NUMERICAL SIMULATION OF AN OPTICALLY ACTIVE MEDIUM OF AN OD—CO_2 LASER

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A quasi-one-dimensional model of an optically active medium of a chemical OD—CO_2 laser with thermal initiation is proposed. Results of calculations are in good agreement with the experiment. The maximal specific power of generation is 66 J/g.

The principle of operation of the laser under consideration is based on the transfer of vibrational energy from the OD radicals, which are formed during exothermal reactions between O_3 and D, to an antisymmetric mode of CO_2. Oxygen and water are final reaction products. Deuterium can be replaced by hydrogen with a certain deterioration in the energy characteristics of the laser. Interest in the OD(OH)—CO_2 laser is explained by the possibility of creation of a highly effective chemical laser with a nontoxic discharge.

The first communication about generation in the mixture of D_2—D—O_3—CO_2 appeared in [1].

In [2], the generation power equivalent to the specific energy output of ~60 J/g was obtained in a shock channel with a nozzle when heating the D_2—Ar mixture to ~4000 K. The mixture O_3—CO_2—He was injected into an ultrasonic flow of D—D_2—Ar at an angle of 45° through the system of holes in the walls of the nozzle. The article [3] described the creation of an H—O_3—CO_2 laser with a chemical source of H atoms.

The work [2] presents the design of a laser based on a mixture of D—O_3—CO_2 with thermal initiation. Due to the complexity of the problem to be solved, a quasi-one-dimensional approximation was used in calculations in the framework of the flame-front model [4]. The length x_k was calculated from the results of measurements of the amplification factor of a probing laser and concentration of ozone in the flow, while the coordinates x_t and x_n were "free" and their values were selected by adjusting the measured and calculated values of the amplification factor. In the region $0 \le x \le x_t$ the function $F_f(x)$ was defined as a power dependence, while for $x > x_t$ it was defined by a linear function [4]. In spite of its obvious simplicity, the proposed model allowed us to explain a number of features of the operation of the OD-CO_2 laser.

This model was used for calculating the processes in a laser with purely chemical initiation [5]. We determined the operating regimes for a chemical generator of H atoms or D atoms that ensures an energy output at a level of the experimental values of ~60 J/g.

In [6, 7], the results of an experimental investigation of the penetration and mixing of gas jets [8] were used when the model of the flame front was realized. The value of x_k was calculated from the formula

$$x_k = \frac{(1+\cos\varphi)^2 s^2}{9{,}05d}\left(\frac{\rho_1 u_1^2}{\rho_2 u_2^2}\right)^{1/2}\frac{[2+(\gamma_2-1)M_2^2]M_1}{2+(\gamma_1-1)M_1^2}. \quad (1)$$

Neither [6] nor [7] presents a formula for calculating x_t. In addition, in [6] and [7] the values of the relaxation constants for OH instead of OD are used, while in [2] the missing values of the constants are replaced by similar constants for DF. As follows from [8], Eq. (1) characterizes the length of only the first stage of interaction of the jets, during which the three-dimensional flow becomes two-dimensional. The second stage of mutual penetration of jets, which is considerably longer than the first stage, is not described by Eq. (1). For the parameters of the flow, described in [6, 7], one can obtain $x_k \approx (3-4)s$ with the help of (1). Therefore, the use of (1) results in a considerable under-

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estimation of the value of x_k and, accordingly, a reduction of the relaxation losses and an overestimation of the energy output.

More complicated is the problem of whether it is correct to use the relaxation rate constants for OH; apparently, calculations with different set of constants are necessary.

Therefore, specific laser characteristics obtained in [6, 7] seem to be overestimated ($q_l \leq 140$ J/g). On the other hand, in model [2], three "free" parameters are used, which have been determined for a narrow region of values of experimental data.

In the present work, a model that has been modified as compared with [2] for calculating an OD—CO_2 laser is proposed assuming the following:

1) the influence of the system of shock waves that arise when the supersonic flow is decelerated by injected jets on gas-dynamic values is taken account of;

2) calculations of trajectories of the jets injected at an angle with respect to the fundamental supersonic flow in an expanding nozzle are performed, and the coordinate of the initiation of chemical and gas-kinetic reactions is determined;

3) from the theory of mixing of turbulent jets of different composition, the profile of the curve $F_f(x)$ and the coordinate of the completion of the motion to a molecular level x_k are determined;

4) the set of relaxation rate constants that guarantees the best agreement between experimental and theoretical results is defined for the OD molecules.

