USE OF AN EXTENDED GAS GLOW DISCHARGE IN A CLOSED-CYCLE CO_2 LASER WITH CONVECTIVE COOLING

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An analysis is made of the operating characteristics of a powerful glow discharge used in a CO_2 laser system for the pumping of an extended uniform stream of working medium circulating through a closed circuit. The velocity of the medium is 30 m/sec and the pressure is about 20 mm Hg. Difficulties connected with instability and the possibility of pinching of the discharge (conversion into an arc) are overcome. The results of systematic experimental studies of the operating conditions of the discharge are presented. It is shown that the power level achieved (10 W/cm^2) depends on the choice of resonator construction and is not limiting for the system selected.

1. In the search for efficient gas laser systems an important role is played by the proper choice of a system and by the specific construction of the system for excitation of the active medium. Electric-discharge CO_2 lasers allow one to obtain an efficiency close to the quantum efficiency [1]. The maximum attainable generation power of such systems, on the assumption of an ideal resonator, is determined by the value $P = \varepsilon NWV/\tau$, where ε is the quantum efficiency (equal to 0.41), N is the number of CO_2 molecules per unit volume, W is the excitation potential of the upper laser level $00^\circ1$, V is the volume of the active medium, and τ is the depopulation time of the lower laser level $10^\circ0$, which coincides with the relaxation time of the level only in a gas with an infinite heat capacity. In a real gas, τ is limited by the cooling rate of the gas. In lasers with a longitudinal (relative to the optical axis) discharge the gas is cooled mainly through conductive heat conduction through the wall of the discharge tube. The diffusion time is

$$\tau_d \approx d_1^2/\lambda v ,$$

where d_1 is the transverse dimension of the tube, λ is the free path length of a molecule, and v is the thermal velocity. In this case the laser power cannot be raised either by increasing the cross-sectional area of the working volume of the active medium (τ_d grows in the same proportion) or by increasing the gas density (because of the simultaneous decrease in the free path length). A more efficient means of preventing overheating is the rapid pumping of the working gas through the discharge region. The time of changing and convective cooling of the active medium is then determined as $\tau_c = d_2/u$, where d_2 is the length of the active medium along the stream and u is the velocity of the stream. The generation power increases linearly with an increase in gas density and the channel width of the discharge chamber.

The changing time τ_c of the gas is determined by the channel cross section of the discharge chamber and cannot be great in lasers with a longitudinal discharge. The tendency toward an increase in the rate of changing the working medium led to the creation of electric discharge lasers with transverse pumping of the gas [2-7], which provided a sharp increase in the generation power compared with previous types of CO_2 lasers. Exceptionally high gas flow rates are required to maintain the high energy efficiency of a laser with transverse pumping, which limits the duration of continuous operation in systems of the open type. The possibility of achieving the operation of a closed cycle with continuous circulation and cooling of the working medium [6] is of interest.

In the present report one of the variants of the CO_2 laser system is described which has a relatively

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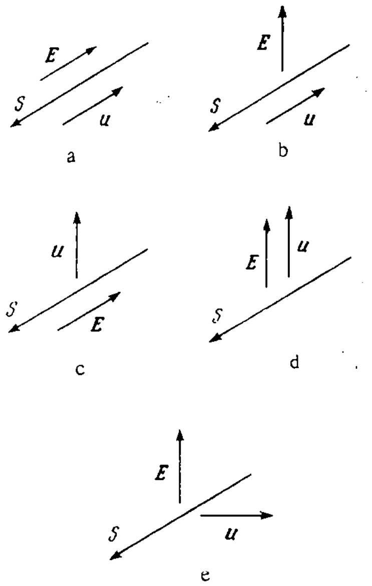

Fig. 1

simple excitation geometry – the use of an extended uniform glow discharge of high power (up to 10 kW) for the pumping with rapid circulation of the working medium through a closed circuit.

