Non-self-sustaining stationary gas discharge induced by electron-beam ionization in N_2-CO_2 mixtures at atmospheric pressure

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A non-self-sustained gas discharge in N_2-CO_2 mixtures at atmospheric pressure is investigated. The external ionizer is an electron beam with energy ∾ 100 keV and current ∾ 50 μA. Stable burning of such a discharge under stationary conditions has been obtained experimentally. The analysis indicates the feasibility of employing such discharges for combined pumping of CO_2 lasers.

One of the methods of exciting CO_2 lasers is combined pumping. The main feature of such a method is the provision of conditions for the maintenance of a non-self-sustaining gaseous discharge. In that case the external ionizer creates the ionized gas medium while the applied electric field provides the electron energy distribution necessary for an effective excitation of the upper laser level of CO_2 molecules. The possibility of an independent variation of the concentration and average energy of electrons allows us to optimize CO_2 laser operation better than with the self-sustaining gaseous discharge[1].

A practical advantage of combined pumping is the possibility to excite generation in large volumes of gas at a high pressure because the external ionization source prevents the inhomogeneous pattern from developing in the initial stage of the discharge. The recent use of high-power ionization sources (high-current accelerators[2–4], and a pulsed reactor[5]) has brought about pulse CO_2 lasers operating at gas pressures exceeding 1 atm.

This paper presents a theoretical and experimental clarification of the feasibility to produce a stationary non-self-sustaining gaseous discharge whose current is due to the transfer of electrons generated by weak-current beams of charged particles. The reduced power of the external ionizer offers the promise of cw CO_2 lasers with combined pumping that would operate at high gas pressures.

1. The following conditions are required to maintain a non-self-sustaining gaseous discharge whose current is due to electron transfer. First, the cathode potential drop required for the electron emission to maintain current must be small relative to the voltage applied to the discharge gap. Second, the electron generation rate in the cathode region due to the external ionizer should exceed the rate of electron multiplication due to the applied field. These conditions ensure the flow of discharge current in electric fields that are lower than the breakdown field. This in turn prevents the development of nonuniform burning typical of the initial stage of high-pressure discharges and eliminates the causes of ionization instability typical of discharges in molecular gas[6].

We first consider the minimally possible electron generation rates of the external ionizer and, consequently, the minimum possible energy input for which the discharge would remain non-self-sustaining. We only consider the case of pure nitrogen as the working medium since the values of physical coefficients determining avalanche multiplication of electrons in N_2-CO_2 mixtures are unknown.

The condition for a non-self-sustaining discharge is written as follows:

$$q > \alpha p n_e v_e. \quad (1)$$

Here q is the electron generation rate of the external ionizer, α is the first Townsend coefficient, n_e and v_e are electron concentration and drift velocity, and p is gas pressure.

On the other hand, if (1) is satisfied, the electron concentration in the main regions of the gas discharge in nitrogen is determined by

$$q = \beta n_e^2. \quad (2)$$

Here β is the dissociative recombination coefficient. Relations (1) and (2) permit us to write the condition for a non-self-sustaining discharge in the following form:

$$q > \frac{(\alpha v_e p)^2}{\beta} \quad \text{for} \quad n_e > \frac{\alpha}{\beta} p v_e. \quad (3)$$

The quantities α, β, and v_e depend on the ratio of electric field intensity to gas pressure E/p (see[7] for example), and the first Townsend coefficient α(E/p) is the most sensitive function. If we use the known values of α, β, and v_e for pure nitrogen[7], then for E/p = 10 V/cm. Torr, that is optimal for the excitation of vibrational levels of nitrogen[8], inequality (3) imposes the following limitation on the minimum electron concentration in a non-self-sustaining discharge for p = 1 atm: $n_e > 10^{11}$ cm^{-3}. Therefore the minimum possible ionizing beams of charged particles should, in the course of dissipation by the medium, maintain this level of electron concentration in order to keep up the non-self-sustaining discharge. The electric power produced in this manner in the medium is close to 1 kW/cm^3.

