SOME CHARACTERISTICS OF MIXING AND RELAXATION IN CO_2 GAS-DYNAMIC LASER WITH SELECTIVE EXCITATION

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It is demonstrated by numerical simulation using the simplified Navier–Stokes equations that the geometric arrangement of the nozzle apparatus affects the energy characteristics of a gas-dynamic laser with parallel supersonic mixing of the components.

The high energy efficiency of CO_2 gas-dynamic lasers with selective excitation (CO_2-GDLSE) and supersonic mixing of the components has been confirmed in a series of theoretical and experimental studies [1-6].

In addition, as pointed out in [3], the achievement of high energy characteristics must be combined with high optical quality of the laser medium. For CO_2-GDLSE it is linked, in particular, with the presence of nonuniformities of the density and gas composition, owing to the imperfection of the mixing process, in the flow.

The natural method for accelerating this process, associated with a reduction of the mixing scale, i.e., the distance between the axes of the jets of the radiating and exciting gases, is limited by the increase in the effect of viscosity when the dimensions of the nozzles feeding the components are reduced. Increasing the initial difference in the velocities of the flows intensifies not only the mixing, but also the relaxation processes, owing to the restoration of the temperature and pressure in the mixing zone. For this reason, changing the relative size of the jets of the radiating and exciting gases is in practice the only available method for affecting the formation of the mixing zone [5].

In what follows we shall study mixing in an infinite system of flat supersonic jets of nitrogen (of width 2B) and of the mixture $CO_2:H_2O = 11.5:1$ (2A). The distance between the axes of the jets and the ratio of their flow rates were the same for all variants ($A + B = 3.5 \cdot 10^{-3}$ m, $G_A/G_B = 0.1$). The initial temperatures of the flows ($T_A = 390$, $T_B = 300$, $T_V = 2000$ K) and the velocity of the jets ($u_A = 1160$, $u_B = 2050$ m/sec) were also the same for all variants, except for those specially mentioned in the text; the Mach numbers of the flows equalled $M_A = 3.6$ and $M_B = 5.8$. The remaining parameters of the mixing jets are presented in Table 1. The total flow rate of the gas per unit area of the nozzle apparatus ρu varied from 25 to 100 $kg \cdot sec^{-1} \cdot m^{-2}$, which corresponded to a variation of the pressure level in the supersonic channel in the range 1400...6000 Pa.

The mixing was calculated based on the system of simplified Navier-Stokes equations for turbulent flows [7]. For purely supersonic flows this system is X-parabolic. It was solved using a conservative implicit marching scheme with scalar factorizations [7]. The effective coefficient of turbulent viscosity was determined based on the semiempirical theory of N. I. Akatnov [8]. The details of the formulation of the problem are given in [9, 10]. Reynolds number, calculated from the parameters of the CO_2 jet, varied in the range 400...4000. According to the estimates of [11], for the indicated conditions the length of the section of laminar mixing is an insignificant part of the entire region studied, which justifies the assumption that the mixing is of a turbulent character. For variants with the minimum flow rate of gas and small values of B/A the boundary layer at the walls of the nozzles feeding the CO_2 has a definite effect, but this factor was not included in the calculations. To avoid instabilities, for large values of the mismatch $P_B/P_A > 10$, a first-order difference scheme in Y was used in the calculations [12]. To obtain reliable data it is sufficient to use a grid with 21 points along Y. For $P_B/P_A = 8.7$ calculations with 41 points along Y were performed, and they did not significantly increase the accuracy.

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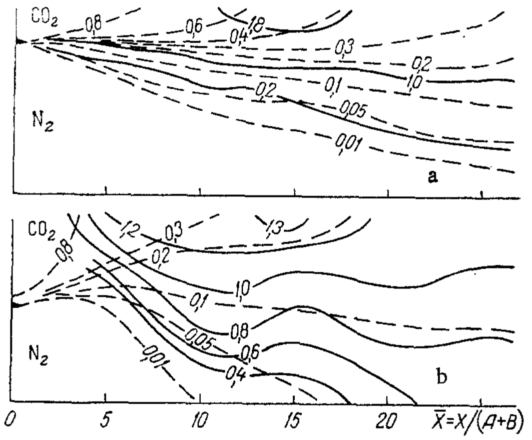

Fig. 1. Distribution of the gain (solid curves), 1/m, and CO_2 concentration (broken curves) in the mixing zone: b) variant II of Table 1, P_B = 2060 and P_A = 430 Pa; a) variant IV of Table 1, P_B = 1287 and P_A = 947 Pa, ρu = 25.

