Plasma column in a gas with a light impurity

Yu. R. Alanakyan

All-Union Scientific Research Institute of Physicotechnical and Radio Engineering Measurements

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It is shown that in a mixture of heavy and light gases the formation of a plasma column, whose hot region contains primarily ions of the light particles is possible, i.e., the heavy particles are removed from the gas in the plasma column. If the concentration of light particles in the gas far from the column is sufficiently small compared with that of the heavy particles, then the consumption of HF radiation power supplied to the column is a factor of $(M_1/M_2)^{1/2}$ smaller than that in experiments with a pure, light gas. (M_1 and M_2 are the masses of the heavy and light particles, respectively.)

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Kapitsa[1] investigated a plasma column with high electron temperature, which was produced in a cavity with a dense gas due to the action of high-power HF radiation. In particular, the following properties of the plasma column were observed in these experiments. The presence of light hydrogen or deuterium impurities in the gas contributes to the appearance of a hot plasma column. At the same time, the lines of multiply ionized atoms are missing in the column's radiation spectrum. A study of the plasma column in a deuterium gas with an argon impurity showed that as the argon concentration increase in the gas mixture the amount of power needed to produce the column discharge decrease (Kapitsa and Filimonov[2]). These properties of the column are consistent with the theoretical results obtained in this paper.

Let us examine a plasma column in a gas mixture for the conditions when the mean free path length of an ion between collisions with particles in the hot region of the column is greater than the characteristic dimensions of the column (the "free transit" regime). Under these conditions a stream of ions appear at the boundary of the hot region due to the action of the dc electric field produced by the separation of charges in the plasma which prevents the neutral particles from entering this region. Such a plasma column, formed in an impurity-free gas, was investigated theoretically in Ref. 3. However, in contrast to Ref. 3, we shall not restrict our discussion by assuming that the potential energy of an ion in an electric field is large in the entire region of the hot column, as compared with the kinetic energy of the neutral particle from which this ion was formed. The fact is that this may not occur in the column, and in the case of a gas mixture this will greatly influence the distribution of the ionic components in the plasma column.

Using the kinetic equations for the different plasma components and the method described in detail in Ref. 3, we obtain in this case of a plane-parallel plasma layer ($|z| < b$) the following formula that characterizes the spatial density distribution of α-type ions in the region $z > 0$

$$n_{\alpha i} = A_\alpha \left(\int_0^z + 2\int_z^{z_\alpha} \right) \frac{n_e(z')\exp(-3\mathscr{E}_\alpha(z')/T)}{[\mathscr{E}_\alpha(z') - e(\phi(z) - \phi(z'))]^{1/2}}, \tag{1}$$

where $A_\alpha = n_{\alpha b} M_\alpha^{1/2} \sigma_{\alpha i}\, v_e / 2\sqrt{6}$, $n_{\alpha b}$ is the density of the α-type neutral particles at $z = b$, $\sigma_{\alpha i}$ is the effective ionization cross section of the particle, and z_α is the root of the equation $\mathscr{E}_\alpha(z_\alpha) + e\phi(z_\alpha) = e\phi(z)$, $\mathscr{E}_\alpha(z) = (T/2)(M_\alpha^{1/2}\sigma_{\alpha i} v_e \int_z^b n_e dz / T^{1/2})^{2/3}$. We note that under the plasma-column conditions $\mathscr{E}_\alpha(0)$ is much larger than the temperature T of the neutral particles. The potential of the dc electric field $\phi(z)$ is determined by the plasma quasi-neutrality condition.

Let us assume that a column is formed in a mixture of two gases, and $\beta \gg 1$, where $\beta = M_1^{1/2}\sigma_{1i}/M_2^{1/2}\sigma_{2i}$.

When $\mathscr{E}_1$, $\mathscr{E}_2 \ll |e\phi|$, we have $z_1 = z_2 = z$ and by using Eq. (1) we obtain

$$n_{1i}(0)/n_{2i}(0) = (A_1/A_2)\exp[3(\mathscr{E}_2(0) - \mathscr{E}_1(0))/T]. \tag{2}$$

Since we have $\mathscr{E}_1(0)\mathrm{PP}\mathscr{E}_2(0) \gg T$ when $\beta \gg 1$, only light ions are contained in the central part of the plasma column filament. The heavy particles, which have a low ionization potential and low thermal velocity, are ionized in the boundary region of the column and are ejected from the column by the dc electric field.

