NUMERICAL INVESTIGATION OF VIBRATIONAL RELAXATION DURING TURBULENT MIXING OF JETS IN A SUPERSONIC NOZZLE

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The results of a calculated investigation of the influence of different operating parameters on the characteristics of a CO_2 gasdynamic laser with selective thermal excitation are presented.

The calculation of the mixing of supersonic jets with allowance for vibrational relaxation is of great interest in connection with the development of the technology of hypersonic wind tunnels [1], with the investigation of spontaneous emission in jet engine streams [2], and in connection with the creation of gasdynamic lasers (GDL) with selective thermal excitation [3-18]. Experimental research conducted in recent years [3-11] points to the possibility of achieving higher values of the amplification factor and specific power output in lasers with mixing than occur for GDL with premixing. Along with the further development of experimental work, a very urgent task is the creation of an adequate numerical model of a laser and carrying out both parametric investigations and an analysis of the influence of separate factors on GDL operation on its basis. At present, however, extensive theoretical study of a mixing CO_2 GDL has been made only on the basis of the model of instantaneous mixing [12-14]. Of course, calculations using this model will agree well with experimental data in the case when the mixing takes place in a nozzle grid [6] or the mixing unit proposed in [5] is used. But if CO_2 + He is mixed through a central body [4, 11], with the injection itself taking place from a plane profiled nozzle [11] or from round openings in the central body (and the distance between openings is approximately equal to their diameter), then effects of two-dimensional mixing will play an important role and neglecting them can lead to considerable overstatement of the laser characteristics. Moreover, in designing an optical resonator one must have data on the profiles of density and amplification factor.

In the literature there are presently examples of the calculation of jet mixing in CO_2 GDL with selective thermal excitation both on the basis of a system of boundary-layer equations (narrow channel) [15-17] and using a system of simplified Navier–Stokes equations [11, 18]. In [17], in particular, the solution is obtained using a semiempirical theory of turbulence based on an equation of balance of pulsation energy with a universal set of numerical coefficients, which was successfully applied earlier to the analysis of free shear flows [19, 20]. The satisfactory agreement of the calculated results of [17] with experimental data [4] on the distribution of the amplification factor g for a weak signal, the CO_2 concentration γ, and the generation power provides a basis for using the proposed method for a numerical parametric investigation of a CO_2 GDL with selective thermal excitation.

Comparison with Experimental Results

Extensive data are presented in [10] on the influence of the pressure and temperature in the chamber of a gas generator, obtained using a nozzle with a central body similar in construction to that of [4]. In making the corresponding calculations it was assumed that the half-height of the jet for CO_2 input is A_{01} = 0.2 mm, the height of the hot nitrogen jet is $(A_{0E} - A_{01})$ = 0.8 mm, the ratio of the exit cross section to the critical cross section is A_E/A_{0E} = 15.7, the length of the supersonic part of the nozzle is x_s = 60 mm, and the nozzle profile was borrowed from [21], in which the results of calculations of nozzles of minimum length having a corner point are given (a profile for a Mach number M = 4.5 and a ratio of specific heats $c_p : c_V$ = 1.4 were used). At the start of the calculation region the Mach numbers were taken as $M_{01} = M_{0E}$ = 1.2, the composition of the mixture of the secondary jet was CO_2 : He = 1 : 4 (by volume), the initial temperature was 300°K, and the values of the remaining parameters are given in Table 1. The length of the resonator along the stream was taken as x_r = 24 cm, the distance between the mirrors was L = 17 cm, the coefficients of absorption of the mirrors were

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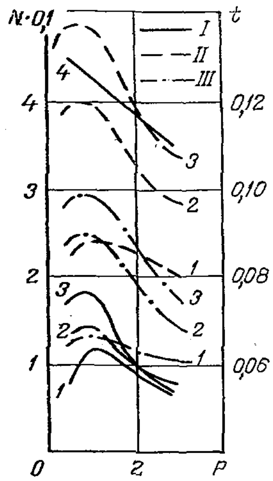

Fig. 1. Specific power output and optimum coefficient of transmission of exit mirror as functions of stagnation pressure: I) expt. [10]; II) calc., α = 0.02; III) $(\alpha + \delta L)$ = 0.05; stagnation temperatures of nitrogen: 1) T_0 = 2000; 2) 2500; 3) 3000°K; 4) t (T_0 = 2500°K), N, J/g; P, MPa.

