one has in mind modes with high values of the discharge current, then estimates of the velocity of the front and the flow velocity can be obtained by multiplying by two the values of the respective quantities measured in the accelerator coaxial. The temperature is estimated by multiplying the plasma temperature behind the shock wave in the accelerator by a number close to three, while estimating the density comes down to multiplying by two the value of the gas density in the accelerator before the discharge. The pressure remains practically what it was in the gas compressed by the shock wave inside the accelerator, with the condition that it is fully engulfed.

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CHARACTERISTICS OF CO_2 LASER MEDIA WITH A HIGH PUMPING LEVEL

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The promise of achieving high specific power levels and efficiencies has stimulated study of continuous CO_2 lasers. Increase in laser radiation power requires an increase in pump power and pressure of the operating medium, which, as a rule, is accompanied by localization of the discharge and termination of energy supply into the gas. The discharge stability limit is determined to a significant degree by the excitation methods used. The best success has been achieved with use of electrical ionization for excitation in CO_2 lasers, with discharge power levels of 10 W/cm^3 being achieved [1].

Significantly higher discharge powers have been obtained in experiments on studies of volume discharges for CO_2 lasers with use of denser electron beams [2]. However, an increase in power level of external ionizers in continuous CO_2 lasers is prevented by heating and destruction of the thin metal foils which separate the gas container and the accelerator vacuum diode [3]. Introduction of electron beams into the operating medium through gasdynamic windows [4] has not yet been used widely because of the complexity of the construction required to produce the large pressure differential between the gas container and accelerator operating volume.

Use of a combined discharge [5-7] is a more promising means of achieving these goals. In this case the major fraction of the energy is introduced into the gas with a lengthy nonindependent discharge in the plasma recombination decay stage, and creation of the charged particle concentration required to maintain the current in the operating volume is accomplished by a brief independent discharge. The major difficulty in exciting gaseous media in this manner at a high power level is the necessity of using means of decoupling the electrical circuits of the independent and dependent discharges which will not limit the current of the dependent discharge.

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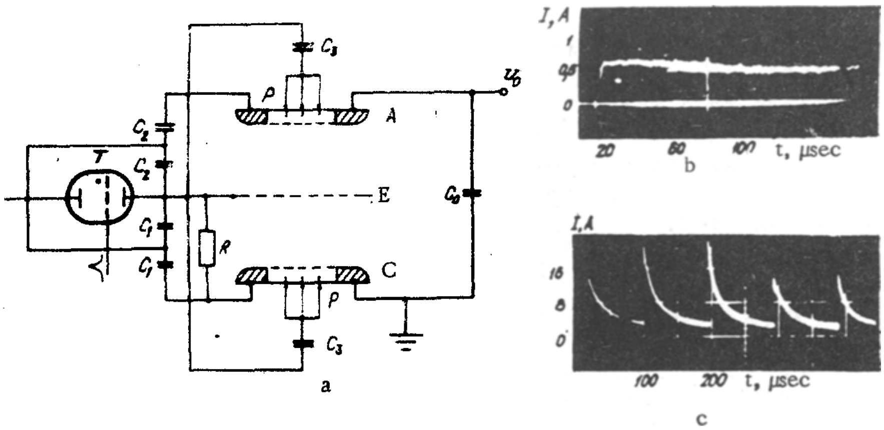

Fig. 1

The present study will investigate the characteristics of a combined discharge at a high power level, reached by use of a discharge excitation system which produces the conditions referred to above. The probable laser characteristics achieved at the high experimental pumping level are considered.

1. Experimental Results. Increase in the power level of a combined discharge under conditions optimum for CO_2 laser pumping requires an increase in charge carrier concentration and provision of sufficiently low inductance in the dependent discharge circuit which provides the major fraction of the induced energy.