We shall now examine a case in which the potential energy of an ion in the column is smaller than the kinetic energy of a neutral particle. Under these conditions the α-type ions, which are produced in the region $z_{\alpha_0} < |z| < b$, leave the column due to the action of the electric field, while those produced in the region $|z| < z_{\alpha_0}$ arrive in the central part of the column. Here, the quantity z_{α_0} is defined by the equation $\mathscr{E}_\alpha(z_{\alpha_0}) = \phi(z_{\alpha_0})$. It can be shown that at $\beta T/T_e < n_{2b}/n_{1b} \ll 1$ the following approximations are valid

$$3\mathcal{E}_1(z_{10})/T \approx \beta^{2/3} \ln(n_{2b} T_e / \beta n_{1b} T),$$

$$3\mathcal{E}_2(z_{20})/T \approx \ln(n_{2b} T_e / \beta^{1/3} n_{1b} T).$$

Using these relations, we obtain from Eq. (1)

$$n_{1i}(0)/n_{2i}(0) \approx (n_{1b} T\beta / n_{2b} T)^{2/3} (T_e / T\beta^{1/3}). \tag{3}$$

It follows from this that when $n_{2b} > n_{1b}(\beta T/T_e)$ at the boundary of the hot plasma column and the parameter β is sufficiently large, the concentration of heavy ions in the plasma column is small compared with that of the light ions.

We point out that in the case of the experiments[1,2] where the light impurity consists of hydrogen atoms (or its isotopes), the effective self-removal of heavy particles from the hot column eliminates almost entirely the production of multiply charged ions in the plasma. Thus, the absence of the lines of multiply ionized atoms in the radiation spectrum of the plasma column does not mean that it has a low electron temperature, as was assumed by the authors.[4]

Let us now determine how the energy losses of the hot plasma column depend on the gas composition. The following relation can be obtained from Eq. (1) for the ion streams at the hot plasma boundary. $\Sigma_\alpha M_\alpha^{1/2} j_{\alpha i} \approx n_e(0) T_e^{1/2}$, from which it follows that the quantity $\Sigma_\alpha M_\alpha^{1/2} j_{\alpha i}$ is invariant with respect to the gas composition. It can be seen from this that the electron flux from the plasma column, which is equal to the total ion flux ($j_e = \Sigma_\alpha j_{\alpha i}$) decreases with decreasing flux of the light ions as compared with the flux of heavy ions. Because the plasma column is in dynamic equilibrium with the surrounding gas and the flux of each kind of ion is equal to the counter flow of neutral particles that arrive in the plasma column with a thermal velocity, the condition that the flux of light ions must be small can be written in the form $n_{2b}/M_2^{1/2} \ll n_{1b}/M_1^{1/2}$. Thus, the energy losses in the plasma column ($\sim T_e j_e$) are a factor of $(M_1/M_2)^{1/2}$ smaller than those in a plasma column than those in a plasma column that is formed in a pure, light gas.

We note that the relative number of neutral components of the mixture at some distance from the plasma column differs from that at the boundary of the hot column. The fact is that the ion stream produced at the boundary of the hot plasma column can have a filtering action on the gas if the cross section for collision of an ion with a neutral particle of the foreign gas is different from the cross section for collision with a particle of the intrinsic gas. When the impurity content in the gas is so small that the convection pressure of the impurity ions can be ignored, the density of the main gas decreases near the plasma column boundary, just as in the case of a homogeneous gas,[3] by a factor of $\gamma \approx \pi (T_e/T)^{1/2}$ compared with the gas density far from the plasma column. Thus, the neutral impurity particles can penetrate the plasma column boundary almost unhindered if the cross section for collision of the neutral particles with the foreign gas ions is much smaller than that with the ions of the intrinsic gas (charge exchange effect). In this case we have $n_{1\infty}/n_{2\infty} \approx \gamma n_{1b}/n_{2b}$.

Estimates show that in the experiments[1,2] the "free transit" regime is achieved only in the "double layer," i.e., in the boundary region where the density of the hot plasma decreases sharply. It should be noted, however, that the results obtained in this paper are valid when the length of the mean free path of an ion, is small compared with the plasma column radius, but much larger than the thickness of the "double layer." The formation of the plasma stream from the column and the removal of heavy particles from the plasma column occur primarily in the boundary "double layer" and, therefore, these are not strongly dependent on how effects depend weakly on the manner in which the ions move in the central part of the plasma column-in the diffusion regime or in the "free transit" regime.

Thus, if a column is produced in a heavy gas with a light impurity, then for $\beta T/\gamma T_e < n_{2\infty}/n_{1\infty} \ll (1/\gamma)(M_1/M_2)^{1/2}$ the plasma column will have primarily light ions, while the heavy ions will play the main role in the formation of the boundary "double layer."

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