TABLE 1. Values of the Relative Size of the Nozzles and Initial Mismatch of the Jets of the Exciting and Radiating Gases

Parameter	Variant			
	I	II	III	IV
B/A	0,5	1,0	2,0	3,2
P_B/P_A	8,7	4,8	2,2	1,4

The calculations yielded the distributions of the parameters in the supersonic channel of the laser (Fig. 1). The completion of the mixing process was determined in each variant by the coordinate L at which the nonuniformity of the density profile $((\rho_{max} - \rho_{min})/\rho_{max})$ in the the transverse section of the flow did not exceed 1%. It is assumed that for $X \geqq L$ coherent radiation from a driving oscillator with an intensity $2 \cdot 10^8$ W/m² is injected perpendicularly to the flow. We note that when this intensity is high enough the maximum specific energy extracted E, determined in this manner in the calculation, in the amplification regime is the upper limit for E in the lasing regime.

The main result of the analysis of the results obtained is that the relative initial size of these jets strongly affects the rate of mixing of the jets of the exciting and radiating gases with parameters characteristic for CO_2-GDLSE (Fig. 2). As the ratio B/A varies from 0.5 to 3.2, under the conditions studied, the mixing length increases by more than a factor of 2.5. Under real conditions the mismatches in the pressure in the initial mixing section, characteristic for variant I in Table 1, can cause the disturbance to move upstream and the jet of radiating gas to separate from the walls of the nozzle, which cannot be taken into account on the basis of the model adopted. The most significant change in the mixing length occurs, however, precisely for variants with moderate mismatch, in which nondetached flow is most likely. It should be noted that a significant reduction in the mixing length is also observed in the experiments with a system of bounded, comoving, subsonic jets as compared with single jets [13].

A strong change in L affects the energy extraction of the CO_2-GDLSE, which, in this case, can vary by a factor of 1.5-2.5 (Fig. 3). The differences in the energy extracted are primarily associated with the losses of vibrational energy in the mixing process. For low pressures these losses are small, and an increase in the mixing length with increasing ratio B/A leads to an insignificant reduction in the energy extracted. As the pressure is raised, the increase in the mixing length leads to significant losses of vibrational energy and, as a consequence, to a drop in E.

For the calculations (curves 1-4, Fig. 3) moderate temperatures in the supersonic channel are characteristic. A calculation in which the initial velocity of the nitrogen and correspondingly the vibrational temperature (u_B = 2345 m/sec, T_V = 2645 K) increased, total flow rate of the gas remaining constant, corresponding to the regime 3 (Fig. 3), was also per-

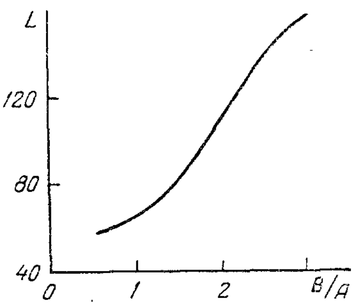

Fig. 1

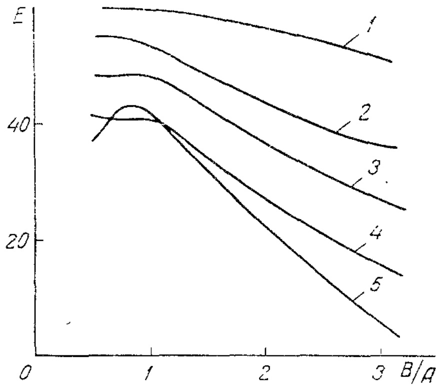

Fig. 2

Fig. 2. Mixing length of the jets versus their relative geometric size; L = x/(A + B).

