LITERATURE CITED

1. V. I. Bukatyi and D. P. Chaporov, "Dynamics of solid aerosol transparency during interaction with a laser radiation pulse," in: Fourth All-Union Symposium on Laser Radiation Propagation in the Atmosphere. Abstracts Reports [in Russian], Tomsk (1977).
2. V. I. Bukatyi and Yu. D. Kopytin, "Effect of light pressure on the transparency of a polydispersed aerosol," Izv. Vyssh. Uchebn. Zaved Fiz., No. 6 (1971).
3. L. T. Matveev, Physics of the Atmosphere [in Russian], Gidrometeoizdat, Leningrad (1965).
4. K. S. Shifrin and I. L. Zel'manovich, "Light pressure on water drops," Opt. Spektrosk., 17, No. 1 (1964).
5. G. H. Chan, "Effective absorption for thermal blooming due to aerosols," Appl. Phys. Lett., 26, No. 11 (1975).
6. K. S. Shifrin and I. L. Zel'manovich, Light Scattering Tables [in Russian], Vol. 3, Gidrometeoizdat, Leningrad (1968).
7. G. A. Askar'yan and E. M. Moroz, "Pressure during evaporation of material in a radiation beam," Zh. Eksp. Teor. Fiz., 43, No. 6 (1962).
8. S. I. Anisimov, Ya. A. Imas, G. S. Romanov, and Yu. V. Khodyko, Effect of High-Power Radiation on Metals [in Russian], Nauka, Moscow (1970).
9. V. A. Pogodaev, "Effect of CO_2 laser radiation on solid microparticles," in: Second All-Union Symposium on Laser Radiation Propagation in the Atmosphere, Abstracts of Reports [in Russian], Tomsk (1973).
10. A. G. Blokh, Thermal Radiation in Boiler Installations [in Russian], Énergiya, Leningrad (1967).

COMPUTATIONS OF THE GAIN COEFFICIENTS OF MULTICOMPONENT WORKING MEDIA IN COMBUSTION-PRODUCT CO_2 GDL

A. P. Genich, N. V. Evtyukhin,
S. V. Kulikov, G. B. Manelis,
and M. E. Solov'yeva

UDC 533.6.011.8+621.375.826

That the real laser working medium is a multicomponent medium [1] must be taken into account in producing powerful CO_2 gasdynamic lasers (GDLs) operating on combustion products. Numerical computations, in addition to the experimental investigations, play an important role in this area. Such computations permit a better conception of the mechanism of population inversion formation in the flow and insofar as is possible the replacement of a tedious experiment.

The optical gain coefficients of complex working media whose compositions are adequate to the compositions of propellant combustion products from the elements C, H, O and N are considered in this paper. The analysis and classification of the results are performed on the basis of an examination of the element composition of the working medium since the atomic composition, the temperature T_0, and the pressure p_0 of the gas in the reservoir uniquely determine all its thermodynamic characteristics: the equilibrium components of the composition, the internal energy, etc. The mathematical model and the method of computation have been described earlier in [2]. In order to assess how correct the model used is, whether the kinetic constants needed to compare the computation results with the experimental data in a broad range of working medium compositions, stagnation parameters, and nozzle characteristics. In this connection, an attempt is made in the first two parts of the paper to select a set of vibrational relaxation rate constants that would permit matching the computational and available experimental results in the best way.

1. Flow of a mixture of the gases CO_2, N_2, and H_2O through a nozzle was examined. The formulation of the problem and the computation method are presented in [2]. Since the computations were performed for $T_0 < 2000°K$, then in all cases the chemical processes were not taken into account. In contrast to [2], an implicit difference scheme with an almost second-order approximation ($s = 0.44$) [3] was used, which permitted shortening the computation time.

Chernogolovka. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 1, pp. 34-43, January-February, 1979. Original article submitted December 28, 1977.