An OD—CO_2 laser is designed for the case of the device described in [2]. The deuterium atoms required for initiating a quasicontinuous chemical laser based on the mixture of D—O_3—CO_2 were obtained in a shock tube. The gas mixture D + D_2 + Ar was injected into a flat nozzle with a sharp edge in a critical cross section. The supersonic part of the nozzle had a logarithmic profile, described by the expression

$$z_c(x) = z_0 + q \ln\left(\frac{x \operatorname{tg}\theta}{q} + 1\right), \tag{2}$$

where $\theta = 45°$ is the initial angle of the nozzle opening. The parameter q was calculated for the given height of the nozzle at a distance x = 20 cm. The initial width of the flow in the nozzle was y_c = 7 cm. When measuring the amplification factor for a weak signal, the flow was bounded by the lateral parallel walls. When working with a reentrant resonator, the walls were removed, and the width of the flow y_c became variable and was determined by the gas pressure P in the flow and by the external ambient pressure P_{ex}.

The oxidizing flow that contained O_3, O_2, CO_2, and He was injected through the holes in the nozzle walls, located at a distance of x_0 = 0.3 cm from the critical cross-section, d = 0.13 cm, s = 0.5 cm. The holes in the upper row were displaced with respect to the holes of the lower row by 0.25 cm, $\phi = 45°$.

The model of an OD—CO_2 laser includes calculations of the equilibrium gas state 1 (D + D_2 + Ar) in a shock tube behind the reflected shock wave; the account of recombination of atomic deuterium in a subsonic part of the nozzle; calculation of the gas flow 1 in a supersonic nozzle with account of the influence of the growing boundary layer up to the cross-section x_0 of gas injection 2 (O_3 + O_2 + CO_2 + He); calculation of the gas characteristics 2 at the input into a supersonic nozzle; calculation of hydraulic losses in gas 1 on shock waves that arise when the supersonic flow on injected jets is decelerated; calculation of the trajectory of injected jets and the coordinate of the initiating of chemical and gas-dynamic reactions; calculation of an ejector with account of the influence of the reaction of walls of a supersonic nozzle on the parameters of the mixed gas 3; investigation of turbulent mixing in the flow, revealing the profile $F_f(x)$ and determining the coordinate x_k; calculation of the kinetics of chemical and relaxation processes in the supersonic flow with account of the influence of the boundary layer.

The gas flow up to the cross-section x_0 is described by the known gas-dynamic functions. Here, as well as in the other regions of a supersonic nozzle, a boundary layer was taken account of when using an iteration method by introducing the thickness of the displacement $\delta^*(x)$ [9]. As distinguished from [2, 7], a laminar boundary layer was calculated, since the Reynolds number did not reach its critical value $Re_{cr} \approx 2 \cdot 10^6$ corresponding to the turbulization of the boundary layer on the plate in the convergent channel of a supersonic nozzle for M ≈ 3 [10].

When calculating the parameters of the gas 2 that is exhausted from the injector, we took into account the pressure drop of deceleration P_2^0 in the valve communications, dissociation of ozone molecules in the valve, and the values of the flow rate measured experimentally for quasistationary exhaust of gas 2. The temperature of deceleration of the mixture was T_2^0 = 300 K. The coefficient of flow rate of the injected gas μG = 0.743 was calculated.

We estimate pressure losses on shock waves in gas 1 that arise when the supersonic flow is decelerated on injected jets. A jet produces a bow shock wave. When the injection spacing s = 0.25 cm, discrete jumps merge into a total bow wave [11]. We assume that the shock wave is located on the front boundary of the injected jet (x_1 = 0.235 cm). In this case the shock wave covers the entire flow cross section. The pressure losses on a direct jump are determined by the resistance of the equivalent solid obstruction [12]. The force of the pressure resistance acting on the leading part of the obstacle (an injected jet) depends on the momentum of the jet:

$$F_x = (G_2 v_2 \cos\varphi)/N, \tag{3}$$

where v_2 is the velocity of the injected gas under isentropic expansion up to the ambient pressure. Then the pressure drop on the shock wave is

$$\Delta P = \frac{F_x N}{y_c z_c (x_1)}.$$

By knowing ΔP and the parameters of flow prior to the shock wave, it is easy to calcualte the state of gas 1 behind the shock wave in a one-dimensional approximation [9].