Figure 1 shows a method of exciting a combination discharge which does not, in principle, impose any limitations on the conditions noted above [7]. The charge is excited in the main interelectrode gap (A–C) and occupies an area of 16.6 cm². The distance between the round electrodes A and C, which have a Rogovskii profile, is 5 cm. To produce preionization a capacitor C_3 = 50 pF is discharged through the holes P to a grid built into the electrode. The distance between the holes P and the operating grid surface of the electrode was 1.5 cm. A capacitor C_0 = 3 μF is attached to electrodes A and C, and carries a voltage U_0, optimum for pumping the 00°1 level of CO_2 and v = 1 of N_2. A distinguishing feature of this system is the introduction into the interelectrode space A–C of a grid E, which is connected to capacitors $C_1 = C_2$ = 228 pF, connected to the gaps C–E and A–E through thyratrons T (type TGI1 = 1000/25).

When the thyratron triggers, a voltage pulse of amplitude U_1 is applied to grid E. On the leading edge of the pulse the operating medium is preionized by an auxiliary discharge in the gaps E–A and E–C. When breakdown voltage is reached on the grid an independent discharge is excited in the main gas gaps E–A and E–C, ensuring creation of the required charge carrier concentration n_0 in the discharge plasma. After capacitors C_1 and C_2 are discharged to a level of $\sim U_0/2$, the major source through which energy is introduced into the gas is the energy stored in C_0 in the plasma recombination decay stage. Since the gaseous medium is not pumped, localization of the discharge is a certain phenomenon, ending energy introduction into the gas. The delay time for formation of an arc channel depended significantly on the electric field intensity, pressure, and discharge current density, but, as a rule, fell into the dependent discharge stage. Oscillograms of current regimes in the dependent discharge in a gas mixture $CO_2:N_2:He = 1:2:4$ at a pressure of $5\cdot10^3$ Pa are shown in Fig. 1b (E/p = 150 $V\cdot m^{-3}\cdot Pa^{-1}$) and Fig. 1c ($E/p$ = 87 $V\cdot m^{-3}\cdot Pa^{-1}$). With an initial current density in the dependent discharge of ~30 mA/cm² (Fig. 1b), over the characteristic interpulse time (10^{-4} sec) the current change does not exceed 10% and the discharge power can remain practically constant. To realize such a regime it is necessary that the dependent discharge current density comprise 0.4 A/cm² ($n_0 \sim 5\cdot10^{10}$ cm^{-3}). In this case the discharge power under optimum CO_2 laser pumping conditions (E/p = 52.5–157 $W\cdot m^{-3}\cdot Pa^{-1}$) is insignificant (2.0–14 W/cm³). However, even at these power levels the discharge becomes unstable if the difference in the interelectrode distances d_{c-e} and d_{a-e} exceeds 3 mm and the condition of electric field equality $d_{c-e}/d_{d-e} = \{U_1 - (\pm U_0)\}/U_1$ in the gaps C–E and A–E is not fulfilled. If this distance reaches 7 mm, discharge localization sets in during the first pulse of the dependent discharge.

As the independent discharge current j_i increases, the average power of the dependent discharge increases, but the discharge power over the time between two pulses can change by

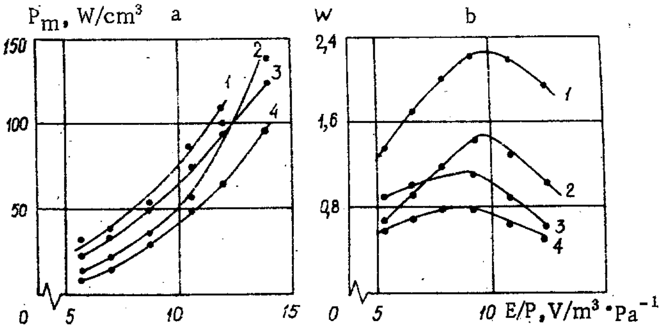

Fig. 2

a factor of 10. An example for an independent discharge current density j_i = 25 A/cm² is presented in Fig. 1c.