0021-8944/79/2001- 0025 $07.50

TABLE 1

	References
$\lg \tau_{CO_2}^{(1.1)} = 17{,}42\ T^{-1/3} - 7{,}85$	[4]
$k'^{(1.1)}_{H_2O} = \begin{cases} 1{,}7\cdot 10^7 [1{,}3\cdot 10^{-4}(T-600)^2 + 7{,}3], & T < 1000, \\ 4{,}78\cdot 10^8, & T \geqslant 1000 \end{cases}$	—
$\lg \tau_{N_2}^{(1.1)} = 17{,}8\ T^{-1/3} - 7{,}808 + \lg 2$	[1]
$\lg \tau_{CO_2}^{(1.2)} = 104\ T^{-1/3} - 11{,}2$	[4]
$\lg \tau_{H_2O}^{(1.2)} = 27{,}65\ T^{-1/3} - 9{,}2415$	[1]
$\lg \tau_{N_2}^{(1.2)} = 95{,}5\ T^{-1/3} - 10{,}76$	[4]
$\lg k^{(1.3)} = 7{,}42 - 1{,}65\cdot 10^{-3}\ T + 5{,}7\cdot 10^{-7} T^2$	[4]
$\ln k_{CO_2}^{(1.4)} = 10{,}684 + 593\ T^{-1/3} - 4760\ T^{-2/3} + 1{,}22\cdot 10^{+4}/T$	[4]
$k_{H_2O}^{(1.4)} = \begin{cases} 10^{-40T^{-1/3}+11{,}7}, & T > 1000, \\ 10^8/(-9{,}25\cdot 10^{-3}\ T + 11{,}45), & 600 < T \leqslant 1000, \\ 10^8/[-5{,}21\cdot 10^{-5}(T-480)^2 + 6{,}65], & T \leqslant 600 \end{cases}$	[5]
$\ln k_{N_2}^{(1.4)} = -4{,}884 + 508 T^{-1/3} + 4580 T^{-2/3} + 1{,}27\cdot 10^4/T$	[4]
$P_{CO_2}^{(1.5)} = P_{N_2}^{(1.5)} = 10^{-4}/T^{1/2}$	[6]
$P'^{(1.5)}_{H_2O} = 0{,}4/T^{1/2}$	[6]

The following vibrational relaxation channels were taken into account

$$CO_2(01^10) + M \rightarrow CO_2(00^00) + M; \tag{1.1}$$

$$N_2(1) + M \rightarrow N_2(0) + M; \tag{1.2}$$

$$CO_2(00^01) + N_2(0) \rightarrow CO_2(00^00) + N_2(1); \tag{1.3}$$

$$CO_2(00^01) + M \rightarrow \begin{cases} CO_2(03^10) + M, \\ CO_2(11^10) + M, \end{cases} \tag{1.4}$$

where M is any of the components CO_2, N_2 and H_2O. With the exception of stipulated special cases, it was assumed that the vibrational degrees of freedom of H_2O are in equilibrium with the translational degrees. In some cases an additional relaxation channel

$$H_2O(01^10) + M \rightarrow H_2O(00^00) + M. \tag{1.5}$$

was taken into account. The vibrational temperatures of all the H_2O modes were hence assumed equal. The dependences of the rate constants $k_M^{(i)}$ ($\mathrm{atm}^{-1}\cdot\mathrm{cm}^{-1}$) and the vibrational relaxation times $\tau_M^{(i)}$ (atm · sec) used in the computations and the probability of a change in the vibrational energy per collision $P_M^{(i)}$ on the temperature T are presented in Table 1. The reaction rate constant $k_{H_2O}^{(1.1)}$ for (1.1) with $M = H_2O$ is one of the most important constants, however its experimental values differ from those of other authors by almost an order of magnitude [7]. The expression presented in Table 1 for $k_{H_2O}^{(1.1)}$ has been selected on the basis of comparing computed values of the weak-signal optical gain coefficient α with those measured in [8], whose results are apparently most reliable (the reproducibility of the values is $\pm 0.04\ \mathrm{m}^{-1}$). The computations were executed for a minimum-length profiled nozzle with the throat height $h = 2.3\cdot 10^{-4}$ m and the degree of expansion $A/A^* = 30$ for $p_0 = 1.25$ atm and $T_0 = 1540$°K. The molar fraction of nitrogen was $Y_{N_2} = 0.7$. Results of these computations (curve 1) are presented in Fig. 1a together with the experimental values from [8], where the value of α was measured at the ranges 6.3 and 14.3 cm from the nozzle throat. Taking account of the relaxation channels (1.1)-(1.4) and the set of constants from Table 1 assure good agreement between the computed values of α and the experimental values in a broad range of variation of the H_2O concentration.

Since the selection of the relaxation model and the kinetic constants, which assure the best agreement between the computational and experimental results, is not unique, it is interesting to clarify the response of the computation results to the selection of the magnitude and form of the temperature dependence of the most important relaxation channel constants, and also to analyze certain assumptions taken for the model.

The rate constant $k_{H_2O}^{(1.1)}$ was first given in a form similar to that proposed in [4] on the basis of [9, 10]:

$$k_{H_2O}^{(1.1)} = b\cdot 10^{21T^{-1/3}+5.46} / [1 - \exp(-960/T)]\ \mathrm{atm}^{-1}\cdot\mathrm{sec}^{-1}.$$

Variation of the factor b showed that the proposed form of the dependence does not assure simultaneous agreement between the computed and measured α for the optimal ($Y_{CO_2}/Y_{H_2O} \sim 10$) and low ($Y_{CO_2}/Y_{H_2O} \sim 30$) water concentrations. (In Fig. 1, the curves 2 correspond to $b = 1.1$ and curves 3 to $b = 1.7$, while the remaining con-

