SOLUTION OF THE PROBLEM OF FINDING THE ENERGY CHARACTERISTICS OF A CARBON DIOXIDE GASDYNAMIC LASER

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The most important energy characteristic of a gasdynamic laser is the power of the generated radiation. The presence of a high-speed program for calculating the flow of a relaxing gas in a nozzle and resonator and the use of efficient methods of finding the extrema of functions of many variables have made it possible to solve the problem of optimizing the amplification factor and the specific generation power [1-3].

The present report is a direct development of the publications [1, 2]; in particular, here we consider a larger number of variants of the functional being optimized and indicate some peculiarities of these functionals which appear at high initial pressures. It should be noted that a number of reports have recently been published in which new measurements have been made of the experimentally determined quantities which characterize the operation of a carbon dioxide, gasdynamic laser. In [3, 4], on the basis of a critical analysis of a large number of experimental data, Volkov et al. offered their own approximations of the temperature dependences of the rate constants for vibrational energy exchange and the Einstein coefficient for the spontaneous transition; these data were used in the present report.

1. We will assume that the generation takes place in a plane-parallel Fabry-Perot resonator with the following dimensions: l along the stream, d across the stream, and m over the height of the stream. To describe the kinetics of the vibrational energy exchange we used the scheme adopted in [2], by isolating three relaxing components of the mixture: nitrogen, the antisymmetric type of CO_2 vibrations, and the symmetric and deformation types of CO_2 vibrations, combined owing to Fermi resonance.

To close the system of equations for gas flow in the resonator we used the condition of steady generation in the form of an approximation of a constant amplification factor, $(1-\alpha-t)\exp(2dk_*)=1$, where t is the coefficient of transmission of the mirror through which the emission occurs; α is the loss factor for two passes of the beam through the resonator; k_* is the value of the amplification factor in the saturation mode. In the zone of establishment of the mode of steady generation the value of the amplification factor varies from k_0 at the nozzle exit to the value k_* (if $k_0 > k_*$). By analogy with [5], the equation of variation of the spectral intensity I can be used to find the law of variation of the respective quantities in this zone.† On the other hand, the characteristic time of establishment of a steady generation level is far less than the time of motion of the gas in the resonator, and in this zone the values of e_2, e_3, k, and I change almost abruptly at the entrance to the resonator (here, as in [2], e_2 and e_3 are the vibrational energies of the ν_2 and ν_3 types of CO_2 vibrations). If the values of e_2 and e_3 before and after the jump are designated as e_2^0, e_3^0 and e_2^*, e_3^*, then the equations

$$k\left(e_2^*, e_3^*\right)=k_*,\ e_1^0+e_2^0+e_3^0=e_1^*+e_2^*+e_3^*,\ e_1=e_2^2/(2e_2+1)$$

allow us to determine the values of e_2 and e_3 beyond the jump. Here $k(e_2, e_3)$ is the functional dependence of the amplification factor on e_2 and e_3; the second equation represents the law of conservation of the total number of quanta. We can show that the power converted into radiation at the jump is calculated by the equation

$$P_*=\frac{mt}{1+r}\,\frac{(\Theta_3-\Theta_1)\,\xi_{CO_2}pu}{T}\int\limits_{e_2^0}^{e_2^*}\frac{6e_2^2+6e_2+1}{(2e_2+1)^2}\,\frac{1}{k\left(e_2, e_3(e_2)\right)}\,de_2,$$

where Θ_3 and Θ_1 are the characteristic vibrational temperatures of the 001 and 010 levels of the CO_2 mole-

†In [6] a variable coefficient of transmission of the mirror was assigned to obtain the solution in this zone.

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cules; p, u, and T are the gas pressure, velocity, and temperature; ξ_{CO_2} is the molar fraction of carbon dioxide. In calculating the amplification factor k we expressed e_3 through e_2 using the equation of conservation of the number of quanta. In such an approximation the total power P extracted from the resonator can be calculated in the form of a sum of two terms,

$$P = P_* + P_1, \tag{1.1}$$

where $P = \frac{mt}{1+r}\int_0^l I\,dl,\ r = 1 - \alpha - t$, while the integration runs over the entire length of the resonator.