The optimum geometry of a circulating discharge chamber must be determined by the mutual orientation of the optical axis S of the resonator, the vector u of the stream velocity, and the vector E of the electric field strength. Five possible variants of the mutual orientation can be distinguished (Fig. 1). From the point of view of obtaining the efficient extraction of the radiation it would be advantageous to locate the optical axis along the major dimension of the discharge chamber. In this case high amplification is obtained in one passage of the electromagnetic wave within the resonator. Such a variant *a* is realized in the traditional laser system with a longitudinal discharge and longitudinal flow [8]. It prevents the achievement of efficient convective cooling. The same drawback pertains to variant b with a transverse discharge and longitudinal pumping [9]. In variant c with transverse pumping and a longitudinal discharge the long discharge is strongly "blown out" along the course of the stream. Stabilization of the discharge can be accomplished by the additional application of an external magnetic field [6]. The configuration d, described in [3], has the drawback that the electrodes are located in the gas stream and retard it. Variant e with mutually orthogonal vectors of stream velocity, electric field strength, and optical axis is free of these drawbacks. In it an essential condition must be satisfied: to provide stability of the transverse discharge over a great length.

Constructions exist in which the discharge chamber consists of a system of a large number of sectioned electrodes uniformly distributed in the plane parallel to the stream [4]. Here the difficulty is connected with the need to create identical conditions of excitation of the active medium in each of the multiple discharge gaps. Even if it is assumed that this condition is satisfied, the "discreteness" of the discharge prevents the attainment of the uniform excitation of the entire circulated mass of gas. We note that the aerodynamics of the stream in such a system are made considerably more complicated and the medium in the resonator is optically heterogeneous. The use of a transverse discharge of a new type having only two long tubular electrodes was proposed in [10]. This simple system is attractive, but there are difficulties connected with maintaining a uniformly hot discharge over a great length and preventing it from pinching into an arc.

The construction of this type of discharge and a laser system using it are described in the present report. Following a study of the role of the phenomena near the electrodes and the hydrodynamics of the discharge in different modes of operation, it was possible to overcome the difficulties connected with the instability of the process and with the possibility of pinching of the discharge (conversion into an arc) and to achieve the stable and efficient operation of the system in a broad range of variation in the composition and density of the medium and the energy characteristics of the discharge.

2. A schematic diagram of a laser instrument with a closed cycle is presented in Fig. 2. Its main points are the ventilator 1, the discharge chamber 2, and cooler 3 enclosed in a hermetic casing, and the resonator 4. Preliminary evacuation is carried out to 0.1 mm Hg. Then the required amount of the gas mixture of nitrogen, helium, and carbon dioxide is introduced into the system from cylinders using calibrated needle valves. A ventilator, set in motion by a motor using a vacuum rotary drive with a "sliding" seal, is used for the gas circulation.

The pumping rate of the gas can be maintained at a level of 30 m/sec with a variation in the pressure of the working medium from 5 to 50 mm Hg. The cooler consists of a branched system of tubes containing running water over which the gas stream emerging from the working chamber flows. The arrangement of the electrodes in the discharge chamber is shown in Fig. 3. The electrodes 100-cm long are made from polished copper tubes 10 mm in diameter and cooled internally by running water. The distance between the anode 1 and the cathode 2 can be varied from 4 to 8 cm. The discharge is supplied from a constant voltage source at 1.5 kV. The voltage drop in the discharge gap is ~1 kV. The gas stream u passes through the discharge in the direction shown by the arrows. The glass deflectors 3, whose position relative to the electrodes is also regulated, are introduced for confinement of the stream and for its more efficient use. Brewster windows made of rock salt are located at the ends of the discharge chamber. There are large trans-

