GASDYNAMIC LASER POWER AT HIGH PRESSURE

S. A. Losev and V. N. Makarov

UDC 533.6.0.118

The problem of relaxing mixture flow in a carbon dioxide gasdynamic laser is solved. Infrared radiation-power density generated is calculated for gas pressures at the nozzle input of 25 and 100 atm. An increase in power with increase in initial pressure is observed for suitable selection of mixture composition and initial temperature.

One of the possibilities for improving carbon dioxide gasdynamic laser operation and increasing the power density generated is operation at high initial gas-mixture pressure. Calculations performed in [1] led the authors to the conclusion that the collision reaction places a limit on the possibility of increasing power with increase in gas pressure; the authors of [1] thus stated that increase in initial pressure (above 60 atm under the conditions considered) was not useful. However, such a conclusion is not necessarily applicable in all cases. In fact, simple considerations as to the level of freezing of oscillatory energy upon cooling in a nozzle [2], as well as calculation of generated power by Rigrod's theory [3], show that increased power may be attained by increasing pressure. This conclusion has been confirmed in experiments with gasdynamic lasers [3, 4]. The experiments performed in [4] show that operating a gasdynamic laser at high pressure (to 100 atm and more) can significantly increase power density, with the power increasing with pressure p_0: while in [1] the power per unit resonator volume at $p_0 = 30$ atm was about 3 W/cm^3, in the experiments of [4] values of 3.3 W/cm^3 were recorded at $p_0 = 10$ atm; 11.9 W/cm^3 at $p_0 = 17.5$ atm; and 83.3 W/cm^3 at $p_0 = 115$ atm.

The problem of increasing power lies in the fact that simultaneously with the increase in p_0, the other parameters characterizing gasdynamic laser operations (initial composition, initial temperature, geometry, nozzle length, etc.) must be changed suitably. The present study will present results of power-density calculations for a gasdynamic laser, illustrating such an approach to the problem.

We will consider the problem of flow of a relaxing mixture in a carbon dioxide gasdynamic laser in a formulation similar to that of [1], i.e., assuming unidimensional stationary flow of a gas with invarying chemical composition CO_2+N_2+He through a nozzle and a planoparallel Febry-Perot resonator. As usual [5, 6], we will assume the existence of Boltzmann equilibrium among molecules for one and the same type of oscillation and neglect the effect of unharmonicity. To describe the oscillatory energy exchange kinetics we use the system employed in [7, 8], distinguishing three relaxing mixture components: nitrogen, the third (antisymmetric) type of CO_2 oscillation, and the combined effects of Fermi resonance of the first (symmetric) and second (deformation) types of CO_2 oscillation; the assumptions made in this approach are indicated in [8].

The relaxation equations for oscillatory energy e_i, expressed in terms of mean number of quanta in a given type of oscillation with consideration of degeneration ($e_i = [\exp(\theta_i/T_i) - 1]^{-1}$, where are the characteristic and present temperatures for the i-th type of oscillation) are given in [8]; also shown there are all initial data on the probability of oscillatory energy exchange and the method used for calculating the small signal optical amplification coefficient (which we denote by k_0) for the transition P20(001) → (100)CO_2. These equations may be used to describe the flow of the active medium outside the resonator.

Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 4, pp. 3-7, July-August, 1975. Original article submitted November 28, 1974.

In describing the flow within the resonator, the constant amplification coefficient k_* approximation [9] was used, whereupon

$$k_* = \frac{\ln(1/r_1 r_2)}{2d}, \tag{1}$$

where d is the flow width (distance between resonator mirrors); r_1 and r_2, are the mirror coefficients of reflection. It was assumed that only one frequency participates in generation, corresponding to the center of the line P20(001)→(100)CO_2. The presence of generation leads to the appearance of an additional molecular transition channel between upper and lower laser levels, and a gas energy-loss channel through radiation. Thus in the corresponding equations for oscillation relaxation and conservation of energy additional terms were introduced, as in [1].† The problem of the change in medium state upon entry into the resonator is solved somewhat differently than in [1]. Starting with the known kinetic equation for mean electromagnetic energy density upon excitation of a resonator [10], we assume that the spectral radiation intensity I in the transition zone of establishing the stationary generation regime varies along the flow as