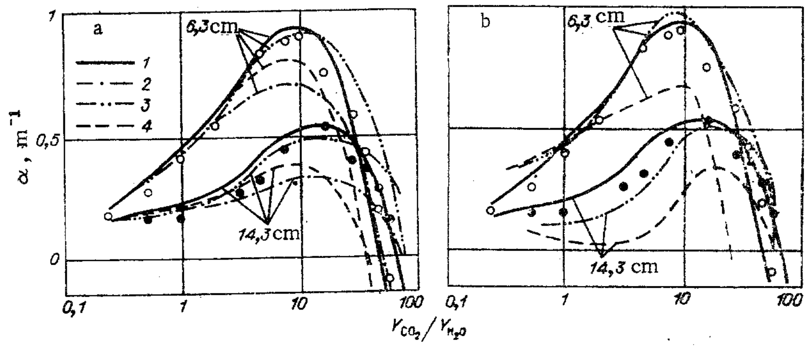

Fig. 1

stants are from Table 1). The investigations of $k_{H_2O}^{(1.1)}$ undertaken in [11, 12] showed that the constant has a positive temperature dependence in the domain T > 600°K. The form of the dependence $k_{H_2O}^{(1.1)}$ (T) proposed in this paper (see Table 1) actually takes account of this feature down to T ~ 1000°K. For T > 1000°K the variation of the temperature dependence showed that the deviation from the quantity $k_{H_2O}^{(1.1)} = 4.78 \cdot 10^8$ atm$^{-1}\cdot$sec^{-1} is insignificant although it degrades the agreement with experiment. The response of the computation results to a change in the quantity $k_{H_2O}^{(1.1)}$ (T) (see Table 1) was studied by varying the numerical factor in front of the constant. Since the deformation type of CO_2 vibrations is practically in equilibrium with the molecule translational motion for high H_2O concentrations, the quantity α is slightly responsive to the variation of the constant for $Y_{CO_2}/Y_{H_2O} < 9$ (a twofold change in $k_{H_2O}^{(1.1)}$ (T) results in a less than 10% change in α). However, the gain coefficient depends strongly on the values of this constant for low H_2O concentrations. Thus for Y_{CO_2} $Y_{CO_2}/Y_{H_2O} = 39$ just a 7% diminution in $k_{H_2O}^{(1.1)}$ (T) results in halving α.

The channel deactivating the upper lasing level (1.4) is an important relaxation channel affecting the quantity α. The rate constants $k_{CO_2}^{(1.4)}$, $k_{N_2}^{(1.4)}$ proposed in [1] are apparently somewhat exaggerated. Use of these constants with values of the remaining constants from Table 1 in computations results in values of α which differ from the experimental values (Fig. 1, curves 4). The results of computations with $k_{CO_2}^{(1.4)}$ and $k_{N_2}^{(1.4)}$ taken in this paper correspond better with experiment. The constant $k_{H_2O}^{(1.4)}$ is borrowed from [5], where is is measured in the range 300-1000°K. For T > 1000°K the temperature dependence of $k_{H_2O}^{(1.4)}$ was extrapolated according to the Landau–Teller law. Computations showed a low response of the quantity α to a change in this constant for T > 500°K.

The computational and experimental values of α were compared for nozzles with very rapidly varying stream parameters in the throat (the characteristic flow time is $\sim 5 \cdot 10^{-8}$ sec). Under these conditions, the assumption of equilibrium between the vibrational and translational degrees of freedom in H_2O requires a special confirmation. Computations taking channel (1.5) into account showed that its inclusion results in small changes in α (less than 6%). The values of $P_{CO_2}^{(1.5)}$, $P_{H_2O}^{(1.5)}$ and $P_{N_2}^{(1.5)}$ (see Table 1) used in these computations are just approximate and apparently reduced for high temperatures, which is indicated by the results of measuring $\tau_{H_2O}^{(1.5)}$, $\tau_{N_2}^{(1.5)}$ at T > 1800°K in [13]. Increasing the constants in the high temperature domain results in a still smaller change in the quantities α. This shows that the assumption about equilibrium between the vibrational and translational degrees of freedom for the H_2O molecules is completely justified.

Results of computations from this paper are compared in Fig. 1b with experimental results of [8] (points) and with computation results of [8] (dashes) and [14] (dash–dot lines). It is seen that the selection of the kinetic constants based on the selection of reliable experimental data, the analysis of the response of the computation results to a change in these constants as well as the computational model which apparently reflects the main features of the relaxation process, permitted an adequate description. Approval of the computational model and the selected constants by other experimental results [1, 15, 16] confirmed this. A comparison between the experimental 1 and computational 2 gain coefficient profiles over a nozzle presented in [1], and the results of this paper 3 is presented in Fig. 2 (x is the distance from the throat of a plane-profiled, minimum-length nozzle, $A/A^* = 20$; $h = 10^{-3}$ m; $T_0 = 1580$°K; $p_0 = 10.2$ atm; $Y_{CO_2} = 0.099$; $Y_{N_2} = 0.890$, $Y_{H_2O} = 0.011$).