The degree of expansion of the stream will be given by analogy with [1]. A transition to dimensionless variables for the problem under consideration (let the nozzle length L be the characteristic length) shows that as the parameters determining the class of similar flows we can take the quantities

$$T_0,\ \lambda,\ \xi_i,\ \alpha_j, \tag{1.2}$$

where $\lambda = p_0 L$; $\alpha_j = 2\tan\beta_j \cdot L/h_*$ $(j = 0, 1, 2)$; T_0 and p_0 are the initial temperature and pressure; ξ_i are the molar fractions; h_* is the critical cross section of the nozzle; β_j are the angles at the separation nodes. In order to show the complete system of parameters for optimizing the amplification factor, we turn to its functional dependence

$$k = B\left(N_n - \frac{g_n}{g_m}N_m\right)\frac{a}{\Delta_c}H(a, 0) = F(\xi_i, e_2, e_3, T_0T^1, p_0p^1), \tag{1.3}$$

where N_n, N_m, g_n, and g_m are the populations and statistical weights of the upper and lower laser levels, respectively; B is a constant; a is the ratio of the collisional half-width Δ_c to the Doppler half-width Δ_D $(a = (\Delta_c/\Delta_D)\ln 2)$; $H(a, 0)$ is the value of the Voigt function at the center of the line; T^1 and p^1 are dimensionless temperature and pressure $(T^1 = T/T_0,\ p^1 = p/p_0)$. Since the dimensionless quantities e_2, e_3, T^1, and p^1 are fully determined by the parameters (1.2), it is seen from (1.3) that the quantity p_0 is an independent optimization parameter. If we fix the parameters (1.2) while we increase the quantity p_0, then we are in a region where collisional broadening Δ_c predominates over Doppler broadening. As an analysis of the dependence (1.3) shows, with such an increase in the pressure p_0 the value of the amplification factor increases monotonically, approaching some limiting value k_∞, i.e., $\lim_{p_0\to\infty} k = k_\infty$ exists.† This allows us to state that if the parameters p_0 and λ are included at the same time among the parameters being optimized, then the value of p_0 will increase without limit in the process of the search. We can avoid this by considering fixed values of the pressure p_0 (or of the characteristic length). As is known, in the vicinity of $a = \infty$ the Voigt function $H(a, 0)$ can be expanded in the series $H(a, 0) = (1/\sqrt{\pi}a)(1 - 1/2a^2 + 3/4a^4 + \ldots)$. Thus, with a given accuracy ε the criterion for fulfillment of the condition $(1 - k/k_\infty) < \varepsilon$ is

$$1/2a^2 - 3/4a^4 < \varepsilon. \tag{1.4}$$

In an analysis of the flow of a relaxing gas in a resonator we add the quantities l^1, t, and k_* to the determining parameters (1.2), where $l^1 = l/L$ is the dimensionless length of the resonator. For given t and α the value of k_* is fully determined by the stream width d, so that the complete set of parameters for optimizing the specific power has the form

$$T_0,\ \lambda,\ \xi_i,\ \alpha_j,\ l^1,\ t,\ d. \tag{1.5}$$

Let us represent the absolute emission power P, determined from (1.1), in the form $P = h_* p_0 \Phi(\overline{\Pi}, p_0)$, where $\overline{\Pi}$ is the set of parameters (1.5); Φ is some function of these arguments. We can show that with such a representation of the power P the function Φ is bounded, $\lim_{p_0\to\infty} \Phi(\overline{\Pi}, p_0) = \Phi_\infty(\overline{\Pi})$, which follows from the existence of a limit for the amplification factor.