TABLE 1. Initial Parameters of Jets

Parameter	γ (CO)							T_0, °K(N_2)			
	0,05	0,1	0,15	0,2	0,25	0,3	0,4	2000	2500	3000	3500
T, °K	207	213	218	223	227	231	237	1552	1940	2328	2720
V, m/sec	823	710	634	575	533	495	441	964	1078	1180	1280

$\alpha_1 = \alpha_2$ = 0.02, the coefficient of transmission t_1 equalled zero, and t_2 was determined in the course of optimization.

The results of a comparison of experimental data with the calculations are presented in Fig. 1. The somewhat higher value of the specific power output obtained in the calculation can be explained by the fact that, first, losses of vibrational energy during flow in the subcritical part of the nozzle were ignored, and second, the actual losses in the resonator (see [22]) were not taken into account. With an increase in the total coefficient of losses per pass $(\alpha + \delta L)$ to 0.05, for example, the calculated curves agree considerably better with the experimental data. The results of the calculated optimization of the coefficient of transmission of the semitransparent mirror, which indicate the need to choose t_2 in the course of multifactor optimization, are also presented in Fig. 1. It is important to note that the values of t_2 obtained in the calculation lie within the limits of the transmissions of mirrors used in the experiment of [10].

Results of Numerical Parametric Investigation

The calculations were made using a nozzle profile borrowed from [4], Mach numbers $M_{01} = M_{0E}$ = 1.2, a static pressure at the start of the calculated region $P_1 = P_E$ = 0.204–1.632 MPa, which corresponds to a pressure of 0.5–4 MPa in the chamber of the gas generator, the temperature and velocity of the streams are given in Table 1, and the values of the remaining parameters are given in [17]. To reduce the number of parameters being varied in this section, the calculations were made with the condition of operation of the laser in the amplification mode, i.e., without allowance for losses at the mirrors. The intensity of the field of the master generator was 10 kW/cm^2 and the length of the resonator along the stream was 8 and 40 cm.

In Fig. 2 we present the results of a calculation of the specific power output and the average value of the amplification factor $g = \int_0^{A_E} g(y)\,dy / A_E$ at the nozzle cut for different values of the operating parameters. We note that for certain sufficiently high values of γ the amplification factor falls to zero at x_r < 40 cm. As seen from the figure, the optimum composition of the secondary jet essentially depends both on the pressure and on the temperature, with an increase in P and T resulting in a decrease in the optimum value of γ. It is important to

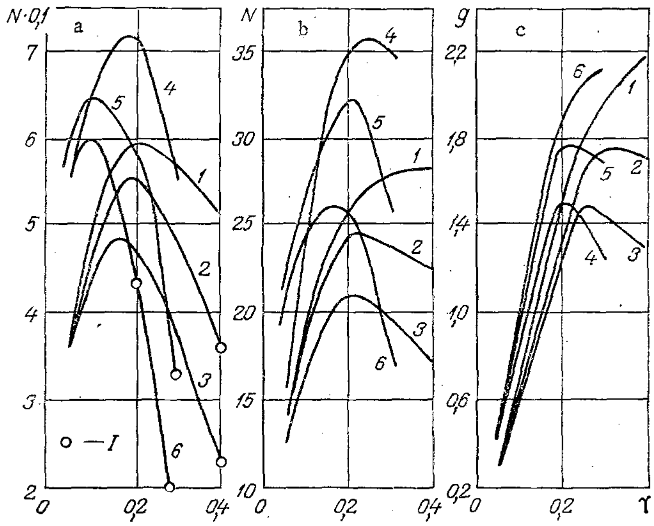

Fig. 2. Specific power output (a, b) and average amplification factor for a weak signal (c) at the nozzle cut as functions of CO_2 content in the secondary stream [a) x_r = 40; b) 8 cm]: 1-3) T_0 = 2500; 4-6) 3000°K; 1, 4) P_0 = 1; 2, 5) 2; 3, 6) 3 MPa; I) amplification factor $g < 0$ at x_r < cm; g, m^{-1}.