2. A thermodynamic analysis shows that in compositions of multicomponent working media, only CO, O_2 and H_2 are present in noticeable quantities in addition to the fundamental laser components (CO_2, N_2, N_2O) for T < 2000°K and take an active part in the vibrational energy exchange processes. Hence, besides the vibrational relaxation channels (1.1)-(1.4), additional vibrational relaxation channels associated with these components were taken into account in computations of the flow of multicomponent media through the nozzle. These are channels (1.1) and (1.4) for M = CO, O_2, H_2 and

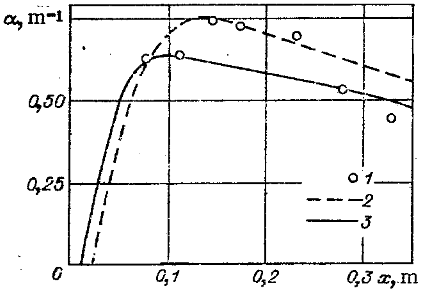

Fig. 2

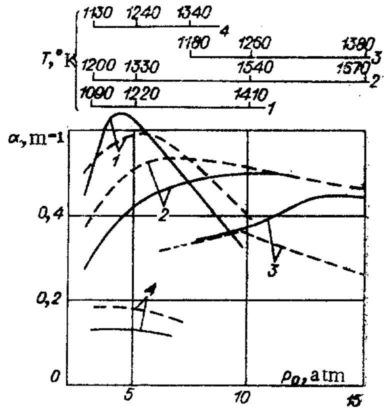

Fig. 3

$$CO(1) + M \rightarrow CO(0) + M; \tag{2.1}$$

$$O_2(1) + M \rightarrow O_2(0) + M; \tag{2.2}$$

$$H_2(1) + M \rightarrow H_2(0) + M; \tag{2.3}$$

$$CO_2(00^01) + CO(0) \rightarrow CO_2(00^00) + CO(1); \tag{2.4}$$

$$H_2O(01^10) + O_2(0) \rightarrow H_2O(00^00) + O_2(1); \tag{2.5}$$

$$CO(0) + N_2(1) \rightarrow CO(1) + N_2(0); \tag{2.6}$$

$$CO(1) + O_2(0) \rightarrow CO(0) + O_2(1); \tag{2.7}$$

$$N_2(1) + O_2(0) \rightarrow N_2(0) + O_2(1). \tag{2.8}$$

The most reliable magnitudes of the kinetic constants for these channels were selected from an analysis of a large quantity of literature data. The dependences of the quantities $k_M^{(i)}$, $\tau_M^{(i)}$ and $P_M^{(i)}$ on T used in the computations are presented in Table 2. The missing vibrational–translational transition probabilities were computed by the Schwartz, Slavskii, Herzfeld theories.

The computed values α of multicomponent media were later compared with the measured values. The experiments were performed as follows. The working media were obtained by igniting propellant combinations of C_2H_2, H_2O, N_2O, O_2, CO_2, and N_2 under isochoric conditions. After the membrane separating the combustion chamber from the nozzle module has been broken, the equilibrium gas mixture obtained flowed through a plane wedge-shaped nozzle into a parallel channel with $A/A^* = 29$. The total nozzle aperture angle was $\varphi = 30°$, $h = 5.5 \cdot 10^{-4}$ m and the nozzle width was 0.4 m. The gain coefficients were measured by a standard method. The beam of the electric discharge CO_2 laser passed through the working medium of the GDL at a distance 0.075 m downstream of the nozzle throat. The shock originating at the transition point to the widening part of the nozzle in the parallel channel was downstream of the observation point. The dependence of α on p_0 and T_0 which varied during the efflux according to an adiabatic law, was recorded in each test. The rms error in determining α was 10%. The solid lines in Fig. 3 represent the results of measuring α for four compositions which are conveniently characterized by the molar fractions ξ_i of the elements therein (in all cases $\xi_N = 0.6$). The passage from the composition 1 ($\xi_G = 0.12$, $\xi_O = 0.26$, $\xi_H = 0.02$) to the compositions 2 ($\xi_C = 0.06$, $\xi_O = 0.32$, $\xi_H = 0.02$), 3 ($\xi_C = 0.16$, $\xi_O = 0.22$, $\xi_H = 0.02$) and 4 ($\xi_C = 0.06$, $\xi_O = 0.20$, $\xi_H = 0.14$) for identical p_0 and T_0 is characterized by the diminution of Y_{CO_2} in the working medium and a corresponding increase in Y_{O_2}, Y_{CO}, Y_{H_2O}. The molar fraction of N_2 hence changes insignificantly. Thus, under equilibrium conditions with $T_0 = 1400°K$ and $p_0 = 10$ atm, the molar % are in the composition 1: N_2 69.0, CO_2 27.7, H_2O 2.3, O_2 1.1; 2) N_2 64.4, CO_2 13.0, H_2O 2.2, O_2 20.4; 3) N_2 63.8, CO_2 11.6, H_2O 1.2, H_2 0.9, CO 22.5; 4) N_2 68.9, CO_2 13.9, H_2O 16.1, O_2 1.1. A pressure of $p_0 = 3$ atm corresponds to $T_0 = 1090°K$ for the composition 1; $T_0 = 1200°K$ for the composition 2 and $T_0 = 1130°K$ for the composition 4 while $p_0 = 7.5$ atm corresponds to $T_0 = 1180°K$ for the composition 3. The computed values of α are shown by the dashed lines in Fig. 3.