Mean dependent discharge power is shown as a function of electric field intensity for laser mixtures in Fig. 2a for the following experimental conditions: j_i = 18 A/cm², mixture composition CO_2:N_2:He = 1:30:30 (curves 1, 2) and CO_2:N_2:He = 1:2:4 (curves 3, 4), pressure p = 10^4 Pa (curves 1, 3) and p = $5\cdot10^3$ Pa (curves 2, 4). The curves have the form characteristic of such curves obtained for dependent discharges initiated by an electron beam. Also, the power levels realized in the discharge for both initiation modes are comparable [4].

Figure 2b shows the limiting energy introduced into the gas as a function of electrical field strength for the same experimental conditions as in Fig. 2a. It is evident that the curves have a maximum in the region 9-12 V·m^{-3}·Pa^{-1}, and are similar in character to the curves presented in [8], which the authors thereof explained by the mechanism of step ionization, inducing formation of an arc channel. The ratio of the energies introduced in the independent W_1 and dependent W_2 discharge stages is W_1/W_2 = 0.1. The data obtained on energy contributions and power levels of the combined discharge are favorable from the viewpoint of constructing CO_2 lasers with high specific power levels. It is thus of interest to consider the theoretically possible characteristics of CO_2 lasers with such a pump level.

2. Mathematical Model. To study continuously acting lasers with constant pumping of the active medium through the excitation region perpendicular to the optical axis one can relate the duration for which a unit volume of gas mixture remains in the excitation region to the distance traversed in the pumping direction. Thus, by using the dependence of amplification coefficient and laser power on time, nonstationary curves of the changes in these quantities as a function of coordinate in the pumpthrough direction can be constructed [9].

To solve the nonstationary laser kinetics problem, we will use a simplified kinetic model which permits obtaining a piecewise-analytical solution for the oscillatory energies W_{12} (energy in symmetric and deformed CO_2 modes) and W_{34} (energy in antisymmetric CO_2 mode and N_2 oscillatory levels) in the CO_2–N_2–He mixture. The corresponding balance equations have the form [10]

$$dW_{12}/dt = \gamma_{12}P_e + (\overline{W}_{12} - W_{12})/\tau_{12} + W_{34}/\tau_{34}, \quad dW_{34}/dt = \gamma_{34}P_e - W_{34}/\tau_{34},$$
$$T = T_0 + \left[(\gamma_{12} + \gamma_{34})P_e t - W_{12} - W_{34} + W_{12}^0 + W_{34}^0\right]/c^*, \tag{2.1}$$

where P_e is the pump power per unit volume; $\overline{W}$, equilibrium value of the energy W, defined by the temperature T; γ_{12}, γ_{34}, fractions of energy supplied to the excitation of the various oscillatory levels; τ_{12} and τ_{34}, relaxation times of W_{12} and W_{34}; c*, specific heat per unit volume of the gas mixture; W^0 and T^0, initial values of W and temperature. Assuming T = const, one can obtain analytical solutions for system (2.1) in the form

$$W_{12} = \left\{W_{12}^0 - [(\gamma_{12} + \gamma_{34})P_e + \overline{W}_{12}]\left(1 - \frac{\tau_{12}\tau_{34}(\gamma_{34}P_e - W_{34}/\tau_{34})}{(\tau_{34} - \tau_{12})[(\gamma_{12} + \gamma_{34})P_e + \overline{W}_{12}]}\right)\right\}e^{-t/\tau_{12}} + [(\gamma_{12} + \gamma_{34})P_e + \overline{W}_{12}]$$
$$\times\left[1 - \frac{\tau_{12}\tau_{34}(\gamma_{34}P_e - W_{34}/\tau_{34})}{(\tau_{34} - \tau_{12})[(\gamma_{12} + \gamma_{34})P_e + \overline{W}_{12}]}\right]e^{-t/\tau_{34}}, \tag{2.2}$$
$$W_{34} = P_e\gamma_{34}\tau_{34} + (W_{34}^0 - P_e\gamma_{34}\tau_{34})e^{-t/\tau_{34}},$$

whence for the amplification coefficient at the center of the j-th rotational line of the P-branch of the band 00°1-10°0 we obtain