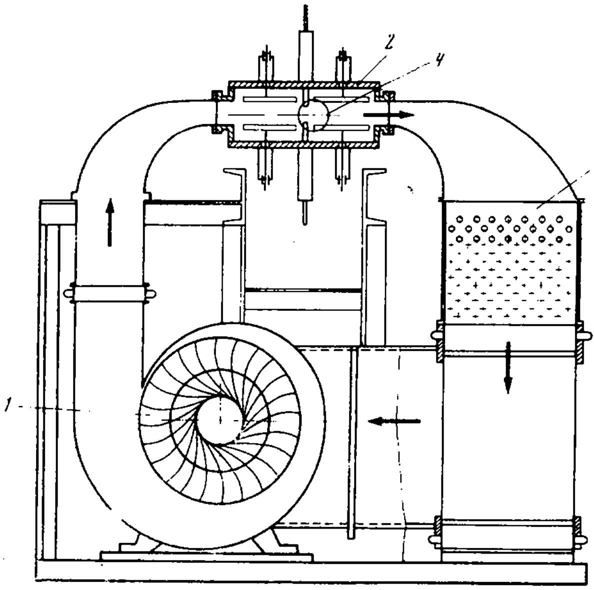

Fig. 2

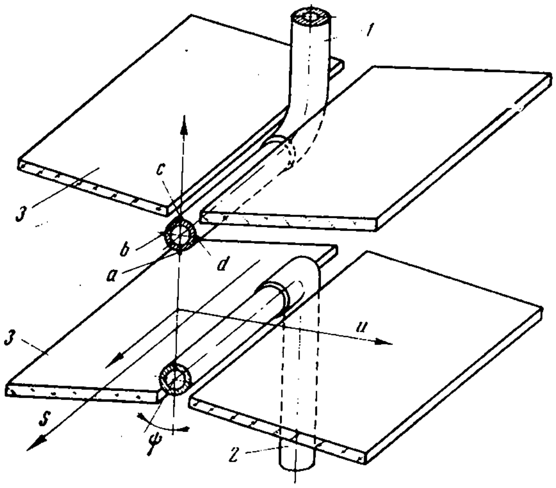

Fig. 3

parent windows on the top, bottom, and side for visual observation of the discharge in the chamber. An electrical probe is mounted in the chamber to determine the stream velocity by the plasma marker method. The laser resonator was not coupled mechanically with the rest of the instrument. A spherical metallic mirror with a radius of curvature of 5 m and a flat exit mirror of germanium were used as the resonator.

3. Let us estimate the conditions for the existence of a stationary discharge in a process with the transverse flow of the medium. The field strength at the axis of symmetry in the space between two long parallel cylinders without allowance for screening of the field by the plasma can be determined approximately from the equation [11]

$$E \approx \frac{U}{\ln(2h/r)} \frac{1}{h},$$

where 2h is the distance between the axes of the electrodes and r is the cylinder radius. For 2h = 7 cm and r = 0.5 cm at U = 800 V we have $E = 7 \cdot 10^3$ V/m. We can estimate the field near the conductors from the equation

$$E = \frac{U}{2r \ln(2h/r)} \approx 2.5 \cdot 10^4 \text{ V/m}.$$

The field strength near the conductors in the absence of a discharge exceeds the strength at the axis of symmetry more than threefold. Let us consider the asymmetry of the field near the conductors. Within the limits of one equipotential

$$\mathbf{E} \approx \frac{U}{2\ln(2h/r)} \frac{h}{r(h + r\cos\psi)} \mathbf{n}$$

where $\mathbf{n}$ is the normal to the surface and ψ is the angle between the normal and the plane of symmetry (Fig. 3). A numerical calculation shows that the field strength at the point *a* is 14% greater than at the middle points b and d, while at the point c it is 14% less.

Let us take into consideration the presence of a gas-discharge plasma between the electrodes and its drift along the stream. In the presence of a discharge, a high field strength exists in the region near the cathode and there is a flux of charged particles (ions) with velocities considerably exceeding the velocity of the gas stream. Because of this the existence of a channel should not have a marked effect on the electrical characteristics of the region near the cathode. The value of the cathode drop in potential and the thickness of the region of the cathode drop are known from [12, 13] for different gases and in the given case they are 400 V and 0.5 cm. With allowance for the cathode drop a more accurate value of the field strength in the interelectrode gap is $\sim 3 \cdot 10^3$ V/m, and in the region near the cathode, $8 \cdot 10^4$ V/m.

