# CONTRACTION OF A CYLINDRICAL GAS DISCHARGE

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## Abstract

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# CONTRACTION OF A CYLINDRICAL GAS DISCHARGE

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A number of experiments are known, for example ([1−3]), establishing that a gas discharge at medium pressures ($P = 1 \div 500$ mm Hg) and under certain current conditions can contract. In this case the discharge may be either in the diffusion regime of burning or in a regime in which diffusion of electrons to the walls may be neglected in comparison with ionization and recombination of electrons (the volume regime) ([1]). There are a number of works that have investigated and explained contraction in the diffusion regime, for example ([2],[3] ).

In the present work the contracted state of a discharge occurring in the volume regime is investigated.

Let us write the energy-balance equation for the electrons and the neutral gas in the form

$$\sigma E^2 - \chi \frac{n_e T_e}{\tau_e} = 0; \tag{1}$$

$$\chi \frac{n_e T_e}{\tau_e} + \frac{1}{r}\frac{\partial}{\partial r}\left(r \frac{n_0 T_0 \tau_0}{M}\frac{\partial T_0}{\partial r}\right) = 0, \tag{2}$$

where $\chi \approx m/M$; $m$ is the mass of the electron; $M$ is the mass of the neutral atom; $\tau_e$ is the time of an elastic electron–neutral collision; $\tau_0$ is the time of an elastic interatomic collision; $n_e, n_0, T_e, T_0$ are, respectively, the density and temperature of the electrons and neutrals of the plasma; $\sigma = n_e e^2 \tau_e / m$ is the conductivity of the plasma.

Equation (1) is valid if the electronic thermal conductivity is small in comparison with Joule heating ($\sigma E^2$) and elastic losses of electron energy. The electron losses are mainly elastic and have the form written in Eq. (1), since a discharge is considered in which the electron temperature is much greater than the atomic temperature but substantially lower than the excitation levels of the neutral atoms. We shall also neglect Coulomb collisions, assuming the plasma to be weakly ionized: $T_e \ll I$, where $I$ is the ionization potential of the atoms.

We shall assume that the concentration and temperature of the electrons are related by the Saha formula (in contrast to the diffusion regime, which is valid at sufficiently small currents), i.e.,

$$n_e = n(T)\exp(-I/2T_e).$$

The boundary conditions for Eqs. (1) and (2) are determined by the experimental arrangement. Usually the gas temperature at the tube wall is specified. Therefore we write the boundary conditions in the form:

$$\frac{\partial T_0}{\partial r}(r=0) = 0, \qquad T_0(R) = T_{0R}, \tag{3}$$

where $R$ is the radius of the tube.

Contraction is due to the fact that near the walls the gas temperature falls and the gas density increases, since the gas pressure is everywhere the same in the tube. Therefore, near the walls the electrons give up a large ener-

to the neutrals and their temperature falls. But since $T_e \ll I$, a sufficiently small decrease in $T_e$ is enough for the electron concentration near the walls to decrease significantly, i.e., for contraction of the discharge to occur.

To solve equations (1) and (2) it is necessary to know the dependence of $\tau_e$ and $\tau_0$ on $T_e$ and $T_0$. Often $\tau_0$ may be regarded as independent of $T_0$, while $\tau_e$ will be expressed in terms of the cross section of elastic electron–atom collision ($S_e$):

$$\tau_e = m^{1/2}T_0/PS_e(T_e)T_e^{1/2}, \tag{4}$$

where $P = n_0T_0$ is the gas pressure, which in many arc-contraction experiments may be regarded as independent of the current passed. From equation (1) one can find a simple relation between $T_e$ and $T_0$:

$$(T_e)^{-1} = \varphi(T_0) = \frac{P\sqrt{\varkappa}}{eE}\,S_e[T_e(T_0)]T_0^{-1}. \tag{5}$$

Now rewrite equation (2) in the form

$$\frac{\varkappa T_e}{\tau_e}\,n\exp\left[-\frac{I}{2}\varphi(T_0)\right] + \frac{P\tau_0}{M}\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_0}{\partial r}\right) = 0.$$

Since in this equation the strongest dependence on $r$ is exponential in character, all coefficients at the derivatives and at this exponential may be regarded as constant and their values taken equal to those which they have at the tube walls.

Introduce new dimensionless variables:

$$\theta = \frac{1}{2} I[\varphi(T_{0R}) - \varphi(T_0)], \qquad x = r/r_0, \tag{6}$$

where

$$r_0^2 = \frac{n_{0R}}{n_{eR}} \frac{T_{0R}}{T_{eR}} \frac{\tau_{eR}\tau_0}{\varkappa M I} \frac{1}{|\partial\varphi/\partial T_0|_R}.$$

Then, taking into account that $I/T_{eR} \gg 1$, equation (2) and the boundary conditions (3) can be written in the form

$$\frac{1}{x}\frac{\partial}{\partial x}\left(x\frac{\partial\theta}{\partial x}\right) = -e^{\theta}, \qquad \theta_x(0) = 0, \qquad \theta(x_R) = 0. \tag{7}$$

Introducing the substitution $\xi = \ln x$, it is easy to find the solution of equations (7):

$$\exp[\theta(x)] = \frac{8}{a^2}\left(1 + \frac{x^2}{a^2}\right)^{-2}, \tag{8}$$

where

$$a_{1,2}^2 = 4 - x_R^2 \pm 4\left(1 - \frac{x_R^2}{2}\right)^{1/2}. \tag{9}$$

It is seen from this that a solution of the stationary equations (1) and (2) exists for $x_R^2 \leq 2$. Analysis of expressions (5) and (6), for example as applied to discharges in inert gases, shows that the condition $x_R^2 \leq 2$ says that the corresponding solution of equations (1) and (2) is possible for electric fields $E \leq E(x_R = \sqrt{2})$.

Using expression (8), it is natural to call $R_k = ar_0$ the radius of contraction of the arc. It follows from equations (8) and (9) that for each value of the electric field there exist two values of $a$, two different distributions of the electron concentration and, consequently, two values for the currents flowing through the tube. For $x_R \approx \sqrt{2}$ one also has $a \approx \sqrt{2}$, i.e., such values of $x_R$ correspond to a weakly contracted arc. For $x_R \ll 1$ there are two values: $a_1^2 \approx 8$; $a_2^2 \approx x_R^4$.

The first value $a_1$ corresponds to small currents and the complete absence of contraction. The second value $a_2$ corresponds to large currents and strong

contraction. An increase in contraction with increasing current in the volume regime of discharge burning has been observed experimentally ([1]).

Let us also note that the model considered gives a linear dependence of the introduced contraction radius on the tube radius at a constant value of the discharge current and for $x_R \lesssim 1$ (i.e., in the case of not very strong contraction). Indeed, in this case $R_k = a_2 r_0 \approx R^2/r_0$, and the expression for the current, knowing the radial distribution of the electron density (8), becomes

$$J \approx \frac{f(E)}{1 + R^2/r_0^2},$$

where $f(E)$ is a power function. Since, on the other hand, the dependence $r_0(E)$ is exponential, the expression for $J$ can, generally speaking, be written in the form

$$J \sim \frac{\ln(\alpha r_0)}{1 + R^2/r_0^2},$$

where $\alpha$ is a certain constant independent of $E$. Hence it follows that at constant current $R \sim r_0$, and consequently $R_k \sim R$.

A linear dependence of the contraction radius on the tube radius was observed experimentally ([4]).

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*Note: Figure translations are in progress. See original paper for figures.*