Let us consider the optimization of various kinds of specific power P_z in the form $P_z = (1/z)(P/h_*) = p_0\Phi(\overline{\Pi}, p_0)/z$, where z is some characteristic of the system. It is obvious that the quantity z must be a function only of $\overline{\Pi}$ and p_0 and does not depend on the critical cross section h_*. Assuming that it is possible to represent z in the form of a product of $\psi_1(p_0)$ and $\psi_2(\overline{\Pi})$, we can write

†The experimentally measurable quantities entering into the expression for the amplification factor are such that under actual conditions the values of k_∞ do not exceed 0.1-0.13 cm^{-1} by estimate. Considering the limitation $k \le k_\infty$, we can state that it is impossible to obtain an amplification factor higher than 0.13 cm^{-1} in a gasdynamic CO_2 laser.

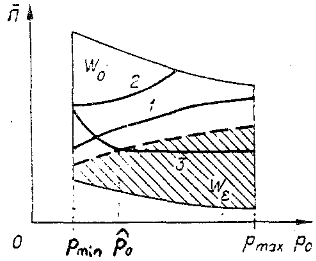

Fig. 1

$$P_z = \frac{p_0}{\psi_1(p_0)} \frac{\Phi(\bar{\Pi}, p_0)}{\psi_2(\bar{\Pi})}. \tag{1.6}$$

Let us consider a closed region of assignment of the optimization parameters,

$$0 < p_{\min} \leqslant p_0 \leqslant p_{\max} < \infty, \quad q_k(\bar{\Pi}) \geqslant 0, \quad k = 1, 2, \ldots, m, \tag{1.7}$$

where $q_k(\bar{\Pi})$ is some function of $\bar{\Pi}$. We designate the subregion of (1.7) where the condition $|1 - \Phi/\Phi/\Phi_\infty| < \varepsilon$ is satisfied as W_ε and the rest as W_0.

Different variants of the functional P_z being optimized and different values of the optimum vector $\bar{\Pi}$ correspond to different representations z for each fixed pressure p_0. The geometrical locus of the optimum points forms curves in the multidimensional space ($\bar{\Pi}$, p_0). Qualitatively different examples of such curves in the region (1.7) are shown in Fig. 1 (curves 1–3). Let z be such that when $p_0 = \hat{p}_0$ the optimum vector $\bar{\Pi}$ lies in the region W_ε. Then when $p_0 > \hat{p}_0$ the function $\Phi(\bar{\Pi}, p_0)$ hardly depends on the pressure p_0 (with an accuracy of order ε), and the optimum values of $\bar{\Pi}$ thereby depend weakly on the pressure (curve 3 in Fig. 1), as seen from (1.6), while the optimum value of P_z in the region W_ε varies by the law $p_0/\psi_1(p_0)$ in this case. Curves 1 and 2 in Fig. 1 correspond to representations z for which the strong dependence of $\Phi(\bar{\Pi}, p_0)$ on the pressure p_0 remains entirely inside the range (1.7) under consideration.

For clearness in presenting the results obtained we will use the quantities S_1 and S instead of the parameters α_1 and α_2, where S_1 and S are the degree of expansion of the supersonic stream at the point (4/9)L and at the nozzle exit [1]. This is possible because the transition from α_0, S_1, and S to the quantities α_j is one-to-one, and the set of parameters for optimizing $\bar{\Pi}$ will have the form

$$T_0, \lambda, \xi_i, \alpha_0, S_1, S, l^1, t, d.$$

Let $z = \prod_k z_k$. As z_k we will consider the characteristics $G_* = G/h_*$, $V_* = V/h_*$, H_0, and $\alpha_0^* = 2\tan\beta_0/h^* = \alpha_0 p_0/\lambda$, where G is the gas flow rate; V is the volume of the system; H_0 is the enthalpy of a unit mass of gas at the nozzle entrance. For a perfect gas, as is known, the flow rate is $G = h_* d p_0/\sqrt{RT_0} \cdot \sqrt{\gamma(2/\gamma+1)^{\frac{\gamma+1}{\gamma-1}}}$, where R is the gas constant; γ is the adiabatic index. Neglecting the variation of γ, for a relaxing gas we can take $G_* \sim p_0 d/\sqrt{RT_0}$. As the volume of the system we will consider the quantity $V = md(L + l) = h_* L(1 + l^1)Sd$, so that $V_* = L(1 + l^1)Sd$. The enthalpy H_0 is a function of the molar fractions ξ_i and the temperature $T_0 (H_0 = H_0(T_0, \xi_i) = H_0(\bar{\Pi})$. In Table 1 we present the forms of $p_0/\psi_1(p_0)$ and $\psi_2(\bar{\Pi})$ for different representations z (without allowance for the multiplier connected with γ).