The drift length along the stream and the width of the discharge can be estimated from data on the ion mobility and the field strength. The ions, which have less mobility than the electrons, are carried away by the stream. The electrons are carried along by the ions. The discharge cannot exist at that distance from the electrodes at which the drift velocity of the ions toward the electrodes is comparable with the stream velocity. The ions are carried off down the stream from this zone and recombine later with the electrons which are carried along with the ions because of the quasi-neutrality of the plasma. Since the ionization potentials for nitrogen (15.6 eV) and carbon dioxide (13.8 eV) are considerably lower than for helium (24.6 eV), it can be assumed that the amount of helium ions in the discharge is insignificant. This is confirmed by the small (compared with nitrogen and carbon dioxide) effect of the helium concentration on the volt-ampere characteristics of the discharge. The mobilities of CO_2 and N_2 ions at p = 10 mm Hg are 100 and 300 $cm^2/V \cdot sec$. The drift velocity of the ions decreases in proportion to the distance from the plane passing through the centers of the electrodes and at a distance of 5 cm, it is 7 and 20 m/sec for CO_2 and N_2 (the field strength in this region is ~ 7 V/cm).

Since the stream velocity is 30 m/sec, the leading front of the discharge cannot be displaced by more than 4-5 cm relative to the electrodes. The position of the trailing front of the discharge must be determined only by the drift of the discharge along the stream since the voltage near the plane passing through the electrodes (~ 30 V/cm) corresponds to a drift velocity for the ions of ~ 100 m/sec and a drift time for the ions of $\sim 4 \cdot 10^{-4}$ sec. The drift of the trailing front should be several millimeters. The width of the active zone should exceed the width of the discharge, since the vibrationally excited nitrogen continues to carry out the pumping of the upper laser level of CO_2 even after leaving the discharge region. The rate constant of this process is $7.5 \cdot 10^{-15}\ cm^3 \cdot sec^{-1}$ [14]. At a nitrogen partial pressure of 3 mm Hg, the characteristic exchange time is $\tau = 1/KN \approx 10^{-3}$ sec, which at a velocity of 30 m/sec corresponds to an excitation length of ~ 3 cm. This analysis presumes the fact of the stable maintenance of a uniform extended glow discharge over the entire length of the electrodes, which is not a trivial task. A local increase in the current density can lead to pinching of the discharge and an irreversible transition to an arc process. Various processes both at the electrodes and in the gas-discharge plasma can be the causes of this phenomenon.

4. Let us enumerate the measures used to accomplish the stabilization of the uniform extended glow discharge. They are the preliminary polishing of the electrodes, their careful degreasing with organic solvents, the ionic cleaning of oxides from the electrodes directly in the working position using a high-frequency discharge at a frequency of 1.5 MHz and a power of 500 W at a pressure in the chamber of ~ 1 mm Hg, and turbulization of the flow near the electrodes by placing the glass deflectors up against the electrode tubes (Fig. 3). As shown in [15], turbulization of the stream is effective because with its help one can smooth the possible heterogeneities in plasma density in the discharge space.

The breakdown of the interelectrode gap during the start-up must be accomplished using an independent generator of pulses with a duration of $\sim 1\ \mu sec$ at a voltage on the order of 10 kV. In such a process the breakdown takes place uniformly over the entire length of the electrodes, which promotes the uniform ignition of the main discharge. The introduction of an ignition system allows a considerable broadening of the range of stable modes of existence of the main discharge which is not limited to the region of self-break-