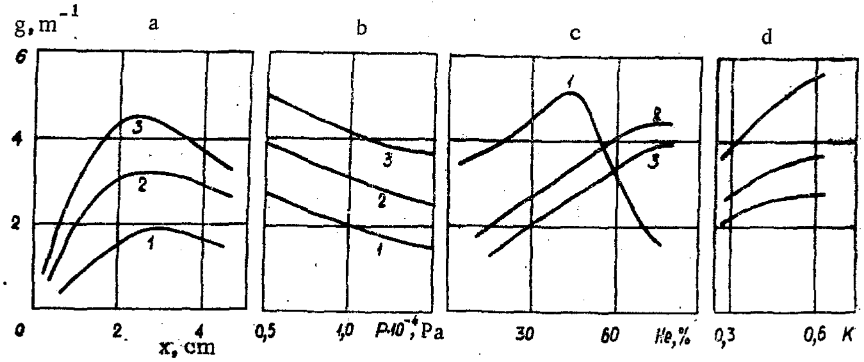

Fig. 3

$$g_j=\frac{S_jA_jc^2}{8\pi\nu_j^2}(2j+1)\frac{2\Theta}{T}\exp\left\{-j(j+1)\frac{\Theta}{T}\right\}N_{CO_2}\left\{\frac{KW_{34}}{KW_{34}+1.29p_{CO_2}}\left[\left(\sqrt{1.44+W_{12}/2.22p_{CO_2}}-1/12\right)^2e^{-146/T}\right]\right\}, \quad (2.3)$$

where S_j and A_j are the spectral line contour and Einstein coefficient for spontaneous radiation; Θ, characteristic temperature of the rotational quantum; N_{CO_2}, the number of CO_2 molecules per unit volume of gas mixture; p_{CO_2}, partial pressure of CO_2 in the gas mixture; $K = N_{CO_2}/(N_{CO_2} + N_{N_2})$.

Generally speaking, with change in W_{12}, W_{34}, i.e., in the process of energy introduction and relaxation, the temperature does not remain constant, and obviously can be represented in the form

$$T=T_0+\left[(\gamma_{12}+\gamma_{34})P_et-W_{12}-W_{34}+W_{12}^0+W_{34}^0\right]/c^*. \quad (2.4)$$

The change in temperature can easily be considered in solving Eq. (2.1), since it affects the speed of the relaxation processes (τ_{12}, τ_{34}). One can use a stepwise change in temperature by recalculating Eq. (2.4), which is then considered constant at each "step," permitting analytical solution of Eq. (2.2).

To apply the nonstationary kinetic model to description of processes in a laser with continuous pumpthrough, we consider that if the x axis is directed along the gas flow, and for the discharge region $0 < x \leqslant x_1$, then the equation of motion of an elementary gas volume entering the discharge region at t = 0 has the form c = vt, where v is the pumpthrough velocity. Therefore, calculating the dependence of the amplification coefficient on time with Eqs. (2.1)-(2.4), we simultaneously obtain the dependence of the stationary amplification coefficient distribution over the flow, since g(x) = g(vt).

It is obvious that in calculating stimulated radiation one should consider the dependence of amplification coefficient upon coordinate along the flow. But since we are not interested in the pitch structure of the radiation, the continuous radiation power $\Delta P_r(x)$ generated by each elementary layer Δx is determined from the condition that its value ensure maintenance of the amplification coefficient in the given layer equal to the resonator losses ($g(x) = g_0$) until the condition $g(x) < g_0$ is not fulfilled due to relaxation processes. It is to be understood that generation begins only at the point when $g(x_0) = g_0$, where x_0 depends on the pump power and flow velocity. The total power generated is obtained by integrating the power over the individual layers: $Q_r = \int_0^{x_1} \Delta P_r(x)\,dx$

Such an approach permits realization of a mathematical model in the form of a quite economical algorithm, since Eqs. (2.1)-(2.4) can be solved with a time step on the order of 10^{-6} sec, which at a pumpthrough rate of v = 100 m/sec corresponds to an individual layer thickness Δx = 0.1 cm.