We note that if z contains the volume V_* as a cofactor then the degree of stream expansion S is in the denominator in the representation P_z. In this case the search for the optimum can lead to such small values of S that the pressure at the nozzle exit will be relatively high and the criterion (1.4) will be satisfied and thus will be a sufficient condition for finding a solution in the region W_ε.

2. The principal results of the solution of the optimization problem are given in Figs. 2–6 and in Tables 2 and 3. In Fig. 2 the optimum values of the parameters T_0, ξ_{CO_2}, ξ_{N_2}, λ, α_0, S_1, S, t, and the maximum value of P_z are given for $z = H_0 G_*$, i.e., the search problem was solved with the aim of obtaining the highest efficiency (the fraction of thermal energy converted into radiation per unit mass of gas). The initial pressure p_0 is laid out along the abscissa. The molar fractions and the value of P_z are given in percent and the quantity λ in atm·cm. The solid lines correspond to the results of a search with the energy-exchange rate constants used in [1, 2] while the dashed lines are the same for [3]. As is seen, an analysis of different temperature approximations of the energy-exchange rate constants leads to some differences in the results.

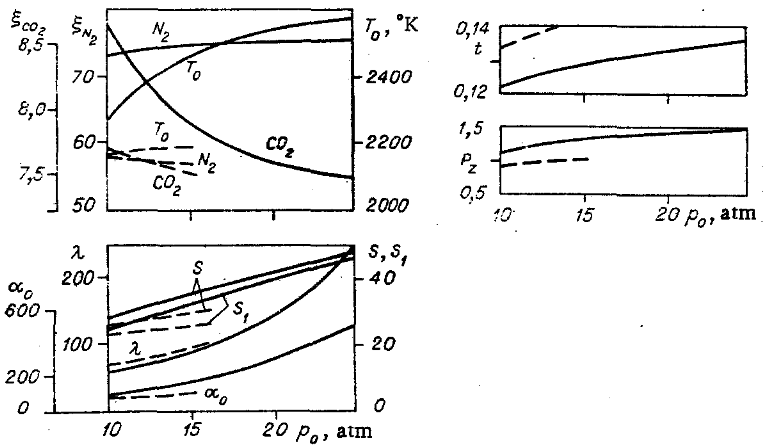

Fig. 2

TABLE 1

z	$p_0/\psi_1(p_0)$	$\Phi_2(\overline{\Pi})$
G_*	1	$d/\sqrt{RT_0}$
G_*V_*	p_0	$Sd^2\lambda(1+l^1)/\sqrt{RT_0}$
H_0G_*	1	$H_0d/\sqrt{RT_0}$
$H_0G_*V_*\alpha_0^*$	1	$H_0Sd^2(1+l^1)\alpha_0/\sqrt{RT_0}$

As the calculations show, the ratio of the power P to the resonator width d grows monotonically with an increase in d, approaching some limiting value. This is connected with the fact that an increase in the width d leads to a decrease in the coefficient k_*, so that the fulfillment of the condition of self-excitation becomes more favorable and, evidently, the value of the intensity I_{un} per unit transverse size of the medium ($I = dI_{un}$) grows monotonically. If $z \sim d$ then the value of the stream width must be fixed in a search for the optimum. We will take $d = 1$ m: Calculations show that the dependence of I_{un} on d is very weak when $d > 1$ m.

Estimates of the characteristic length $l^* = \tau^* u$ of relaxation of the populations of the laser levels in the presence of radiative transitions (τ^* is the characteristic relaxation time) show that l^* does not exceed 20–30 cm, and at distances $l \approx 1$ mm the intensity is close to zero in the presence of generation. That length where the value of the intensity I is exactly reduced to zero will naturally be optimum for the functional under consideration. Such a length, generally speaking, is also determined by the characteristic relaxation length l^0 in the absence of radiative transitions. Estimates show that l^0 is several tens of times greater than l^*. In solving the problem of searching for the resonator length we imposed the restriction $l < 1$ m, which permits a reduction in calculation time without a significant change in the results of the optimization.