Under lateral injection of gas in a supersonic flow, the flow exhibits an evident three-dimensional nature. In close proximity to the injection point, the fundamental and secondary flows practically do not mix. A noticeable mixing of flows is observed when the flows become parallel [13]. In this case it is important to know the characteristic length of a mixing chamber x_* [14], where the injected jet "touches" the nozzle's walls.

For $x > x_*$, the gas-dynamic parameters quickly level off along the cross section of the nozzle. It is assumed that the chemical and gas-kinetic reactions at turbulent mixing start at the point x_k.

The region of interaction of the flows was calculated in two stages. At first, by following [13], we determined the location of the central line and the thickness of an injected jet that did not mix with the fundamental flow in an expanding nozzle by step-by-step integration. Then, by following the theory of turbulent jets [9], we took account of the jet expanding in the so-called "initial" portion of the region of mixing by the formula:

$$\frac{d\delta}{dx} = 0{,}135 \frac{(\rho_1 + \rho_2)(u_2 - u_1)}{\rho_1 u_1 + \rho_2 u_2}. \tag{4}$$

As a result, we calculated the coordinate $x_* \approx 0.9$ cm. We note that in the cross section x_* the jets that discharge from the neighboring injection holes also "touch."

The parameters of the mixed flow 3 in the cross-section x_* were found on the basis of the theory of the gas ejector [9] when taking account, in the equation of the momentum, of the injected gas that was injected at an angle ϕ with respect to the fundamental flow and a longitudinal component of the reaction force of the walls, proportional to the half-sum of the pressures P_2 and P_3:

$$P_3 = P_1 \frac{\bar{z}_c(x_0)}{\bar{z}_c(x_*)} \sqrt{(1+n)(1+n\Theta\varkappa)} \frac{B_3 \lambda_1 \tau(\lambda_3)}{B_1 \lambda_3 \tau(\lambda_1)}, \tag{5}$$

$$z(\lambda_1) + n\frac{A_2}{A_1} z(\lambda_2)\cos\varphi + \frac{(P_2 + P_3)(\bar{z}_c(x_*) - \bar{z}_c(x_0))\, y_c}{2G_1 A_1} = (n+1)\frac{A_3}{A_1} z(\lambda_3), \tag{6}$$