Fig. 3. Energy extracted, J/g, of CO_2-GDLSE versus the relative geometric size of the N_2 and (CO_2:H_2O) jets and the total flow rate of the gas mixture, $kg \cdot sec^{-1} \cdot m^{-2}$: 1) ρu = 25, 2) 50, 3 and 5) 75, 4) 100.

formed. In this case, significant restoration of the static temperature and acceleration of relaxation processes is observed. The fact that the mixing length depends on the relative size of the jets becomes even more important here, since it can cause an almost order of magnitude drop in the energy reduction as the ratio B/A increases from 1 to 2. It is interesting that this drop occurs when the mismatch of the jets decreases, i.e., when the losses of stored vibrational energy are reduced owing to the appearance of shock waves. The additional increase in the associated relaxation losses in the flow owing to the increase in the static temperature is, naturally, larger in the regime with a high static temperature in the mixing zone (curve 5 in Fig. 3). In the other cases the shock waves, formed owing to the difference in the pressures in neighboring jets, also have a negative, but smaller, effect.

The curves shown in Fig. 3 illustrate the different character of the effect of the flux density in the resonator zone on the energy extracted from the GCL. Thus for low densities, and correspondingly low pressures, in the supersonic channel (P ~ 1400 Pa, curve 1, Fig. 3) the values of the specific energy extracted for different ratios B/A are quite close to one another, whereas in forced regimes of laser operation (ρu increased by a factor of 4) the energy extracted decreases by a factor of 2.5 as B/A increases from 1 to 2.

The strong effect of mixing zone geometry on the energy efficiency of CO_2-GDLSE was also observed in the calculations based on the quasi-one-dimensional phenomenological model [5]. However, this was attributed entirely to the relaxational losses of the vibrational energy stored in the CO_2 for different types of mixing, depending on the ratio B/A for the same overall mixing length of the components.

The difference in the extracted energy, depending on the geometric arrangement of the nozzles, is a consequence of the fact that the radiation extraction begins after the mixing process is completed. When radiation is extracted from the mixing zone the dependence of E on B/A presented above changes, but the effect of the difference in the mixing processes is manifested even in this case. It is evident here (Fig. 4) that it is linked primarily with the unequal rate at which the maximum energy extraction is achieved, depending on the length of the lasing zone downstream.

To evaluate correctly the results obtained it is important to clarify which parameters of the mixing jets have a determining effect on the value of L. Because of the complexity of the process it is difficult to answer this question unambiguously. Under the conditions of the numerical experiment performed, only two parameters were varied simultaneously — the ratio of the geometric dimensions of the jets and their mismatch. In this case, under otherwise equal conditions, the mixing length L changed substantially.

Judging from the CO_2 concentration field beyond the cutoff of the nozzle (see Fig. 1) the flow pattern changes appreciably as B/A varies from 1 to 3.2. For a small relative size of the jet (CO_2:H_2O), low molar fraction of the radiating gas in the final composition, and relatively close initial pressures of the components, the flow pattern corresponds most

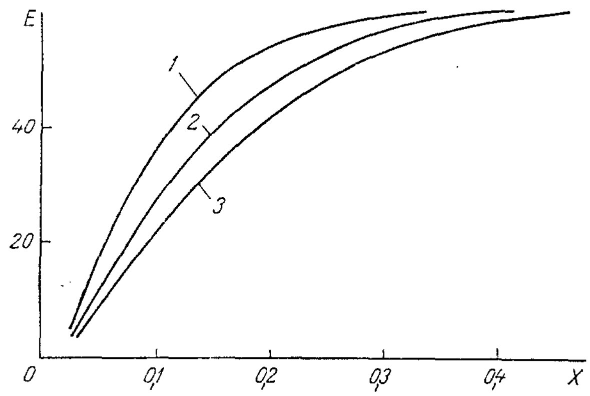

Fig. 4. Energy extracted from a CO_2-GDLSE versus the length of the lasing zone downstream, beginning at the cutoff of the nozzles of the block, m, and the relative geometric size of the jets: 1) B/A = 1; 2) 2; 3) 3.2; ρu = 100.

closely to the case of smoothing of a turbulent jet in an unbounded comoving flow [14], when the increase of the mixing zone is linear, while the CO_2 concentration profile is smoothed over a distance on the order of 100-200 mixing scales (A + B). Increasing the relative size of the jets of radiating gas already leads to a situation characteristic for substantially bounded jets with more rapid smoothing of the CO_2 concentration profile in the flow, which is what reduces correspondingly the value of L.