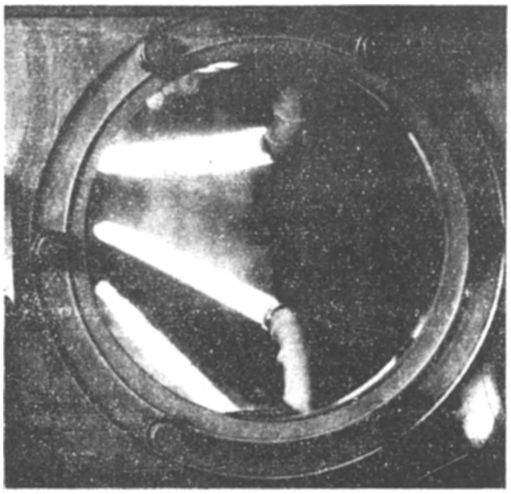

Fig. 4

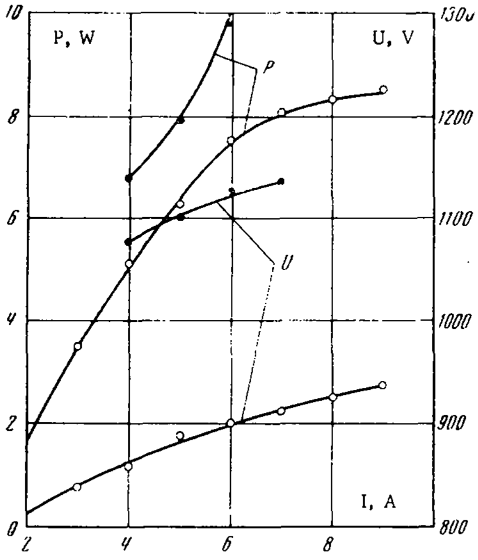

Fig. 5

down voltages. Only when all these conditions are satisfied is it possible to assure the stable operation of the discharge instrument for at least several hours.

The discharge was achieved at pressures of 10-20 mm Hg. The outward appearance of the discharge is unusual (Fig. 4). The cathode layer shines uniformly along the entire length of the electrode. Weak emission is observed along the anode. There is no visible emission in the interelectrode gap at currents of less than 4 A. With a further increase in the current, a luminous anode layer appears which spreads toward the cathode and at a current of ~10 A fills the greater part of the interelectrode space. The electrodes do not have to be strictly parallel to maintain a uniform discharge. It was established experimentally that uniformity of the emission in the cathode region is retained even when one electrode is deflected by several centimeters. The emission of the gap (at low currents) and the anode occur only in the case of poor cleaning of the electrodes. The relatively small distance between the electrodes permits the assumption that the space near the cathode pertains to the Faraday dark space, except for the negative glow near the cathode.

The shape of the discharge "cloud" can be brought out visually by applying a weak (~200 W) high-frequency field to the main discharge. In this case the leading front of the discharge is shifted downstream by 3 cm while the trailing front lags behind the plane passing through the centers of the electrodes by 0.5 cm. It must be mentioned that in the presence of helium in the mixture there is a considerable decrease in the displacements of the leading and trailing fronts. This is explained by the high mobility of the helium