The results of the search for the maximum of $P_{H_0G_*}$ show that the optimum values of $\overline{\Pi}$ (in the entire range of variation of p_0) lie in the region W_0, so that the function $\Phi(\overline{\Pi}, p_0)$ has a strong dependence on p_0 and the criterion (1.4) is not satisfied. We also note that under the optimum conditions (in all the cases under consideration) the value of the emission power P_* at the jump is far less than the total power P ($P_*/P \ll 1$).

The results of a determination of the maximum for $z = H_0G_*V_*$ are presented in Fig. 3. The search for the maximum of this functional allows us to determine those conditions under which there is the maximum fraction of thermal energy converted into radiation for each unit volume of the system. The optimum values of the parameters are given in relative units in Fig. 3. The values of the corresponding quantities at a pressure $p_0 = 25$ atm are taken as unity, while Table 2 allows one to reconstruct the absolute values of the parameters. The solution of the problem for such functionals also allows us to determine the optimum sizes d, l^1, and S. The results presented show rather convincingly that as the pressure p_0 increases, the sequence of values of the components of the vector $\overline{\Pi}$ approach some limiting values, and the search for the optimum is carried out in the region W_ε. Analogous results of a search for the maximum of the functional P_z for $z = H_0G_*V_*\alpha_0^*$ are presented in Fig. 4.

The sizes L and l and the ratio $\tan\beta_0/h_*$ corresponding to the pressure p_0 are determined from the

TABLE 2

z	T_0, °K	λ, atm · cm	ξ_{CO_2}, %	ξ_{N_2}, %	α_0	S_1	S	d, cm	t, %	l^1	P_z	p_0, atm	
G_*V_*	1961	11,61	12,4	15,0	37,7	7,35	8,45	9,52	5,44	2,741	$9{,}12\cdot10^{-3}$ $\frac{W\cdot sec}{g\cdot cm^3}$	(10)	I
G_*	3465	49,85	7,38	35,1	94,4	22,6	27,1	(100)	14,6	16,01	47,9 $\frac{W\cdot sec}{g}$	(10)	I
	3471	80,51	7,66	31,3	81,3	22,4	29,6	(100)	16,2	11,58	42,1	(10)	II
$H_0G_*V_*$	1575	13,38	16,2	26,4	46,9	7,02	8,41	5,46	2,04	1,654	$10{,}76\cdot10^{-6}$ cm^{-3}	(25)	I
	1552	17,50	12,6	24,1	60,5	7,51	7,69	6,31	2,23	1,440	$6{,}31\cdot10^{-6}$	(25)	II
$H_0G_*V_*\alpha_0^*$	1585	18,63	11,2	32,6	8,87	4,94	7,39	7,42	1,93	1,356	$9{,}44\cdot10^{-8}$ cm^{-2}	(25)	I
	1660	22,09	9,1	28,2	9,20	5,08	7,60	8,19	1,96	1,262	$6{,}92\cdot10^{-8}$	(25)	II
$G_*V_*\alpha_0^*$	1915	21,75	8,18	18,1	9,71	5,31	8,01	7,66	2,13	1,503	$2{,}45\cdot10^{-6}$ $\frac{W\cdot sec}{g\cdot cm^2}$	(15)	I
	1980	18,85	8,17	19,0	8,94	4,96	7,32	7,78	1,89	1,772	$2{,}43\cdot10^{-6}$	(10)	II

Note. In the division by α_0^* at the optimum, $\alpha_2 \approx \alpha_1 \approx \alpha_0$. The quantities fixed in a given variant of the solution are in parentheses; $\xi_{He} = 100 - \xi_{CO_2} - \xi_{N_2}$.