3. Results of Calculations. Calculations were performed for an active zone 2.5 × 100 cm with the product of the mirror reflection coefficients r_1r_2 = 0.4 (smooth mirror and germanium), which corresponds to resonator losses g_0 = 0.5 m^{-1}. The main body of calculations were performed at a gas pump rate of v = 100 m/sec.

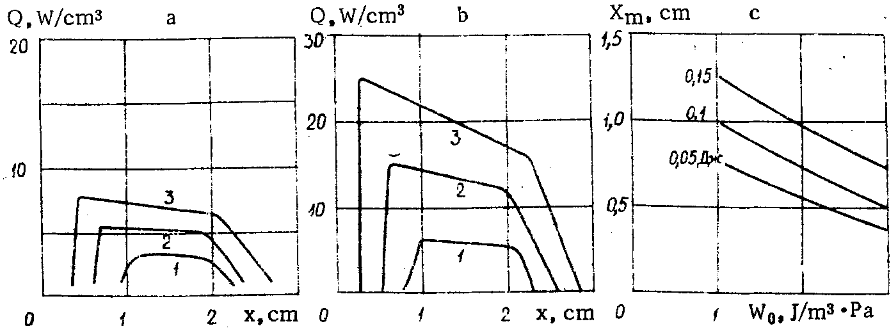

Fig. 4

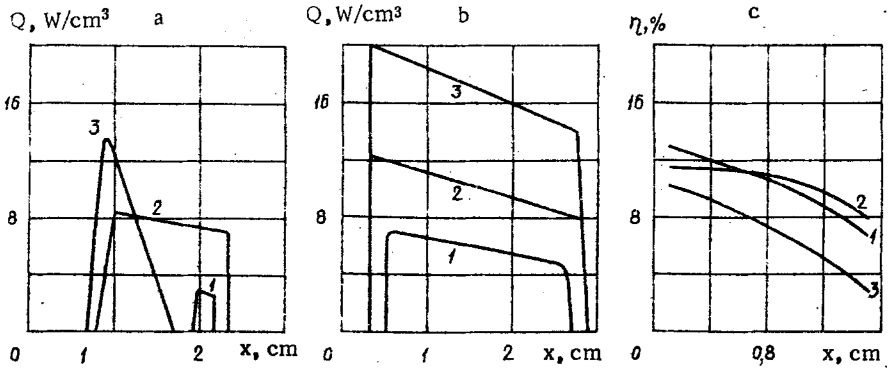

Fig. 5

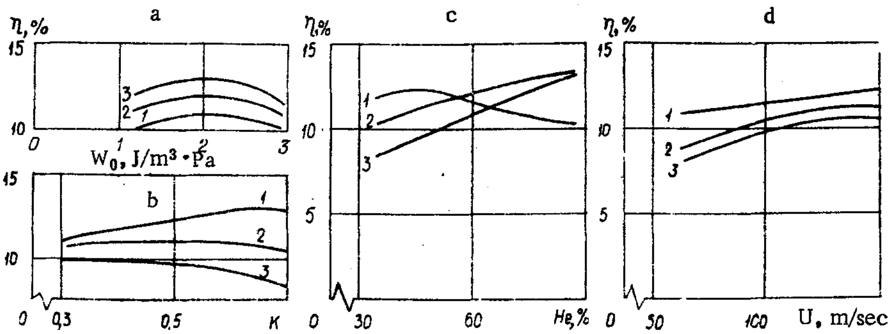

Fig. 6

Figure 3a shows the stationary amplification coefficient for a mixture CO_2:N_2:He = 20:50:30 at a pressure of $5 \cdot 10^3$ Pa for energy contributions of 1, 2, 3, $J \cdot m^3 \cdot Pa^{-1}$, respectively, for curves 1–3. We note that these curves also reflect the time evolution of the amplification coefficient (1 cm = 10 μsec). It is evident that g(x) attains its maximum value at the end of the excitation zone. In Fig. 3b–d, for $g = g(x_{max})$ amplification coefficient is shown as a function of pressure (b) for a mixture CO_2:N_2:He = 15:35:50, and as a function of helium content at $p = 5 \cdot 10^3$ and K = 0.5 (c) for the same energy conditions as in Fig. 3a. By x_{max} we understand the coordinate at which g is maximum. The effect of molecular component content is shown by Fig. 3d, for $W = 2\ J \cdot m^{-3} \cdot Pa^{-1}$ and concentration He = 30%. The behavior of the curves can be explained commencing from the following competing processes: 1) increase in pressure or content of the molecular component at constant energy contribution leads to spectral line broadening, i.e., decrease in g; 2) the same factors cause reduction in gas temperature, which attenuates the increase in g.

In Fig. 4a, b ($W = 1, 2, 3\ J \cdot m^{-3} \cdot Pa^{-1}$ in curves 1–3, respectively) the distribution of specific power generated by the laser over coherent radiation beam section is shown. The characteristic feature of these curves is the fall in power with approach to the discharge gap, which can be explained by heating of the gas in the radiation process. In fact, the slope of the energy falloff increases with increase in energy contribution or pressure, the speed of relaxation processes increasing, so that the energy stored in oscillatory levels is transformed into heat. Figure 4c shows the change in the coordinate of the power maximum with increase in energy contribution for various pressures. Comparing these data to the results presented above for stationary amplification coefficients, it can be concluded that generation begins practically immediately after the amplification coefficient in the resonator exceeds g_0, i.e., at $x < 1$ cm for the conditions considered.