note that in the operation of a laser with the operating parameters P_0 = 3 MPa and T_0 = 3000°K a mixture of CO_2:He = 1:9 is optimum from the point of view of obtaining the maximum power output, while a transition to a 1:4 mixture, used most often in experiment, decreases the power output by 25%. It is interesting that for both short and long resonators the decrease in N with an increase in γ at $\gamma > \gamma_{opt}$ is weaker at T_0 = 2500°K. This happens because the gas temperature in the resonator decreases in the given case, i.e., greater relaxation losses, which grow with an increase in the CO_2 concentration, are possible. The results presented in Fig. 2 indicate that for all values of the operating parameters, the value of γ needed to achieve the maximum g is considerably higher than needed to obtain the maximum specific power output. As is known, this fact has already been noted repeatedly in the literature (see [23], for example) in application to GDL with premixing. The results obtained indicate that the specific power output is about half as great for a short resonator as for a long one. Evidently, an increase in the field intensity (due to an increase in the distance between mirrors) does not lead to a significant increase in N for x_r = 8 cm, since along with the limiting influence of the rate of transfer of vibrational energy from N_2 to $\nu_3 CO_2$ for the calculated mixing unit it is important that the mixing continues in the resonator.

These results do not permit an estimate of the influence of different factors on the specific power output, and therefore in Fig. 3 we present data on the efficiencies of the nozzle (η_n) and the resonator (η_r), the mixing efficiency $\beta = c_{N_2}(y = 0) : c_{N_2}(y = A_E)$, and the average value of the amplification factor at the gas exit from the resonator. As seen from the figure, η_n decreases with an increase in the CO_2 concentration and exceeds the value of η_n = 0.65 in all cases. For a GDL with mixing, however, this quantity does not characterize the nozzle efficiency so fully, since closeness of η_n to unity indicates poor mixing of N_2 and CO_2 + He. Therefore, the values of the mixing efficiency at the nozzle cut and at the end of the resonator are also given in Fig. 3a. It is seen that β increases with an increase in the CO_2 concentration. This is explained by the fact that at a fixed value of M_{01} an increase in γ leads to a decrease in the velocity of the secondary stream (see Table 1), and hence the difference in the velocities of the N_2 and CO_2 + He streams increases and the effective coefficient of turbulent viscosity increases accordingly. The presence of inflection points on the curves is evidently explained by the complexity of the process of turbulent mixing in the presence of a strong negative pressure gradient. The mixing efficiency does not exceed 60%, which points to the need for further improvement of the nozzle units being used. An increase in pressure leads to a slight decrease in β, while an increase in nitrogen temperature causes a certain increase in it, which is connected with the increase in the velocity V_{0E} (see Table 1).

Data on the resonator efficiency are presented in Fig. 3b and c. The efficiency of a resonator with x_r = 8 cm does not exceed η_r = 0.35. With x_r = 40 cm the efficiency reaches 65% for the mode of flow with the parameters T_0 = 2500°K, P_0 = 1 MPa, and γ = 0.25. As seen from a comparison of Figs. 2a, and 3b and c, with x_r = 40 cm one observes similarity in the dependences of N and η_r on γ. Such similarity is not observed with x_r = 8 cm, however. With x_r = 8 cm, P_0 = 2 MPa, and T_0 = 2500°K, for example, N reaches the maximum value at $\gamma \approx$ 0.2, whereas η_r continues to increase at higher values.