The agreement obtained between the computed and experimental quantities in a sufficiently broad range of variation of p_0, T_0 and composition indicates that the computational model and the selected constants are suitable for a quantitative description of CO_2 GDLs even with complex multicomponent working media.

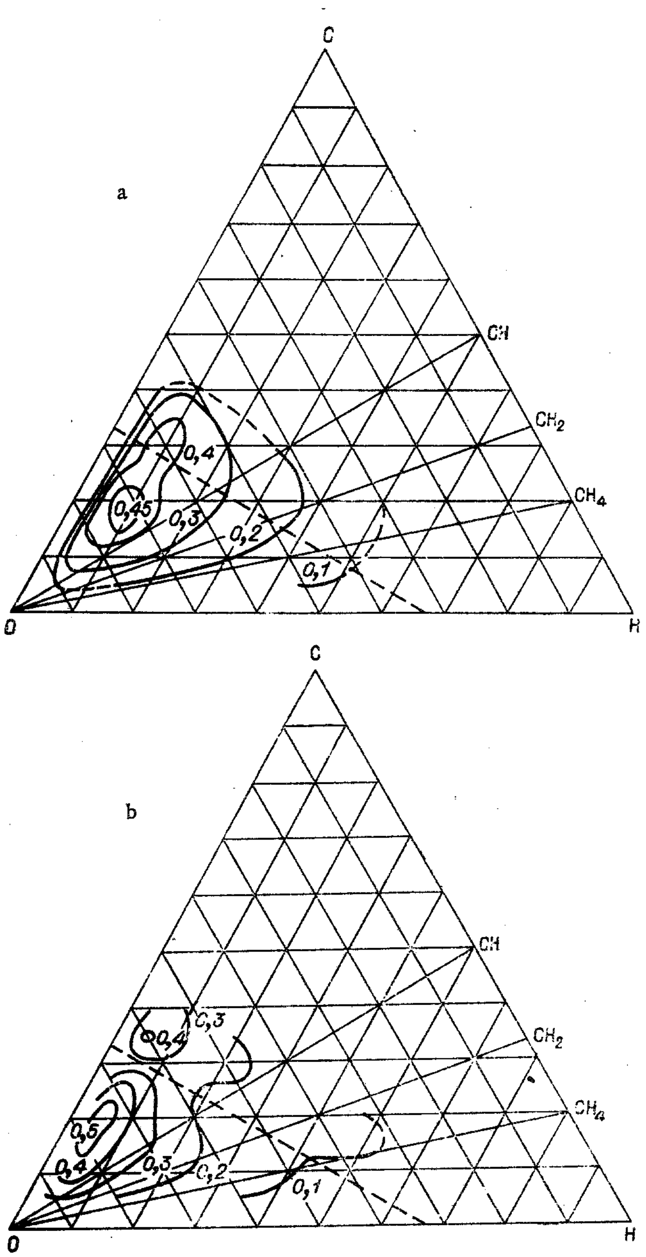

Fig. 4

3. In order to clarify the nature of the dependence of the gain coefficient of multicomponent media on their composition, the nozzle shape, and the initial conditions, computations of α were executed for 64 compositions with a fixed $T_0 = 1600°K$ and a range of p_0 from 5 to 20 atm during expansion in plane nozzles of two kinds, wedge-shaped (see Sec. 2) and profiled minimum-length ($h = 2 \cdot 10^{-4}$ m, $A/A^* = 30$).

The results of the computations are represented in Figs. 4 and 5 in the form of equal gain-coefficient lines on triangular C, H, O diagrams ($\xi_N = 0.6$ for all the compositions). The elected area of element compositions corresponds to those which it is expedient to use as laser-active media (absence of soot, not too high a H_2O concentration [25]). There is an area on the diagrams where the CO, H_2, O_2 concentrations in the corresponding compositions are quite low. This area is located along a line called the triple-mixture line (the dashed lines in Figs. 4 and 5 where $\xi_O = 2\xi_C + 0.5\ \xi_H$). The points on this line correspond to compositions which contain only N_2, CO_2 and H_2O for the p_0 and T_0 under consideration. The domain above this line corresponds to compositions containing CO and H_2 in addition, while the domain below this line corresponds to compositions where the main impurity is O_2.