$$\frac{dI}{dx} = \frac{I}{u\tau_c}\left(\frac{k}{k_*} - 1\right), \tag{2}$$

where u is flow velocity; τ_c is the damping time for electromagnetic oscillations in the resonator ($\tau_c = d/c\alpha$; c is the velocity of light; α is the resonator loss coefficient) k and $k*$ are present and stationary values of resonator amplification coefficient. At the resonator input $I=I_0$ (I_0 is the spontaneous radiation intensity), $k=k_0$; for $k_0 < k_*$ generation is absent. Equation (2) closes the system of equations describing the flow upon entrance into the resonator, where $k \to k_*$; for $k=k*$ this equation is replaced by Eq. (1). Thus, continuous change of all parameters characterizing the state of the medium in the gasdynamic laser is ensured.

For the sake of simplicity we will assume that all losses and radiation output are connected with only one mirror, i.e., $r_1=r$, $r_2=1$. Then, considering the direction of radiation propagation, we obtained for the power extracted from the resonator

$$P = \frac{ht}{1+r}\int_0^l I\,dl,$$

where h is the height of the resonator mirror);l is the resonator length along the flow; t is the mirror transmission coefficient. A more meaningful quantity is the power generated per unit area of nozzle critical section P^* (W/cm^2); this value is the final goal of the calculation.

Simultaneous solution of the gasdynamic equation system and the relaxation equations for oscillatory energy with consideration of Eq. (2) upon entry to the resonator and Eq. (1) for description of the flow within the resonator was performed numerically with the aid of an implicit method. The results obtained are illustrated in Fig. 1, where the left side refers to gas flow in the nozzle before entrance into the resonator, and the right side, to flow within the resonator. Shown are the distributions of translation temperature T and oscillatory temperature T_i along the nozzle and resonator (indices 1, 2, first and second type CO_2 oscillation; 4, nitrogen), optical amplification coefficients k_0 and $k*$ in percent per cm, generation intensity I (in relative units), and power density $P*$ (calculated per unit nozzle critical section area). The flow width is 50 cm, the mirror transmission coefficient t=0.11, and the loss coefficient α=0.01. Solid lines characterize conditions for initial pressure P_0=100 atm, temperature T_0 = 3680°K for a mixture 5.3% CO_2 + 69.3% N_2 + 25.4% He; dashes are for initial pressure P_0 = 25 atm, temperature T_0 = 3310°K and composition 8.1% CO_2 + 57.9% N_2 + 34% He. The supersonic nozzle-section profile (height ratio h/h_*; h_* is

---

† The corresponding expression in [1] erroneously shows a plus sign before the term considering energy output through radiation, which leads to contradiction of the law of conservation of energy. The resultant error is evidently small, since the contribution of radiation to total flow enthalpy is insignificant.

