similar in the two cases.

A detailed examination of ignition of a glow discharge without consideration of gas heating was performed in [7, 8]. Figure 2 shows integral characteristics U_c and j of a discharge burning in an intensely anomalous regime (dashed lines, parameter change without consideration of gasdynamic processes; solid lines, with consideration). At times $t_f \sim 5$ nsec the integral characteristics change abruptly, and formation of the discharge occurs. This time is comparable to the ion transit time through the cathode layer. In the initial stage of development, before the ions reach the cathode, the basic process at that electrode is photoemission $\gamma_{ph}\alpha d \ll \gamma_i$ and the number of secondary electrons is small. This leads to an increase in the size of the cathode layer and the cathode voltage drop with a decrease in discharge current. When the ions generated by shock ionization of the gas reach the cathode the number of secondary electrons increases, d_c and U_c decrease, and the current increases. Since $t_f \ll t = d_c/c_0$ (where $c_0 = 433$ m/sec is the speed of sound in the undisturbed gas), motion of the medium cannot affect the integral characteristics of the discharge. Over the course of 20 nsec the gas at the cathode heat isochorically. Then in the cathode dark space the discontinuity decays and a shock wave propagates in the direction of the anode, while a rarefaction wave travels toward the cathode. Convective removal of heat from the cathode region occurs. With decrease in gas density the ionization rate falls off. The electric field in the cathode dark space readjusts to maintain combustion of the independent discharge. In mass coordinates the E distribution remains practically constant. The boundary between the high and low electric field regions $z = d_c$ moves behind the shock wave together with the gas, the width of the cathode dark space increasing. Figure 3a shows the E-field distribution in the cathode dark space (1, without; 2, 3, with consideration of gasdynamics), while Fig. 3b shows temperature profiles for various times at $j_0 = 200$ A/cm².

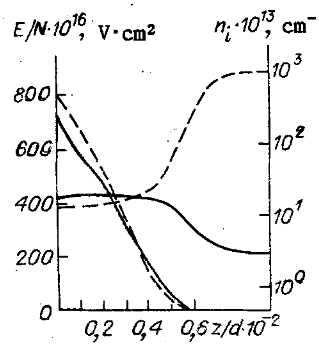

Fig. 1

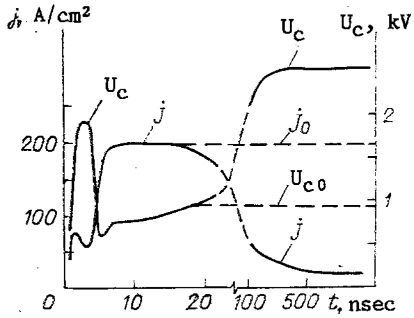

Fig. 2

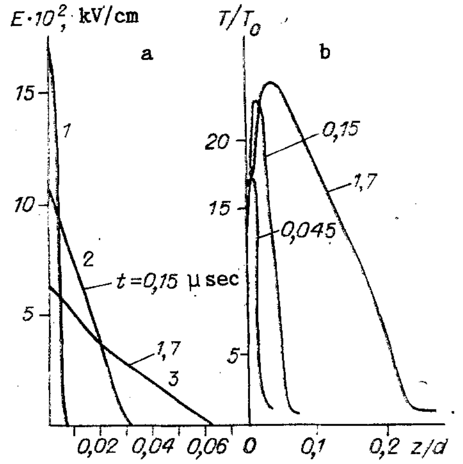

Fig. 3

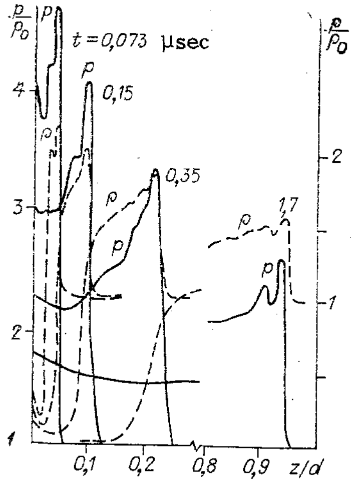

Fig. 4

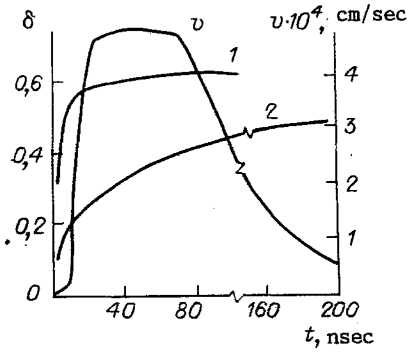

Fig. 5

At t ~ 150 nsec the shock wave departs a distance large enough that the pressure at the cathode equalizes (Fig. 4), and the gas velocity falls (Fig. 5). Figure 4 shows pressure (solid lines) and density (dashes) profiles behind the shock-wave front at various times. Figure 5 shows the gas velocity at the point $z = d_c$ and the fraction of heat δ removed by thermal conductivity to the cathode in the intensely anomalous (1) and slightly anomalous (2) cases. The gas at the cathode is rarefied; therefore a higher cathode drop is required to ensure conditions for existence of the discharge (see Fig. 1). The voltage drop across the positive column decreases and the discharge current falls.