To clarify the problem of the relative value of cathode drop, i.e., to determine the condition for a non-self-sustaining discharge whose current is determined by electron mobility, we have solved the following system of equations describing stationary transfer of electrons and ions in pure nitrogen:

$$\frac{d(n_e v_e)}{dx} = -\frac{d(n_i v_i)}{dx} = q + \alpha p n_e v_e - \beta n_e n_i,$$
$$dE/dx = 4\pi e(n_i - n_e). \quad (4)$$

Boundary conditions were represented by the electron emission current at the cathode and the electric field in the cathode region of the discharge:

$$n_e(0)v_e(0) = -\gamma_i n_i(0)v_i(0), \quad E(x\to\infty)\to E_0. \qquad (5)$$

We solve this system of equations using the following approximation of the coefficients based on data from[7]:

$$\alpha[\text{cm}^{-1}\cdot\text{Torr}^{-1}] = Ae^{-Bp/E},$$

where A = 2.4, B = 155 for E/p < 100 V/cm · Torr, and A = 12, B = 342 for E/p > 100 V/cm · Torr;

$$v_e[\text{cm/sec}] = 4\cdot 10^5\, E/p;$$

$$v_i[\text{cm/sec}] = \begin{cases} 1.7\cdot 10^3 E/p & \text{for } E/p < 50 \text{ v/cm-Torr} \\ 8.5\cdot 10^4 & \text{for } 50 \text{ v/cm-Torr} < E/p < 100 \text{ v/cm-Torr;} \\ 8.5\cdot 10^3\sqrt{E/p} & \text{for } E/p > 100 \text{ v/cm-Torr;} \end{cases}$$

$$\beta = 2\cdot 10^{-7}\ \text{cm}^3\text{-sec}^{-1}.$$

Numerical solutions of (4) with boundary conditions (5) for various values of E_0, γ_i and q (and consequently for various values of n_e in the main region of the gaseous discharge) are given in Fig. 1. The obtained solutions can be used to determine the cathode voltage drop (U_c) and the size of the cathode layer (l_c). For example, for p = 1 atm, E_0/p = 10 V/cm. Torr, and $\gamma_i = 10^{-2}$ for $n_e = 2\times 10^{11}$ cm^{-3}, we have U_c = 1300 V, $l_c = 10^{-2}$ cm, while for $n_e = 10^{12}$ cm^{-3} we have U_c = 750 V, and $l_c = 5\times 10^{-3}$ cm. It follows that a non-self-sustaining discharge with a power input of ~ 1 kW/cm^3 can be obtained with an electrode spacing of the order of a few centimeters and consequently with an applied electric field of the order of tens of kV. The cathode voltage drop here is a small fraction of the applied voltage and thus the discharge current is determined by electron conductivity due to the external ionizer. To obtain stationary burning of such a non-self-sustaining discharge we now merely eliminate the causes of thermal instability[9]. The characteristic time of development of this instability is

$$\frac{\gamma}{\gamma-1}\frac{p}{W} = 4\cdot 10^{-4}\ \text{sec}$$

(p = 1 atm, W = 1 kW/cm^3, γ = 1.4 is the adiabatic index of pure nitrogen). Therefore, the development of thermal instability can be prevented by pumping gas at the rate of several tens of m/sec through a system whose dimension in the direction of pumping is several cm long.

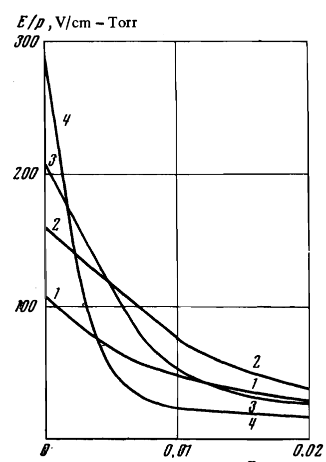

FIG. 1

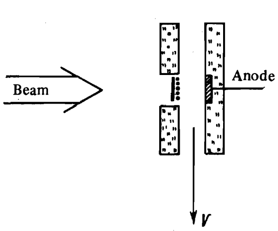

FIG. 2

FIG. 1. Electric field distribution for a discharge in nitrogen at atmospheric pressure (cathode at x = 0). Line 1—q = 10^{16}, E_0/p = 4, $\gamma_i = 10^{-1}$; line 2—q = 10^{16}, E_0/p = 4, $\gamma_i = 10^{-3}$; line 3—q = 10^{16}, E_0/p = 10, $\gamma_i = 10^{-3}$; line 4—q = 2×10^{17}, E_0/p = 10, $\gamma_i = 10^{-2}$; q is in cm^{-3} · sec^{-1} and E_0/p in V/cm · Torr.