Values of α are presented in Figs. 4a and b ($p_0 = 5$ and 10 atm, respectively) for a range of 0.075 m from the nozzle throat, while α_{max} ($p_0 = 10$ atm) are presented in Fig. 5.

TABLE 2

	References
$\lg \tau_{CO}^{(1.1)} = 15,55\ T^{-1/3} - 8,06$	[17]
$\tau_{O_2}^{(1.1)} = \tau_{N_2}^{(1.1)}$	[6]
$\lg \tau_{H_2}^{(1.1)} = -15,5\ T^{-1/3} - 5,55$	[17]
$k_{CO}^{(1.4)} = \begin{cases} 10^{-13T^{-1/3}+7,36}, & T \geqslant 735, \\ 10^6/(-9,64 \cdot 10^{-3} T + 8,33), & 450 \leqslant T < 735, \\ 10^6/[-5,34 \cdot 10^{-5} (T-375)^2 + 4,3], & T < 450 \end{cases}$	[18–20]
$k_{O_2}^{(1.4)} = k_{N_2}^{(1.4)}$	[18]
$\lg k_{H_2}^{(1.4)} = \begin{cases} 6,67 - 6,1 \cdot 10^{-4} T, & T \geqslant 428, \\ 6,41, & T < 428 \end{cases}$	[17]
$\lg \tau_{CO_2}^{(2.1)} = 83\ T^{-1/3} - 10,52$	[17]
$\tau_{H_2O}^{(2.1)} = 1,7 \cdot 10^{-7}$	[17]
$\lg \tau_{N_2}^{(2.1)} = \lg \tau_{CO}^{(2.1)} = \lg \tau_{O_2}^{(2.1)} = 175\ T^{-1/3} - 23,4$	[21]
$\ln \tau_{N_2}^{(2.2)} = \ln \tau_{O_2}^{(2.2)} = 129\ T^{-1/3} - 22,28$	[6]
$\tau_{H_2}^{(2.3)} = 3,9 \cdot 10^{-9} \exp(100\ T^{-1/3})$	[22]
$k^{(2.4)} = \begin{cases} 10^{11,95 - 58,8 T^{-1/3}}, & T \geqslant 1500, \\ 2,45 \cdot 10^8/\sqrt{T}, & T < 1500 \end{cases}$	[17]
$k^{(2.5)} = 6 \cdot 10^7$	[6]
$\lg k^{(2.6)} = 8,65 \cdot 10^{-2} (T^{-1/3} - 0,1)^2 + 5,796$	[23, 24]
$P^{(2.7)} = \exp(-106 T^{-1/3} - 1,56)$	[24]
$P^{(2.8)} = \exp(212 T^{-2/3} - 141,5 T^{-1/3} + 1,94)/\sqrt{T}$	[6]

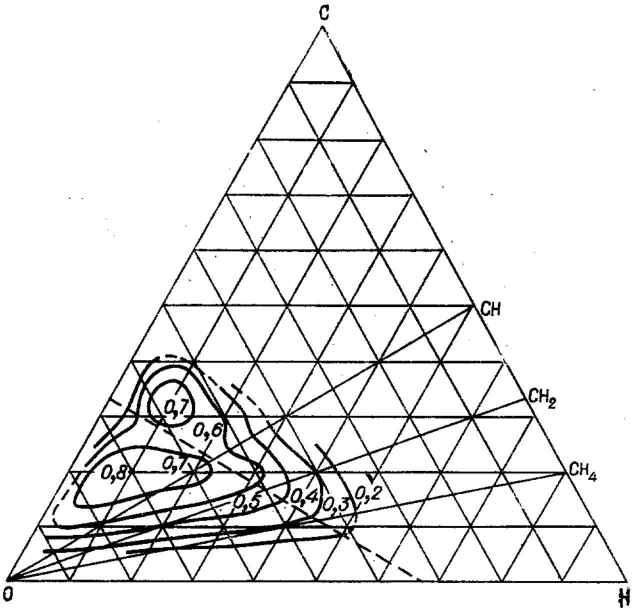

Fig. 5

There are two composition domains (and their corresponding compositions) in the expansion of multicomponent media in a wedge-shaped nozzle (see Fig. 4), which are characterized by comparatively high values of α. These domains are on different sides of the triple-mixture line. The domains contract as p_0 increases, and shift towards element compositions with smaller ξ_H (low Y_{H_2O}). The maximums on both sides of the triple-mixture line are hence denoted more sharply and a minimum value domain (trough) is formed alongside. An analogous nature for the dependence of α on the composition and pressure was observed experimentally earlier [26].