$$T_3^0 = T_1^0 \frac{1 + n\Theta\varkappa}{1 + n\varkappa}, \tag{7}$$

TABLE 1. Rate Constants of the Processes of Chemical and Vibrational Kinetics

Reaction No.	Process	Rate constant K, $cm^3/mole \cdot sec$ or $cm^6/mole^2 \cdot sec$;	Components of Mi
27	$D+D+M_i \rightarrow D_2+M_i$	$3{,}4 \cdot 10^{17} T^{-1/2}$	1[22]
		$1{,}0 \cdot 10^{17} T^{-2/3}$	3[22]
		$1{,}0 \cdot 10^{18} T^{-1}$	10, 13[22]
44, 45	$CO_2(00^01)+M_i \rightarrow CO_2(nm^l0)+M_i$	$1{,}8 \cdot 10^{12} T \exp(-128{,}8\, T^{-1/3} - 354{,}0\, T^{-2/3})$	1, 3[23]
		$1{,}6 \cdot 10^{-8} T^{6{,}3} \exp(1157{,}5/T)$	2, 4—7[27]
		$0{,}6\, T^{3{,}7} \exp(322{,}1/T)$	8, 9, 11, 12[27]
		$8{,}2 \cdot 10^{7} T \exp(4{,}138 + 7{,}495 T^{-1/3} T - 691{,}2\, T^{-2/3} + 2239\, T^{-1})$	10[27]
		$6{,}4 \cdot 10^{11} T^{1/2} \exp(58{,}8\, T^{-1/3})$	14[24]
		$K_{13} = 0{,}2\, K_{14}$	
46	$CO_2(01^10)+M_i \rightarrow CO_2(00^00)+M_i$	$4{,}5 \cdot 10^{10} T \exp(7{,}42\, T^{-1/3})$	1, 3[24]
		$158{,}5\, T^{2{,}9} \exp(100{,}7/T)$	2, 4, 5, 9, 11, 12[27]
		$5{,}9 \cdot 10^{8} T \exp(-29\, T^{-1/3})$	10[24]
		$81{,}9\, T \exp(16{,}32 - 13{,}17^{-1/3})$	13[25]
		$2{,}9 \cdot 10^{13} \exp(-40{,}69\, T^{-1/3})$	14[24]
47	$D_2(1)+M_i \rightarrow D_2(0)+M_i$	$7{,}6 \cdot 10^{12} \exp(-2434/T)$	1[25]
		$1{,}5 \cdot 10^{-5} T^{4{,}6}$	2, 4—9, 11, 12,[22]
		$2{,}0 \cdot 10^{17} \exp(1027\, T^{-1} - 174{,}3\, T^{-1/3}$; $K_{14} = 0{,}25\, K_{13}$	3[22]
		$5 \cdot 10^{-4} T^{4{,}3}$	10, 13,[26]
48	$O_2(1)+M_i \rightarrow O_2(0)+M_i$	$1{,}0 \cdot 10^{12}$	2[27]
		$7{,}2 \cdot 10^{8}$	3[27]
		$1{,}2 \cdot 10^{8}$	4—12[27]
		$8{,}4 \cdot 10^{8}$	14[27]
49	$OD(1)+M_i \rightarrow OD(0)+M_i$	$6{,}3 \cdot 10^{11}$	1, 2, 5, 8, 9
		$6{,}0 \cdot 10^{10}$	3
		$4{,}2 \cdot 10^{10}$	4
		$1{,}0 \cdot 10^{11}$	6, 7, 10—12
		$2{,}0 \cdot 10^{9}$	13, 14 [15,16,17]
50	$O+O_3 \rightarrow O_2+O_2$	$5{,}4 \cdot 10^{12} \exp(-4{,}3/\theta)$	[21]

$$n = \frac{G_2}{G_1}, \quad \Theta = \frac{T_2^0}{T_1^0}, \quad \varkappa = \frac{(c_p)_2}{(c_p)_1}, \quad \vartheta = \frac{\gamma_2}{\gamma_1},$$

$$\gamma_3 = \gamma_2 \frac{1 + n\varkappa}{\vartheta + n\varkappa}, \quad \mu_3 = \frac{1+n}{\frac{1}{\mu_1} + \frac{n}{\mu_2}},$$

$$B_i = \sqrt{1 - \frac{1}{\gamma_i^2}}, \quad A_i = \sqrt{\frac{\gamma_i + 1}{2\gamma_i} \frac{RT_i^0}{\mu_i}}.$$

In correspondence with the accepted model of the OD-CO_2 laser, we assume that the rate of chemical and gas-kinetic reactions in a supersonic flow in the region $x > x_*$ is determined by the rate of dissociation of turbulent moles (according to Prandtl) up to the molecular level, which is described by the function Ff(x). It follows from [8, 14] that in the cross section x_* the flow is already completely turbulized, i.e., the coordinate of turbulization $x_t = x_*$, and it is unnecessary to introduce the region of laminar mixing, as was done in [2, 7]. The function $F_f(x)$ correlates with the distribution of pulsations of concentration c'. In [14], from the condition of the existence of the Korsin invariant, the following relationship is obtained:

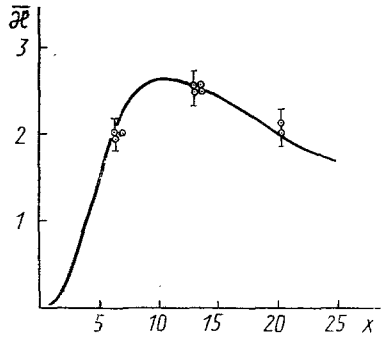

Fig. 1

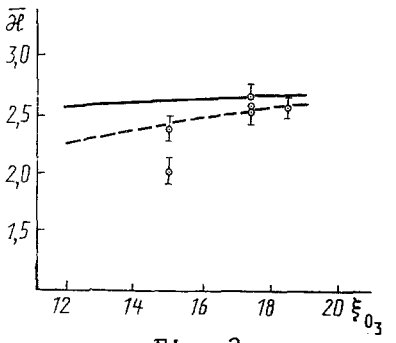

Fig. 2

Fig. 1. Distribution of $\bar{\varkappa}$ along the flow. The solid curve represents calculations, while points represent experiment [2]. The measurement conditions are $c^0_{D_2}:c^0_{Ar} = 1:5$; $c^0_{O_3}:c^0_{CO_2}:c^0_{He} = 1:14:35$; $P^0_1 = 8.22$ kPa, $T^0_1 = 3935$ K, $P^0_2 = 5.0$ kPa, $z_0 = 0.00045$ m, $z_c(0, 2) = 0.036$ m. $\bar{\varkappa}$, m^{-1}; x, cm.

Fig. 2. The dependence of $\bar{\varkappa}$ on the ozone concentration. The content of the remaining components is close to the data shown in Fig. 1. The solid curve represents the calculation for the cross section x = 0.05 m; the dashed curve is for x = 0.13 m; the data are from the experimental work [20]. ξ_{O_3}, %

$$\frac{c'}{\bar{c}} \simeq 0{,}6\left(\frac{x-x_0}{x_*-x_0}\right)^{-3/4} \quad (x>x_*), \tag{8}$$

where $\bar{c}$ is the impurity concentration averaged along the cross-section. Based on the admissible level of inhomogeneity of the concentration of pulsations, it is possible to determine the cross-section x_k from (8). Thus, for the level of inhomogeneity $c'/\bar{c} = 5\%$, $x_k \simeq 17$ cm. Then the following dependence can be assumed for the function $F_f(x)$:

$$F_f = \begin{cases} 0, & 0 < x \leqslant x_*, \\ s\left(\dfrac{x-x_0}{x_k-x_0}\right)^{3/4}, & x_* < x < x_k, \\ s, & x > x_k. \end{cases} \tag{9}$$

We estimate in this case the level of inhomogeneity of the averaged impurity concentration from the equation [14]

$$\frac{\Delta c}{\bar{c}} = 2\exp\left[-\frac{\pi\rho D_t N}{G_1+G_2}(x-x_*)\right]. \tag{10}$$

The coefficient of turbulent diffusion D_t due to the injection of jets and corresponding blocking of the cross section of the fundamental flow can be estimated on the basis of data from [8]. As a result, we obtain for $x_k = 17$ cm the level of inhomogeneity $\Delta c/\bar{c} \simeq 5\%$.

Therefore, for $x_k = 17$ cm, the total level of inhomogeneity of concentration $(\Delta c)_\Sigma/\bar{c} = (\Delta c + c')/\bar{c} \simeq 0.1$ is a measure often accepted in the chemical kinetics as an indication of completion of the process of turbulent mixing.

When calculating the gas-dynamic parameters of the flow in an expanding nozzle for $x > x_*$, we took account of heat evolution in the reaction zone. The flows in the reaction zone and in the external flow were characterized by the same gas-dynamic parameters. At the same time, the composition of the mixtures and the average content of the oscillation quanta of the j-th mode per molecule of the i-th mixture (in the reaction zone and in the external flow) are different. Under the assumption that the heat capacity of the mixture, which is

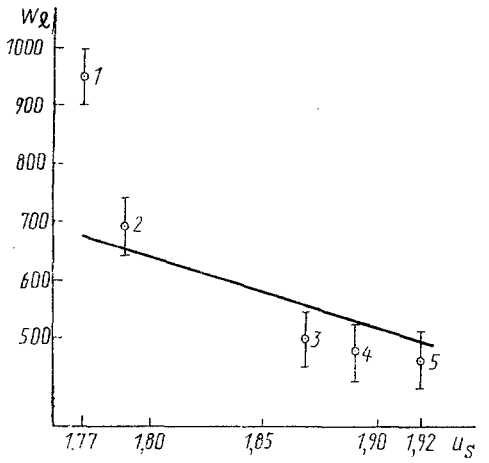

Fig. 3. A comparison of the calculated and experimental [20] values of the output power of the laser radiation W_ℓ. The reflection coefficient of the output mirror is R = 0.8. The composition of the flows is similar to the one given in Fig. 1 (u_S is the velocity of the shock wave). The corresponding temperature T^0 behind the front of the reflected shock wave is: 1) 3716 K; 2) 3826; 3) 3908; 4) 4029; 5) 4164. W_ℓ, W; u_S, km/sec.