FIG. 2. Diagram of experimental setup.

Experiments described below were performed to study the non-self-sustaining discharges under stationary conditions.

2. Non-self-sustaining discharge with a weak-current electron beam ionizer was studied with a setup shown in Fig. 2.

The electron beam was produced by a 50 Hz electron gun. A ~ 100 keV 50 μA electron beam was introduced into the discharge chamber through an aluminum foil window 15μ thick. The duration of beam injection was 8 msec. Gas was pumped through the discharge chamber at the rate of 10—100 m/sec, so that the time of flight amounted to fractions of a millisecond. This is significantly shorter than the time of electron injection and consequently the duration of current flow, so that the discharge can be considered stationary. The gas channel in the quartz discharge chamber was 1 × 1 cm in cross section. The surfaces of the discharge chamber electrodes were made flush with the channel wall in order to minimize flow perturbation in the discharge region. The cathode was either a stainless steel mesh or an aluminum plate coated with a thin oxide layer and having a large number of perforations. This electrode admitted the beam into the discharge chamber. The electrode spacing was 1 cm and the electrode area was 1 × 1 cm. Voltage from a transformer was applied to the discharge chamber; the voltage phase was adjusted so that the mesh electrode was the cathode when the electron beam appeared. The current and voltage amplitudes were used to plot the volt-ampere characteristics of the discharge. Technically pure gases were used in the experiments. Velocity was measured with a Pitot tube and an oil pressure gauge. Gas pressure in the chamber was 1 atm.

Figure 3 shows experimental volt-ampere characteristics of the discharge in pure nitrogen and in mixtures of nitrogen with carbon dioxide for a pumping rate of 62 m/sec, different cathodes and different electron gun currents. In the range of high current and voltage values the curves break off in the unstable burning region where the discharge becomes an arc localized in a narrow channel.

In the range of low currents all the volt-ampere characteristics show a sharp change of slope. This is caused by the electric field in plasma being completely shielded (concentrated in the cathode layer) at low voltages when the current is mainly determined by the mobility of ions. As the applied voltage increases, the cathode drop portion of the potential decreases because the positive layer formed near the cathode provides the required emission of electrons. In this case we can consider that the current is carried by the electrons at a drift velocity equal to the applied voltage.

This mechanism of plasma conductivity is verified by the theoretical volt-ampere characteristics for pure nitrogen plotted from the solutions to (4) with the following boundary conditions:

$$n_e(0)v_e(0) = -\gamma_i n_i(0)v_i(0), \quad \int_0^L E(x)\,dx = U;$$

where L = 1 cm is the electrode spacing and U is the applied voltage.

Figure 4 shows theoretical volt-ampere characteristics corresponding to various powers of the external ionizer. Areas of negative conductivity are unstable and apparently correspond to the plateaus in the volt-ampere characteristic obtained in the experiment.

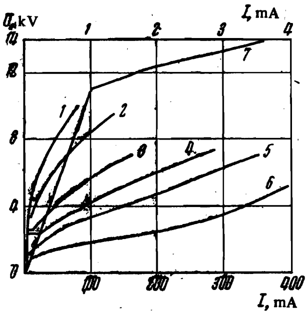

FIG. 3

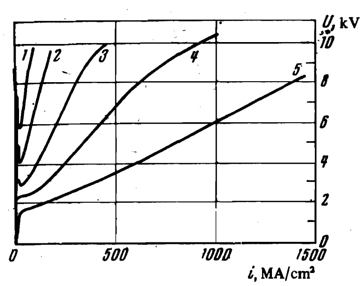

FIG. 4

FIG. 3. Volt-ampere characteristics of non-self-sustaining discharge at 1 atm. Line 1—$N_2:CO_2$ = 3:2; 2—$N_2:CO_2$ = 4:1; 3—$N_2:CO_2$ = 10:1; 4—N_2; 5—N_2, oxide cathode (lines 1-5 are for 10 μA beam current); 6—N_2, oxide cathode, 40 μA beam current; 7—air (top scale of current values refers to line 7); V = 62 m/sec.