TABLE 3

z	T_0, °K	λ, atm · cm	ξ_{CO_2}, %	ξ_{H_2O}, %	α_0	S_1	S	d, cm	t, %	l^1	P_z	p_0, atm
H_0G_*	1938	51,51	9,78	2,64	135,1	42,7	58,46	(100)	14,8	17,21	1,167 %	(10)
	2280	108,5	8,36	3,81	402,6	92,8	97,83	(100)	15,2	22,02	1,469	(25)
G_*	2200	62,02	9,87	4,23	193,4	50,4	61,52	(100)	12,3	13,35	29,1 $\frac{W\cdot sec}{g}$	(10)
$G_*V_*\alpha_0^*$	1303	11,35	14,5	4,67	15,41	7,85	12,05	9,85	1,93	1,603	$4{,}76\cdot10^{-6}$ $\frac{W\cdot sec}{g\cdot cm^2}$	(10)
	1372	13,75	11,44	4,31	17,06	8,57	12,33	9,72	1,81	1,817	$4{,}36\cdot10^{-6}$	(25)
$H_0G_*V_*$	1145	5,10	23,8	8,58	44,88	8,97	13,73	6,79	1,92	1,340	$5{,}94\cdot10^{-6}$ cm^{-3}	(10)
$H_0G_*V_*\alpha_0^*$	1175	10,91	15,2	4,02	13,31	6,91	10,57	11,5	1,93	1,342	$3{,}51\cdot10^{-7}$ cm^{-2}	(10)

Note. In the division by α_0^* at the optimum, $\alpha_1 \approx \alpha_2 \approx \alpha_0$. The quantities fixed in a given variant of the solution are in parentheses; $\xi_{N_2} = 100 - \xi_{CO_2} - \xi_{H_2O}$.

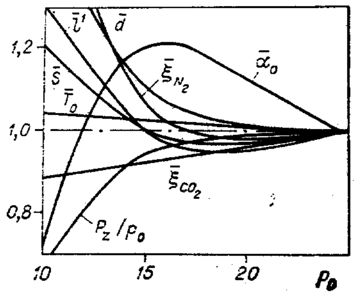

Fig. 3

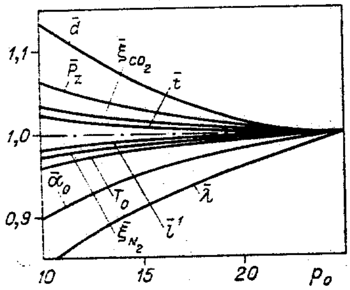

Fig. 4

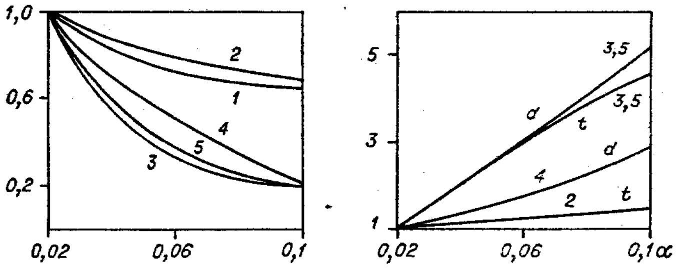

Fig. 5

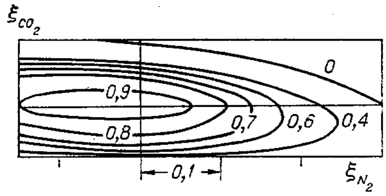

Fig. 6

equations $L = \lambda/p_0$, $l = l^1 L$, and $\tan\beta_0/h_* = \alpha_0/2L$, i.e., with an increase in the pressure p_0 in the region W_ε the lengths of the nozzle and the resonator decrease while the ratio $\tan\beta_0/h_*$ increases. The actual properties of the gas and demands of an optical nature impose limits on the physical parameters of the system, so that $\beta_0 \le \beta_{max}$, $h_* \ge h_{min}$, and $l \ge l_{min}$. The maximum expansion angle β_{max} can be chosen both from the requirement of assuring the "one-dimensionality" of the gas stream and from considerations of the absence of the development of shocks in the supersonic stream. The viscosity of the gas in turn hinders the use of extremely small values of h_*. The resonator length l can be limited by the maximum attainable divergence of the output radiation. These limits determine the upper boundary for the pressure p_0 below which we can use the results of the solution of the problem in the region W_ε: $p_0 < \min(p_1, p_2)$, where $p_1 = l^1\lambda/l_{min}$ and $p_2 = 2\lambda\tan\beta_{max}/\alpha_0 h_{min}$. For $p_0 > \max(p_1, p_2)$ one evidently must consider $l = l_{min}$, $h_* = h_{min}$, and $\beta_0 = \beta_{max}$.