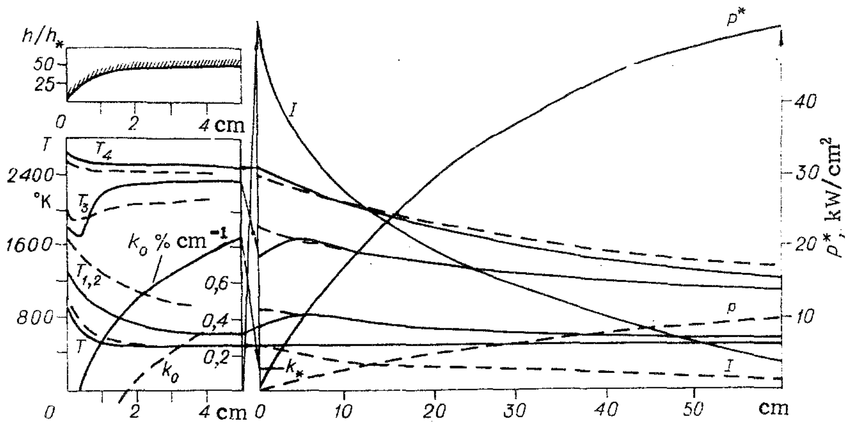

Fig. 1

the critical height) is shown in the upper left of Fig. 1 (for p_0 = 100 atm). The indicated values of temperature T_0, mixture composition, and nozzle profile and length were obtained by solving the optimization problem by a configuration method in analogy to previous calculations for optimizing the optical amplification coefficient [8]. We note that the ratio h/h* at the nozzle output comprises 50 at p_0 = 100 atm and 33.3 at p_0 = 25 atm. The length of the resonator portion was taken large enough (60 cm) to ensure removal of practically all oscillatory energy exceeding the generation threshold. In fact, it is evident from the graphs that the difference between T_3 and $T_{1,2}$ becomes quite small toward the resonator output, while the intensity I tends to zero. The power density P* extracted from the resonator increases with resonator elongation, but toward the output of the generator this growth is retarded. We note that the gas temperature T and other gasdynamic characteristics are practically continuous upon entry to the resonator and vary insignificantly over the length of the resonator.

The results presented here indicate that it is possible to select conditions (initial parameters, gas composition, nozzle geometry) under which power generation will rise with increase in pressure up to high values. A major role is played by the choice of initial mixture composition, nozzle form, and temperature. Comparison shows that the results of our calculations as to power generated per unit resonator volume agree within a factor of two with the measurements of [4]; in light of certain differences in initial conditions and nozzle and resonator configuration such agreement should be considered satisfactory. This not only supports the validity of the calculations performed, but indicates that the experimental conditions of [4] were close to optimal.

Thus, a directed search for optimal operation conditions can lead to a significant increase in power density at high initial gas mixture pressures in the gasdynamic laser. The role of collision-type deactivation of upper laser level oscillations proves to be less significant than would follow from the conclusions of [1]. It is important that the entire set of parameters be optimized simultaneously, not just any single parameter. For example, from the results of [11] for fixed nozzle geometry (critical section height, initial aperture angle, etc.; see Fig.3 in [11]) the power density, optimized solely for resonator output mirror transparency, will fall with increase in initial pressure.

In the present case, further power increase with pressure may be limited only by dissociation of the carbon dioxide, not considered here, which occurs at the temperatures considered.

LITERATURE CITED

1. I. A. Generalov, G. I. Kozlov, and I. K. Selezneva, "Calculation of gasdynamic laser characteristics," Zh. Prikl. Mekh. Tekh. Fiz., No. 5 (1972).
2. W. H. Christiansen and G. A. Tsongas, "Gain kinetics of CO_2 gasdynamic laser mixture at high pressure," Phys. Fluids, 14, No. 12 (1971).
3. G. Lee, F. E. Gowen, and J. R. Hagen, "Gain and power of CO_2 gasdynamic lasers," AIAA J., 10, No. 1 (1972).
4. D. M. Kuehn, "Importance of nozzle geometry to high pressure gasdynamic lasers," Appl. Phys. Lett., 21, No. 3 (1972).

5. N. G. Basov, V. G. Mikhailov, A. N. Oraevskii, and V. A. Shcheglov, "Obtaining population inversion of molecules in a supersonic flow of a binary gas in Laval nozzles," Zh. Tekh. Fiz., 38, No. 12 (1970).
6. J. D. Anderson, "Time-dependent analysis of population inversions in an expanding gas," Phys. Fluids, 13, No. 8 (1970).
7. S. A. Losev, V. N. Makarov, V. A. Pavlov, and O. P. Shatalov, "Gasdynamic laser processes in a large diameter shock tube," Fiz. Goreniya Vzryva, No. 4 (1973).
8. S. A. Losev and V. N. Makarov, "Amplification-coefficient optimization in a carbon dioxide gasdynamic laser," Kvant. Élektron., 1, No. 7 (1974).
9. T. A. Cool, "Power and gain characteristics of high-speed flow lasers," J. Appl. Phys., 40, No. 9 (1969).
10. R. Pantell and H. G. Puthoff, Fundamentals of Quantum Electronics, Wiley (1969).
11. A. P. Napartovich and V. F. Sharkov, "Calculation of CO_2 gasdynamic laser power," Teplofiz. Vys. Temp., 12, No. 3 (1974).