strongly diluted by the inert gas, is constant and by neglecting the relaxation of vibrational energy in the external flow, we obtain:

$$\frac{dT}{dx} = \frac{T(\gamma-1)}{1-\dfrac{\gamma RT}{\mu u^2}}\left[-\frac{1}{\bar{z}_c}\frac{d\bar{z}_c}{dx} - \frac{1}{y_c}\frac{dy_c}{dx} + \frac{\bar{F}_f\mu}{uRT}\left(1-\frac{RT}{\mu u^2}\right)\chi\right], \tag{11}$$

$$\frac{d\rho}{dx} = \frac{1}{1-\dfrac{\gamma RT}{\mu u^2}}\left[-\frac{1}{\bar{z}_c}\frac{d\bar{z}_c}{dx} - \frac{1}{y_c}\frac{dy_c}{dx} + \frac{\bar{F}_f(\gamma-1)}{u^3}\chi\right], \tag{12}$$

where

$$u = \frac{G}{\rho\bar{z}_c y_c};\quad \bar{F}_f = \frac{F_f}{s};\quad G = G_1 + G_2; \tag{13}$$

χ is a function of the heat source, equal to

$$\chi = \frac{1}{\rho}\sum_n\left(1-\sum_k\eta_{nk}\right)Q_n S_n + \frac{R}{\rho}\sum_k r_k\theta_k\varepsilon_k^0 V_k - \frac{R}{\rho}\sum_k r_k\theta_k c_k\left(\frac{d\varepsilon_k}{dt}\right)_{\text{rel}}; \tag{14}$$

$(d\varepsilon k/dt)_{rel}$ is the contribution of the relaxation, caused by collisions, to the rate of change of the average content of oscillation quanta in the k-th mode per molecule.

The presssure in the flow was determined from the equation of state of an ideal gas.

The constants of the reaction rates are taken from the table in [7], except for the constants that are listed below in Table 1.

Here, just as in [2], the following numeration of the components is assumed: 1, D; 2, O; 3, D_2; 4, O_2; 5, OD; 6, DO_2; 7, D_2O_2; 8, D_2O; 9, O_3; 10, CO_2; 11, CO; 12, DCO; 13, Ar; 14, He. We introduce the notation $\theta = 10^{-3}$ RT.

The vibrational relaxation of molecules is described in the framework of a harmonic approximation with the use of assumptions accepted in the theoretical analysis of the CO_2 laser [18]. In the calculated model, the exchange of vibrational energy between the molecules of OD, CO_2, D_2, and O_2 is taken account of. It is assumed that the oscillational and translational motions of molecules of D_2O, O_3, D_2O_2 and DO_2 are in equilibrium.

The equations that describe the change in the zone of reaction of the mole-fractional concentrations c_j and content of the oscillation quanta ε_k of molecules CO_2, OD, D_2, and O_2 are obtained in [2] and listed in [7]. The equations of chemical and vibrational kinetics were solved simultaneously with the equations of gas dynamics (11)-(12) and the equation that describes the change in total power of generation for the laser along the length of the resonator [18]:

$$\frac{dW_{\ell}}{dx} = \frac{1}{2}\ln\left(\frac{1}{R}\right) J\bar{z}_c, \tag{15}$$

where R is the coefficient of reflection of the output mirror of the resonator and J is the radiation intensity.

The equations were integrated numerically based on the Runge-Kutta scheme of the fifth order of accuracy [19].

By solving the system of equations, we determined the distribution of vibrational temperatures $T_V(x)$ of the vibrational modes under consideration in the resonator:

$$T_{Vk} = \frac{\theta_k}{\ln\left(1 + \frac{r_k}{\varepsilon_k}\right)}. \tag{16}$$

The values of the spectroscopic constants are adopted from [18].

The generation power of the OD—CO_2 laser was calculated in a quasistationary approximation with the amplification factor sustained at the threshold level

$$\varkappa \geqslant \frac{\ln\frac{1}{R} - g(y_c - F_f)}{F_f}, \tag{17}$$

where g is the absorption coefficient in the zone of the external flow.