Figure 5 shows operating characteristics of a laser with working mixture $CO_2:N_2:He = 15:35:50$ at a pressure of 10^4 Pa for various resonator lengths L_R and mirror reflection coefficients r_1 and r_2 (conditions and notation as in Fig. 3c). In fact, in the model considered, the resonator parameters appear in the combination $(\ln r_1 r_2)/L_R$, which gives the amplification coefficient g_0. Active length was varied from 50 to 150 cm with change in $r_1 r_2$ from 0.2 to 0.8, which corresponds to a change in g_0 from 0.07 (Fig. 5b) to 1.6 cm^{-1} (Fig. 5a). The dependence of laser efficiency (see Fig. 3c) on g_0 reflects a tendency to decrease in efficiency with increase in resonator losses. It is characteristic that at an energy contribution of 10^4 $J \cdot m^{-3} \cdot Pa^{-1}$, $g_0 = 1.6$ m^{-1} proves close to the limiting value of permissible resonator loss.

Figure 6 shows the dependence of laser efficiency on energy introduced into the gas (a), gas mixture composition (b, c) and gas pumpthrough rate (d) for pressures of $5 \cdot 10^3$, 10^4, and $1.5 \cdot 10^4$ Pa (curves 1-3, respectively) for the following experimental conditions: a) $CO_2:N_2:He = 15:35:50$, v = 100 m/sec; b) He = 50%, v = 100 m/sec, W = 2 $J \cdot m^{-3} \cdot Pa^{-1}$; c) K = 0.3, v = 100 m/sec, W = 2 $J \cdot m^{-3} \cdot Pa^{-1}$; d) $CO_2:N_2:He = 15:35:50$, W = 2 $J \cdot m^{-3} \cdot Pa^{-1}$. The behavior of the dependences on gas composition and energy contribution can be explained by the considerations presented above with respect to the effect of temperature and spectral line width on laser energy characteristics [11]. Increase in pumpthrough velocity with simultaneous increase in induced energy has a positive effect on laser energy characteristics (Fig. 6d), since in this case energy losses due to relaxation of the upper laser level decrease. It is characteristic that for the conditions considered the greatest role is played by increase in pumpthrough speed from 50 to 100 m/sec, with more effective laser operation being thus realized.

Thus, the results obtained permit the conclusion that construction of continuous CO_2 lasers with specific radiant power of ~10 W/cm^3 and efficiency of 10% is completely practical.

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