FIG. 4. Computed volt-ampere characteristics of a discharge in nitrogen at atmospheric pressure ($\gamma_i = 10^{-2}$). 1—$q = 10^{15}$; 2—$q = 10^{16}$; 3—$q = 5 \times 10^{16}$; 4—$q = 2 \times 10^{17}$; 5—$q = 10^{18}$ (q is in units of $cm^{-3} \cdot sec^{-1}$).

Since the function $v_e(E/p)$ for pure nitrogen is well known[7], we can evaluate in this case the electron concentration in gas discharge plasma from the slope of the experimental volt-ampere characteristic in the high current range. This yields $n_e = 5 \times 10^{11}$ cm^{-3} which corresponds to $q = 5 \times 10^{16}$ cm^{-3} sec^{-1}. A comparison of the volt-ampere characteristic computed for this value of the external ionizer power with the experimental data provides a quantitative verification of the conductivity mechanism for the non-self-sustaining gaseous discharge considered above. We note that the computation of charged particle concentration from the ionization losses of the electron beam in pure nitrogen gives the value of $n_e = 3 \times 10^{11}$ cm^{-3}.

The reduced plasma conductivity resulting from increasing partial pressure of CO_2 observed in the experiment can be attributed to the equilibrium concentration of electrons due to the capture of electrons by CO_2 molecules[10]. The stronger the electro-negativity of the gas the more pronounced should this effect appear. In fact, when nitrogen is replaced by air, plasma conductivity drops sharply because of the presence of oxygen (line 7 in Fig. 3).

The volt-ampere characteristic obtained from the oxide cathode with its high coefficient of electron emission shows that the use of high γ_i materials makes it possible to reduce the cathode drop.

An additional indication of the volume nature of the discharge under our experimental conditions is supplied by photographs of the channel that is transverse to the gas flow. Figure 5 shows a typical photograph of a stable discharge. For comparison, Fig. 5b shows a photograph of a discharge in which an instability develops when gas flows through the chamber leading to the formation of a localized arc. The luminous region near the cathode, whose size depends on the power supplied to the discharge and the gas flow rate, shows that gas heats up in the cathode region, a consequence of a high electric field intensity in this region. We note that taking this heating into account may affect the results of computing volt-ampere characteristics especially in the range of low current values.

The experimental results and theoretical computations thus indicate that by using external ionizers producing electron concentrations in gas of $10^{11}-10^{12}$ cm^{-3} we can

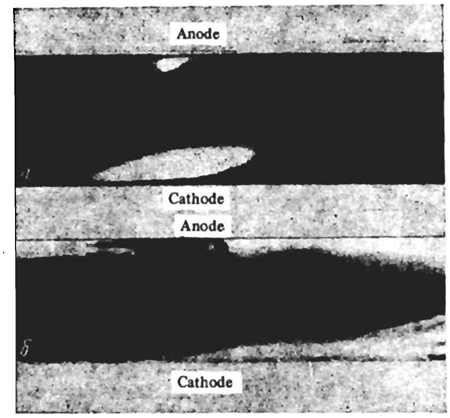

FIG. 5. Photographs of a discharge in a mixture of $N_2:CO_2$ = 4:1, exposure 0.5 sec; a—stable regime; b—unstable regime.

obtain non-self-sustaining stationary gaseous discharges in $N_2 - CO_2$ mixtures for $E/p \sim 10$ V/cm·Torr with a power input of ~ 1 kW/cm³. We note that such a power input provides an optically active medium for p = 1 atm. Considering that the electric power input is expended on the excitation of the vibrational levels of nitrogen and thus on the excitation of the upper laser level of CO_2 molecules, and that the lower laser level is populated at the gas temperature, the gain of the active medium for W = 1 kW/cm³ and a 20% CO_2 content comes out to $\sim 0.5\%$ per cm.

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