The general form of the dependence of α on the composition is conserved for the expansion of multicomponent media into a profiled nozzle (see Fig. 5), however, the influence of the pressure is weaker in this case.

So complex a form of the diagrams presented is due to the following in the authors' opinion. The Y_{CO_2} in the compositions diminishes with the shift to either side of the triple-mixture line on the diagram, and Y_{CO} or Y_{O_2} increases. The diminution in Y_{CO_2} reduces the gain coefficient but the growth of Y_{CO} or Y_{O_2} increases α because of the simultaneous increase in the rate of cooling the gas in the nozzle (growth of the adiabatic index) and of the relaxation time of the upper lasing level. However, this latter becomes less essential with the increase in the fraction of the element H in the medium, and also with the increase in the rate of gas cooling in the nozzle.

The authors are grateful to V. M. Vasil'yev for aid in making the computations of the equilibrium compositions.

LITERATURE CITED

1. J. D. Anderson, Gasdynamic Lasers: An Introduction, Academic Press, N.Y.–San Francisco–London (1976).
2. V. M. Vasil'yev, S. V. Kulikov, and O. V. Skrebkov, "On computation of the chemically and vibrationally nonequilibrium multicomponent gas flow through a nozzle," Prikl. Mekh. Tekh. Fiz., No. 4 (1977).
3. A. N. Kraiko, "On the computation of nonequilibrium gas flow in nozzles," Tr. Inst. Mekh., Mosk. Gos. Univ., No. 21 (1973).
4. S. A. Losev, V. N. Makarov, V. A. Pavlov, and O. P. Shatalov, "Investigation of processes in a gasdynamic laser in a large-diameter shock tube," Fiz. Goreniya Vzryva, No. 4 (1973).
5. A. N. Vargin, V. V. Gogokhiya, V. K. Konyukhov, and L. M. Pasynkova, "Determination of the vibrational relaxation time of the CO_2 molecule 00°1 level in pure CO_2 and in a mixture with H_2O." Zh. Tekh. Fiz., 45, No. 3 (1975).
6. R. L. Taylor and S. Bitterman, "Survey of vibrational relaxation data for processes important in the CO_2-N_2 laser system," Rev. Mod. Phys., 41, No. 1 (1969).
7. S. A. Losev, "Kinetics of vibrational energy exchange in carbon dioxide and its mixtures with other gases," Fiz. Goreniya Vzryva, 12, No. 2 (1976).
8. R. A. Meinzer, "Experimental gasdynamic laser studies," AIAA J., 10, No. 4 (1972).
9. M. I. Buchwald and S. H. Bauer, "Vibrational relaxation in CO_2 with selected collision partners, 1. H_2O and D_2O," J. Phys. Chem., 76, No. 22 (1972).
10. J. W. Z. Lewis and K. P. Lee, "Vibrational relaxation in carbon dioxide/water-vapor mixtures," J. Acoust Soc. Am., 38, No. 5, 813 (1965).
11. K. Bulthuis, "Laser power and vibrational energy transfer in CO_2 lasers," J. Chem. Phys., 58, No. 12 (1973).
12. M. C. Gower and A. I. Carswell, "Laser-induced plasma perturbation studies of energy transfer in CO_2 glow-discharge lasers," J. Appl. Phys., 45, No. 9 (1974).
13. R. T. V. Kung and R. E. Center, "High-temperature vibrational relaxation of H_2O by H_2O, He, Ar, and N_2," J. Chem. Phys., 62, No. 6 (1975).
14. A. T. Jones, "Time dependent solution of the vibrational nonequilibrium flow of $CO_2-N_2-H_2O-O_2$ mixtures in gasdynamic lasers," J. Phys. D: Appl. Phys., 9, No. 8 (1976).
15. J. S. Vamos, "Small signal gain measurements in a high-ratio nozzle shock tunnel," AIAA Paper No. 74-177 (1974).
16. J. Tulip and H. Sequin, "Explosion pumped gasdynamic CO_2 laser," Appl. Phys. Lett., 19, No. 8 (1971).
17. V. N. Makarov and S. A. Losev, "On the influence of impurities on the optical gain coefficient during relaxing gas flow in a supersonic nozzle," Fiz. Goreniya Vzryva, 11, No. 5 (1975).
18. A. N. Vargin, V. V. Gogokhiya, V. K. Konyukhov, and L. M. Pasynkova, "Investigation of the relaxation time of the CO_2 molecule 00° level in mixtures with O_2 and CO," Kvantovaya Elektron., 2, No. 6 (1975).
19. W. A. Rosser, R. D. Sharma, and E. T. Gerry, "Deactivation of vibrationally excited carbon dioxide (001) by collisions with carbon monoxide," J. Chem. Phys., 54, No. 3 (1971).
20. P. Borrell and G. E. Millward, "Vibrational energy transfer processes in shock-heated binary gas mixtures of CO with CO_2, N_2O and COS," J. Chem. Phys., 57, No. 1 (1972).
21. R. G. Millican and D. R. White, "Systematics of vibrational relaxation," J. Chem. Phys., 39, No. 12 (1963).
22. J. H. Kiefer and R. W. Lutz, "Vibrational relaxation of hydrogen," J. Chem. Phys., 44, No. 2 (1966).
23. C. W. Rosenberg, K. N. C. Bray, and N. H. Pratt, "Shock-tube vibrational relaxation measurements; N_2 relaxation by H_2O and CO_2-N_2 V–V rate," J. Chem. Phys., 56, No. 7 (1972).
24. J. Sato, S. Tsushiya, and K. Kuratani, "Shock-wave study of vibrational-energy exchange between diatomic molecules," J. Chem. Phys., 50, No. 5 (1969).