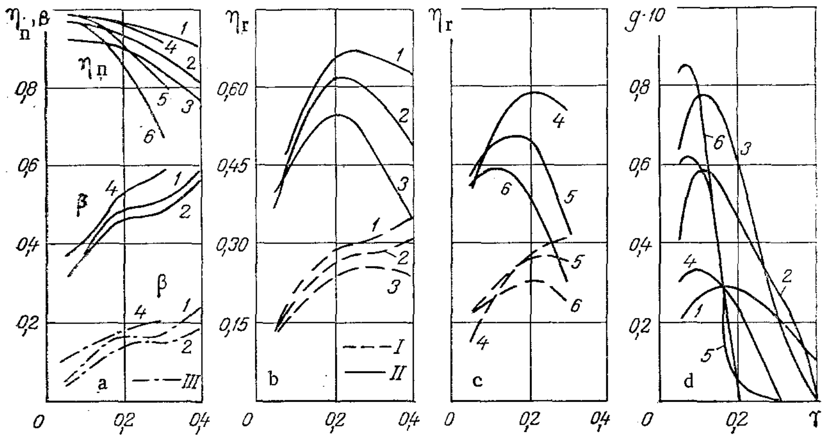

Fig. 3. Nozzle efficiency, mixing efficiency (a), resonator efficiency (b, c), and amplification factor for a weak signal at the gas exit from the resonator (d) as functions of CO_2 content in the secondary stream: I) $x_r = 8$; II) 40 cm; III) mixing efficiency β at nozzle cut. 1-6) Same as in Fig. 2.

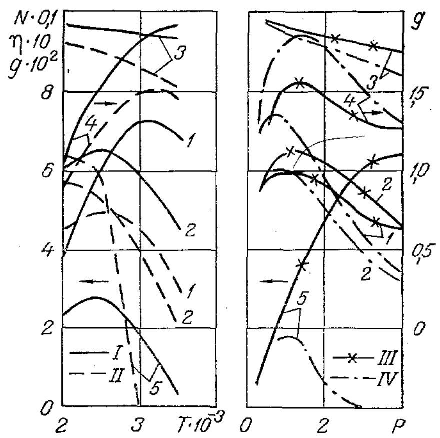

Fig. 4. Influence of stagnation temperature and pressure on GDL characteristics: I) $P_0 = 1$; II) 3 MPa; III) $T_0 = 2500$; IV) 3000°K; 1) N, J/g; 2) η_r; 3) η_n; 4) amplification factor at nozzle cut; 5) amplification factor at exit from resonator.

The resonator efficiency can also be estimated from the amplification factor at the gas exit from the resonator, and so the corresponding calculated data are presented in Fig. 3d. It is seen from the figure that for modes with the maximum power output, its further increase is possible either through an increase in the resonator length or through an increase in the field intensity.

The results of an investigation of the influence of the initial nitrogen temperature on the GDL characteristics are presented in Fig. 4. It is important to emphasize that at $P_0 = 3$ MPa the power output at $T_0 = 3500$°K is almost half as much as at the optimum temperature of 2500°K, whereas the amplification factor at the nozzle cut at the maximum temperature decreases insignificantly compared with its maximum value. An analysis of the nozzle and resonator efficiencies as functions of T_0 shows that the decrease in N is due mainly to the decrease in η_r owing to the increase in the gas temperature in the resonator.

An investigation of the dependence of the specific power output on the stagnation pressure is of great interest, since an increase in P_0 simplifies the problem of restoring the pressure in the stream to atmospheric (see [11], for example). The results of the corresponding calculations are presented in Fig. 4. As seen from the figure, for $T_0 = 2500$ and 3000°K the maximum power output is reached at pressures of 1 and 0.5 MPa, respectively. The fact that at $P_0 > 2.2$ MPa the power output is higher for $T_0 = 2500$°K than for 3000°K is of considerable interest. In this case also, the decrease in power output is due mainly to the decrease in the resonator efficiency, due first to the increase in gas temperature in it and second to the increase in relaxation losses.

Thus, the results presented above indicate the possibility of achieving high specific power output in GDL with selective thermal excitation with the appropriate optimization of all the operating parameters. The calculated data allow one to estimate the mixing efficiency and the nozzle and resonator efficiencies and make recommendations on their improvement. The investigation of the influence of the nozzle shape and the mixing cross section on the power output and a comparison of CO_2 and N_2O GDL remained outside the scope of the work. It is proposed to do this in the future.