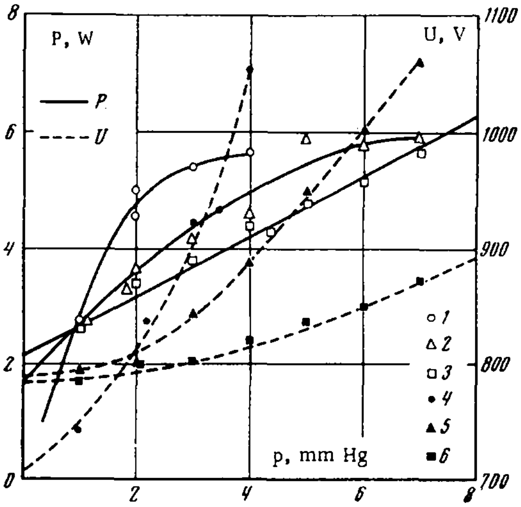

Fig. 6

ions (relative to CO_2 and nitrogen). At moderate currents the cathode section is fully "covered" by the discharge region while the anode is approximately one third "filled." The current in the discharge was varied from 2 to 10 A (Fig. 5). For this, the voltage U on the electrodes was varied slightly (from 810 to 950 V at a pressure of 10 mm Hg) and the outward appearance of the discharge was practically unchanged. The increasing volt–ampere characteristic classified the discharge as an anomalous glow-discharge. The current density and electric field strength in the discharge can be judged from the volt–ampere characteristic. For example, for a current of 8 A the current density at the cathode is 0.025 A/cm^2, at the anode (allowing for the nonuniformity of the glow) it is $\sim$0.075 A/cm^2, and in the gap between the electrodes it is $\sim$0.025 A/cm^2.

5. The purpose of the present study was to clarify the properties of the operating conditions of the discharge, to determine the range of allowable variations in its gasdynamic and electrical parameters, and to estimate the limiting value of the electric power which can be applied to an extended glow-discharge while retaining the stability of its combustion process. It was not intended to determine the limiting output powers of the laser or to estimate its energy efficiency. However, the series of dependences of the output power level on variations in the basic parameters of the operating conditions and the state of the working medium obtained in tests with generation are of interest from the point of view of their use as a diagnostic method – a control on the efficiency of the discharge used in order to obtain the optimum inversion processes.

The dependence of the generation power on the discharge current, the ventilator rotation rate, and on the composition of the gas mixture was studied experimentally. The axis of the resonator was displaced 1.5 cm downstream relative to the axis of symmetry. The voltage drop in the discharge was recorded simultaneously. In order to eliminate errors connected with a possible change in the chemical composition of the original gas mixture, partial injection of gas through the system was carried out in the tests. The composition of the gas was renewed by 0.1% after one cycle.

The generation power was recorded with a standard thermolectric calorimeter. The dependence of the generation power P on the discharge current I is presented in Fig. 5 for the composition of the gas mixture of helium–nitrogen–carbon dioxide corresponding to 5 : 3 : 2 and 7.5 : 4.5 : 3 (in mm Hg). The output power of the beam has a tendency toward saturation with an increase in the current. An increase in the partial pressure p of any of the gas components at a fixed current (Fig. 6) leads to an increase in the generation power. An increase in the content of carbon dioxide (1) has the strongest effect, the effect is less for nitrogen (2), and still less for helium (3). A tendency toward saturation of the generation power is noted with a change in the concentration of one component of the mixture. An increase in the total pressure with a fixed composition of the working gas has a different effect. The level of the output power of generation grows rapidly with an increase in the pressure and the applied electric power.

The dependence of the output power at a current of 4 A on the stream velocity u is presented in Fig. 7. Here there is also a tendency toward saturation. This may be connected with the fact that at a fixed gas composition the generation power must be determined by one of the limiting factors: either the electric power applied to the discharge or the stream velocity. The voltage drop in the discharge region, as seen

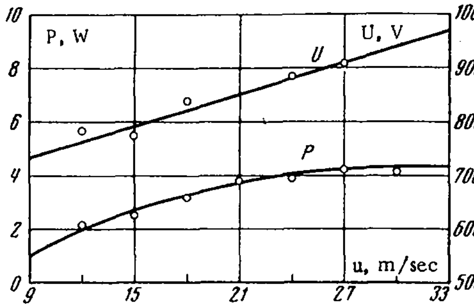

Fig. 7

from Fig. 6, is determined mainly by the concentrations of carbon dioxide (4) and nitrogen (5) and depends little on the helium content (6). The enumerated properties of the generation process clearly correlate with the effect of the analogous factors (composition, total gas pressure, stream velocity, etc.) on the main characteristics of the discharge.

The solution of the main problem of the present study – the stabilization of a powerful extended glow-discharge with transverse gas injection – in a broad range of hydrodynamic and electrical characteristics provides the prerequisites for the use of such instruments in laser systems with high efficiency in the conversion of electrical energy into light.

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