The specific power of generation q_{ℓ} and the chemical coefficient of efficiency of a laser η were calcualted from the formulas

$$q_{\ell} = \frac{W_{\ell}}{G}, \tag{18}$$

$$\eta = \frac{W_{\ell}}{mQ}, \tag{19}$$

where Q = 326 kJ/mole is the thermal effect of the reaction of pumping; m = min × $[G_1c_D^0/\mu$; $G_2c_{O_3}^0/\mu_2]$ is the incoming molar flow rate of one of the reagents (D or O_3), which is less than that of the other one.

The results of calculations of the laser characteristics for an OD—CO_2 laser are given in Figs. 1-4. Figure 1 shows the distribution $\bar{\kappa}$ along the flow. The experimental results [20] are also given here. Figure 2 shows the dependence of $\bar{\kappa}$ that characterizes the content of ozone in the mixture 2; calculations were performed for the cross section x = 13 cm, for which the experimental data were obtained. The same figure shows the dependence of the maximal amplification factor (solid curve) on ξ_{O_3}, which is realized in the early stages of the flow of the relaxing mixture. We observed good agreement between the calculated and experimental values of the amplification factor for a weak signal.

In Fig. 3, the calculated and experimental values of the output power of the laser radiation W_{ℓ} are compared. The point associated with the velocity of the incident wave u_s = 1.77 km/sec falls out from the general dependnece, which is, apparently, due to the inconsistency in the listed parameters [2, 20] that are characteristic of the given experiment. We note that for other flow regimes of the laser mixture we obtained values of the output radiation power that exceed noticeably the indicated value W_{ℓ}.

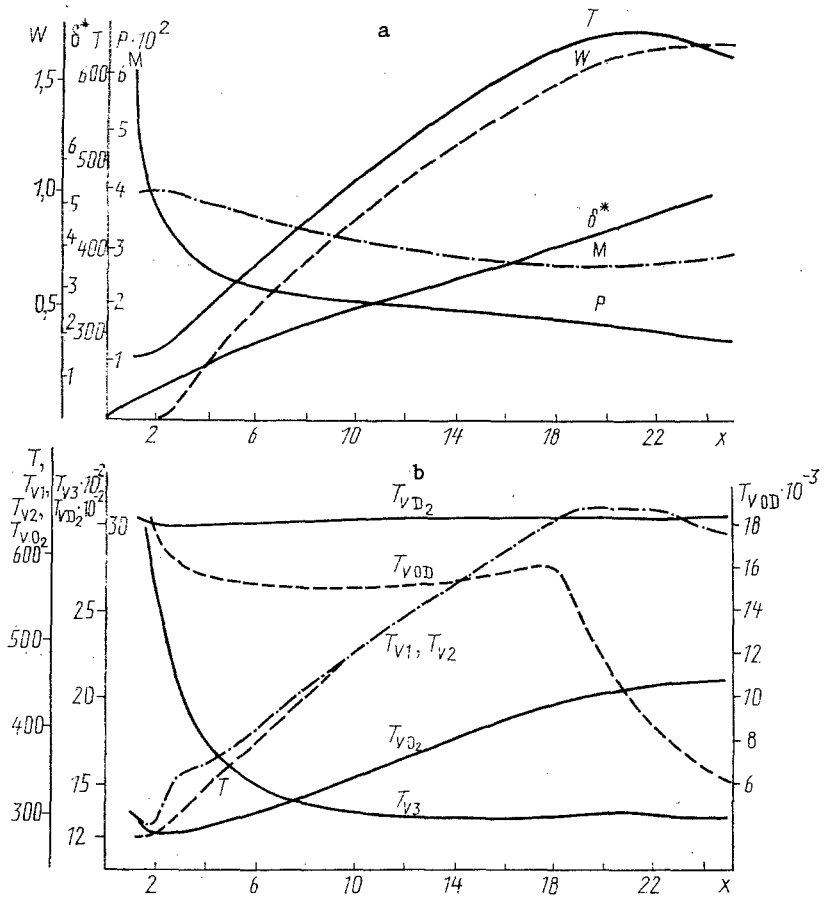

Fig. 4. Distribution along the flow of (a) gas-dynamic values and (b) oscillation temperatures. T, K; P, atm; δ, mm; W, kW.