Some results of a solution of the search problem with helium and water vapor are given in Tables 2 and 3. The number I in Table 2 corresponds to finding the maximum of P_z for the energy-exchange constants of [1, 2], while the number II corresponds to the same for [3]. With water vapor the energy-exchange probabilities were taken in accordance with [3] in all cases. In the division by the volume V_* (see Table 3) the optimum values of the initial temperature are $T_0 < 1400$°K while the optimum water vapor content is not less than 4%. We note that the probabilities of energy exchange under the action of water vapor are determined only for low temperatures $T < 1000$° K, and at such relatively low initial temperatures the results obtained have a higher reliability.

In the solution of the search problem it was assumed that the loss factor in the resonator is $\alpha = 0.02$. Under actual conditions, naturally, the losses may be considerable. In this connection it was decided to perform the optimization for higher values of α up to 0.1. The calculations showed that the optimum values of the parameters (except for the stream width d and the coefficient of transmission t of the mirrors) change slightly for different α. In Fig. 5 we give (in relative units) the optimum values of P_z, d, and t for different representations z: 1) $z = G_*$; 2) $z = H_0G_*$; 3) $z = H_0G_*V_*\alpha_0^*$; 4) $z = H_0G_*V_*$; 5) $z = G_*V_*\alpha_0^*$. The values of the respective quantities at $\alpha = 0.02$ are taken as unity.

Topographic lines of equal values of the functional for $z = G_*V_*$ in the coordinates $\xi_{CO_2} - \xi_{N_2}$ are presented in Fig. 6. The value of P_Z at the optimum point is taken as unity. Such pictures give a concept of the functional in the vicinity of the optimum point.

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CALCULATIONS OF ENERGY CHARACTERISTICS OF MULTICOMPONENT WORKING MEDIA IN CO_2 GASDYNAMIC LASERS BASED ON COMBUSTION PRODUCTS

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The working media of CO_2 gasdynamic lasers (GDL) operating on the combustion products of fuels containing the elementary composition C, H, O, N are, as a rule, multicomponent media. At stagnation temperatures $T_0 < 2000°K$ there are mainly CO, O_2, and H_2 present in them along with the main components CO_2, N_2, and H_2O. Before entering the nozzle the multicomponent media are in a state of total thermodynamic equilibrium. This makes it possible to use the thermodynamic approach developed earlier [1], based on the fact that a complex medium is characterized by the elemental composition and the stagnation temperature and pressure (T_0, p_0), for the analysis of their laser properties. Calculations of the amplification factors of such media and the corresponding analysis are presented in [2, 3]. The useful radiant energy $\bar{w}$ which can be obtained from a unit mass of the working medium is investigated in the present report.

Reports on calculations of the radiant energy and power in GDL can be divided arbitrarily into three groups. Estimating reports, which do not consider the generation process at all, belong to the first group. These are simple calculations either of the maximum energy attainable for extraction [4] or of an estimate of the generation power [5, 6]. The second group of reports includes more realistic calculations [7-12]; processes of generation and vibrational kinetics in the resonator are now considered in them, but their influence on the gasdynamic parameters of the stream are neglected. The stream in the resonator is assumed to be isothermal and to have a constant velocity.

Since the assumption of constancy of the gasdynamic parameters in the resonator is not always justified, the further improvement of the calculations is connected with allowance for the mutual influence of the vibrational kinetics, emission, and gasdynamics of the stream. This is the third group of reports [13-15]. In

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