The mismatch also apparently causes the mixing to be intensified, owing to an increase in the local ratio of the velocities in the jets of the exciting and radiating gases in the pressure equalization process.

The results presented are quite important for understanding the process of formation of a laser medium in CO_2-GDLSE, if it is assumed that the qualitative nature of this process does not change with the transition from the two- or three-dimensional mixing characteristic for real nozzle systems.

For example, in the nozzle array of [3] the dimensions of the jets of the radiating and exciting gases are approximately equal to one another, and it is this that makes it possible, as is evident from Fig. 3, to preserve the high energy efficiency of the laser when the components are injected under high pressure. In addition, the structural layout of the nozzle array consisting of axisymmetric nozzles is so successful that even the use of small output cross sections in the nozzles for the radiating gas (acoustic blow-in [15]) or small degrees of expansion [16] can lead to good results with an increase of the pressure, owing to the rapid equalization of the dimensions of the jets beyond the cutoff of the nozzle array in the presence of significant bottom regions.

High mixing efficiency was also achieved in the experiments of [2] with an increase in the relative size of the jets of radiating gas.

Thus one of the basic problems of the supersonic channel of GO_2-GDLSE — providing minimal losses of vibrational energy accompanying mixing of the components — can be solved by choosing an optimal initial geometry of the mixing jets.

NOTATION

Here P is the pressure; ρ is the density; v is the velocity; G is the flow rate of the gas; L is the mixing length; E is the maximum energy extraction in the amplifying regime; T_V is the vibrational temperature of nitrogen; A and B are the heights of the CO_2 and N_2 jets, respectively. Indices: A is the flux of the radiating gas and B is the flux of the exciting gas.

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KINETIC COEFFICIENTS FOR ELECTRONS IN AIR IN AN HF ELECTRIC FIELD

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The characteristics of a low-temperature air plasma created by an hf electric field are calculated.

The form of the electron distribution over energy and values of the related electron kinetic coefficients in air in an hf field are of interest in connection with studies of air breakdown by an hf field, interaction of hf radiation with the ionosphere, etc. [1-3]. The present study will calculate kinetic constants in dry air (i.e., a mixture $N_2:O_2 = 8:2$) for the case where the frequency of field variation ω is significantly higher than the transport frequency of electron interaction with molecules ν. The calculation was performed for a wide range of the parameter E/ω, where E is the intensity of the electric field. The effect of oscillatory excitation of oxygen and nitrogen molecules on the results obtained was studied.

The Boltzmann equation was solved numerically for the zeroth harmonic of the electron energy distribution function f(u), which for the case $\omega \gg \nu$ can be written in the form

$$\left(\sum_j y_j k_{ij} - 0{,}2k_{\text{ad}}\right) f u^{1/2} \left(\frac{2e}{m}\right)^{-1/2} - \frac{1}{3}\frac{2e}{m}\left(\frac{E}{\omega}\right)^2 \times \\ \times \frac{\partial}{\partial u}\left(u^2 \frac{\partial f}{\partial u} \sum_j y_j Q_{i\text{t}}\right) - \frac{\partial}{\partial u}\left[u^2\left(f + \frac{kT}{e}\frac{\partial f}{\partial u}\right)\sum_j y_j Q_{j\text{t}}\right] = St_1 f + St_2 f. \quad (1)$$

The electron energy u is expressed in eV. The collision integral St_1f describes inelastic collisions which do not lead to a change in the number of electrons (excitation of rotational, oscillatory, and electron levels, collisions of the second type), while St_2f describes processes leading to change in the number of electrons (ionization and dissociative adhesion of electrons to an oxygen molecule):

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