Over the course of 20 nsec gasdynamic effects do not manifest themselves and the gas temperature at the cathode rises to 4500 K. The time for establishing the temperature distribution then becomes related to establishment of gas velocity in the cathode dark space. For the highly anomalous regime this time t ~ 150 nsec, over the course of which the gas heats to 9000 K. In the slightly anomalous regime, where the energy production rate is lower, the gas heats to 1500 K. At later times the energy contribution to translational degrees of freedom of gas atoms in the narrow cathode zone becomes equal to the thermal flux to the cathode and into the gas of the positive column. The temperature profile is approximately symmetric (see Fig. 3b) and the thermal fluxes are similar. The later rate of temperature increase in the cathode dark space is determined by the time required for gas heating over the entire discharge interval. The quantity of heat removed by thermal conductivity to the cathode increases and $\delta \to 1$.

We note that the calculations were performed for a small interelectrode gap with the goal of machine-time economy (one calculation variant required ~2 h). This does not decrease the generality of the conclusions reached as to the effect of gas heating on the characteristics of a discharge with arbitrary interelectrode gap. While the discharge burns the gas region near the cathode serves as a perturbation source and the amplitude of the wave changes only slightly. In the calculated intensely anomalous regime the Mach number $M = 2$ ($M = D/c_0$, where D is the shock-wave front velocity), and at $t = 1.5$ µsec, $M = 1.4$. Shock-wave attenuation intensifies with motion through the decaying plasma. The pressure behind the shock-wave front falls off as $z^{-1/2}$.

LITERATURE CITED

1. F. E. Culick, P. I. Shen, and W. S. Griffins, "Acoustic waves and heating due to molecular energy transfer in an electric discharge CO laser," IEEE J. Quant. Electron., 12, 566 (1976).
2. W. M. Clark, "Optic homogeneity of ultraviolet-preionized CO_2-laser discharge," Appl. Opt., 13, No. 9 (1974).
3. A. N. Lobanov, Ya. M. Londer, et al., "Cathode layer dynamics in a dependent glow discharge," Zh. Tekh. Fiz., 52, No. 10 (1982).
4. A. L. Ward, "Calculation of cathode-fall characteristics," Appl. Phys., 9, 2789 (1962).
5. D. H. Pringle and W. E. J. Farvis, "Electron groups in the helium negative glow," Phys. Rev., 96, 536 (1954).
6. V. A. Shveigert and I. V. Shveigert, "The cathode region of a glow discharge in inert gases," in: High Power CO_2-Lasers for Plasma Experiments and Technology [in Russian], Novosibirsk (1986).
7. S. Ya. Bronin, V. M. Kolobov, et al., "Normal current density in a dependent glow discharge," Teplofiz. Vys. Temp., 18, No. 1 (1980).
8. V. V. Zakharov, A. A. Karpikov, and E. V. Chekhunov, "Volume gas discharge in nitrogen with steady-state external ionization," Zh. Tekh. Fiz., 46, No. 9 (1976).

EFFECTS OF AEROSOL PARTICLES ON CORONA-DISCHARGE PARAMETERS AND TRANSPORT CURRENT IN A ONE-DIMENSIONAL ELECTROHYDRODYNAMIC FLOW

N. L. Vasil'eva, G. L. Sedova,
and A. V. Filippov

UDC 532.5:537

A unipolar charged aerosol consists of a gas, ions of one sign, and dispersed-phase particles, in which the latter may be charged by the ions [1]. Here we present a theoretical study on this as affecting electrohydrodynamic flows. We have examined continuous stationary one-dimensional flows on the basis of particle electrification between two parallel grids perpendicular to the flow. The electric field and the particles influence the gas motion to a negligible extent. We envisage cases where the first grid is a corona source, while the incident flow contains the particles, and also where the first grid is the particle source and the incident flow contains the positive ions. Such flows are one-dimensional analogs for an aerosol flow around a corona source and flow of a unipolar gas around an aerosol source. We have examined how the particles influence the voltage–current characteristics in the corona and the total current arising from transport of ions and charged aerosol particles between the grids. In both cases, we have calculated the electrification for the aerosol flowing

---

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 5, pp. 19-25, September-October, 1988. Original article submitted March 27, 1987.