In Fig. 4, the distributions along the flow of gas-dynamic parameters and of temperatures T_V are shown. We note that a number of parameters of the flow are practically constant along a considerable part of the exapnding nozzle: pressure P, number M, concentrations c_{O_3}, c_{OD}, c_{D_2O}, temperatures T_{D_2}, T_{OD}, T_3. All this apparently results in a high efficiency for an OD—CO_2 laser. The maximal values of the total power of generation W_ℓ = 1656 W and specific power q_ℓ = 40.6 J/g for the chemical coefficient of efficiency $\eta \approx 7\%$ were obtained under the following conditions: $x_0 = 4.5 \cdot 10^{-2}$ cm; $z_c(x = 20\ \text{cm}) = 3.6$ cm; $T^0_1 = 4036$ K; $P^0_1 = 8.36$ atm; $\xi_{D_2} = 4$; $T^0_2 = 300$ K; $P^0_2 = 5$ atm; $\xi_{O_3} = 3$; $\xi_{CO_2} = 2.6$; $P_{ex} = 5$ mm Hg; R = 0.8.

We note that the given calculations were performed for a working mixture that contained argon. The use of such a mixture [2] is related to the specifics of operation of a shock tube. When using different techniques of obtaining atomic deuterium, helium is usually used as an inert diluent. By substituting formally helium for argon, we obtain a maximal specific power of generation recalculated for helium: $(q_1)_{He} = 66.6$ J/g.

When we conducted calculations, we discovered the operation regimes of the OD—CO_2 laser that yield the maximal chemical coefficient of efficiency $\eta = 17.4\%$.

The analysis that we conducted has shown that the geometry of the mixing units suggested in [6, 7] cannot provide for the specific energy output shown in the given studies: 110-140 J/g. This is explained by the fact that Eq. (1) was used incorrectly.

The calculations were conducted with the kinetic constants that were used in [2] and [6, 7]. In the first case the specific energy output increased by a factor of 1.2-1.5; in the third case, it decreased 6-8 times as compared with the main version. This divergence is related mainly to the fact that in [2] the values of the constants for OD that correspond to a slower relaxation of molecules DF are assumed, while in [7], the higher-speed values that correspond with the high-energy levels of OH are assumed.

The calculations showed that the nozzle geometry used in [2] is not optimal since the flow is overheated. By changing the nozzle profile, the efficiency of the laser can be increased.

The mixing model proposed in the given work and the selected values of constants allow us to describe adequately the results of measurements [2] both for the amplification factor and the generation power. The calculations confirm that the OD—CO_2 laser has considerable promise and that it is advisable to continue theoretical and experimental research.

The quasi-one-dimensional model is economical, it does not require a large amount of computational time, and it can be used for solving different problems of mixing of gas jets.

NOTATION

$z_c(x)$, nozzle profile; $F_f(x)$, boundary along which the chemical and gas-kinetic processes are initiated; x_t, point of transition from the laminar regime of mixing to the turbulent regime; x_k, length of mixing; ϕ, injection angle; s, distance between the injection holes; d, hole diameter; N, number of injection holes; z_0, height of the critical cross section of the nozzle; u, velocity; P, pressure; ρ, density; T, temperature; P^0 and T^0, parameters of deceleration; M, mach number; γ, adiabatic index; c_j, molar fraction of particles j; G, flow rate, kg/sec; λ, reduced velocity; $\tau(\lambda)$ and $z(\lambda)$, gas-dynamic functions [9]; μ, molecular mass; c_p, specific heat; ε_k, and ε^0_k, average number of oscillation quanta of the k-th mode calculated per molecule; r_k and θ_k, degree of degeneration and characteristic oscillation temperature of the k-th mode; Q_n and S_n, thermal effect and rate of the n-th reaction; η_{nk}, fraction of heat evolution of the n-th reaction, which exhibits itself initially as oscillations of the k-th mode; V_k, rate of formation of the component related to the k-th mode; R, gas constant; q_ℓ, specific power of generation of the laser, J/g; $\xi_{O_3} = c^0_{CO_2}/c^0{}_{O_3}$; $\xi_{CO_2} = c^0{}_{He}/c^0{}_{CO_2}$. Indices i = 1, 2, 3 refer to the fundamental flow, injected flow, and flow in the mixing zone, respectively; κ, local amplification factor in the reaction zone; κ, value of κ averaged along the nozzle width; $z_c(x) = z_c(x)-2\delta^*$.

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