NOTATION

c, mass concentration; g, amplification factor for a weak signal; t, coefficient of transmission of mirror; x_s, length of supersonic part of nozzle; x_r, length of resonator; A_{01}, half-height of jet for delivery of CO_2 + He; A_{0E}, half-height of initial cross section of nozzle; A_E, half-height of exit cross section; L, distance between mirrors; M, Mach number; N, specific power output; P, pressure; T, temperature; P_0, T_0, nitrogen stagnation pressure and temperature; V, velocity; α, coefficient of absorption of mirror; β, mixing efficiency; γ, volumetric concentration of CO_2 in secondary stream; δ, coefficient of linear attenuation of radiation; η_n, nozzle efficiency; η_r, resonator efficiency.

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DISSOLUTION OF A SOLID PHASE BY FLUID FLOWING IN A CYLINDRICAL PIPELINE

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The problem of mass transfer from the inner surface of a cylindrical pipeline in the presence of dissolution of a solid phase in the turbulent fluid flow is examined.

The heterogeneous transformation surface relative to the inner wall of a pipeline is

$$h = h_0(1-\varepsilon_0\cos\varphi)(1+k\eta). \tag{1}$$

The distribution (1) occurs in main pipelines after they are cleaned with heavy mechanical devices — scrapers and separators. Due to their intrinsic weight, solid deposits are more completely removed from the bottom of the pipe: $\varphi = 0$, $h = h_0(1-\varepsilon_0)(1+k\eta)$ is the smallest thickness of the deposits along the lower generatrix of the pipe; $\varphi = \pi$, $h = h_0(1+\varepsilon_0)(1+k\eta)$ is the greatest thickness along the upper generatrix, $0 \le \varphi \le \pi$. The factor $(1 + k\eta)$ takes into account the change in thickness of the solid phase along the pipe as a result of deformation and wear of the packing elements of the separators and scrapers.

Particular cases of the problem proposed are examined in [1], which is concerned with the problems of mass transfer in main pipelines.

We are examining the case of large diffusion Prandtl numbers $Pr = \nu/D$. Then, the concentration of the impurity in the fluid will change within the viscous sublayer [2] and for a one-dimensional stabilized flow, its average (over the cross section of the pipe) value can be determined from the following equation [3-5]:

$$\frac{\partial\Theta_i}{\partial\tau}+\frac{\mathrm{Pe}}{2}\frac{\partial\Theta_i}{\partial\eta}-\mathrm{St}\,\mathrm{Pe}(\Theta_\omega-\Theta_i)=0,\quad i=1 \text{ for } \frac{\mathrm{Pe}}{2}(\tau-\tau_1)\leqslant\eta\leqslant\frac{\mathrm{Pe}}{2}\tau,\quad i=2 \text{ for } \xi_1(\tau)\leqslant\eta<\frac{\mathrm{Pe}}{2}(\tau-\tau_1). \tag{2}$$

With the appearance of a clean pipe surface, for any cross section, Eq. (2) has the form

$$\frac{\partial\Theta_3}{\partial\tau}+\frac{\mathrm{Pe}}{2}\frac{\partial\Theta_3}{\partial\eta}-\mathrm{St}\,\mathrm{Pe}(\Theta_\omega-\Theta_3)\left(1-\frac{\varphi}{\pi}\right)=0, \tag{3}$$

which stems from the form of the distribution of the third phase (characteristic (1)) and occurs for $\xi_1(\tau) \le \eta \le \xi_2(\tau)$. Here and in (2) above, $\xi_1(\tau)$ and $\xi_2(\tau)$, which are functions determined from the conditions $\varphi(\xi_1(\tau), \tau) = 0$, and $\varphi(\xi_2(\tau), \tau) = \pi$, indicate the boundary coordinates of the clean border of the pipe. The impurity concentration function is continuous along the pipe, so that the following boundary conditions are valid:

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