25. A. P. Genich, N. V. Evtyukhin, and G. B. Manelis, "Equilibrium compositions of high-temperature systems based on C, H. O, N for a gasdynamic CO_2 laser," Fiz. Goreniya Vzryva, 11, No. 5 (1975).
26. N. V. Evtyukhin, S. V. Kulikov, V. M. Vasil'yev, A. P. Genich, G. B. Manelis, and O. V. Skrebkov, "Investigation of the gain coefficients of multicomponent working media in a combustion CO_2 GDL," in: Chemical Physics of Combustion and Explosion Processes. Kinetics of Chemical Reactions [in Russian], Chernogolovka (1977).

TAKE-OFF OF ENERGY FROM EXPLOSIVE-MAGNETIC GENERATORS TO AN INDUCTIVE LOAD USING THE BREAKING OF A CIRCUIT

V. A. Demidov, E. I. Zharinov,
S. A. Kazakov, and V. K. Chernyshev

UDC 538.4:621.31

The use of explosive-magnetic generators (EMG) for plasma experiments [1, 2] and for other physical investigations, along with questions of increasing the electromagnetic energy [3-9], poses the problem of the formation, in the external load, of current pulses with steep leading fronts in the microsecond range.

One method for the rapid take-off of energy to the load is the breaking of the finite circuit of the explosive-magnetic generator. This is done using commutators based on the electrical explosion of thin conductors [10-12] or on the basis of the mechanical breakdown of conductors by a charge of explosive [3, 6, 13, 14].

The efficiency of the transfer of energy to the load depends on the active resistance introduced by the commutator into the breaking circuit, and on the ratio of the inductances of the accumulator and the load. The parasitic inductance of the commutator has a great effect on the steepness of the rise of the current in the load.

The aim of the present work was a determination of the form of the pulses of the current and the energy in an inductive load as a function of the resistance of the discontinuity introduced into the circuit of an explosive-magnetic generator, taking account of the parasitic inductance of the commutating device.

1. Within the framework of an electrotechnical model, the work of an explosive-magnetic generator can be represented as the decreasing inductance L_1, connected to an explosive commutator with the parasitic inductance L_3 and the variable ohmic resistance R (Fig. 1). At the start of the compression of the magnetic flux, in an explosive-magnetic generator with the inductance L_0 there flows the current I_0. At the moment $\tau = 0$ (when the inductance of the generator has decreased to $L_1(0)$), a switch connects the load L_2 to the circuit and the commutator breaks the current in the circuit. Before the start of the discontinuity, the resistance of the commutator is equal to zero; during the discontinuity it rises according to the law $R(\tau)$ up to some final value. Taking account of the losses of the magnetic flux arising with deformation of the main circuit of the explosive-magnetic generator, the current at the moment of the start of the discontinuity, expressed in terms of the coefficient of the ideality of the system F [4], rises to the value

$$I_1(0) = I_0\left(\frac{L_0 + L_3}{L_1(0) + L_3}\right)^F.$$

Assuming that, starting from the moment $\tau = 0$, there are no losses of the flux in the generator, in accordance with the Kirchhoff law we set up the starting system of differential equations for finding the current in the load

$$I_1\dot{L}_1 + \dot{I}_1 L_1 + \dot{I}_3 L_3 + I_3 R = 0,$$
$$\dot{I}_2\dot{L}_2 + \dot{I}_2 L_2 - \dot{I}_3 L_3 - I_3 R = 0,\ I_1 = I_2 + I_3 \qquad (1.1)$$

(a dot indicates the derivative with respect to the time; the parameters of the system (1.1), with the exception of L_3, the parasitic inductance of the commutator), are functions of the time).

As initial conditions we take with $\tau = 0$

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 1, pp. 43-48, January-February, 1979. Original article submitted January 11, 1978.