VIBRATIONAL TEMPERATURES OF CARBON DIOXIDE IN THE PRODUCTS OF THE REACTION OF CARBON MONOXIDE WITH NITROUS OXIDE UNDER GASDYNAMIC LASER CONDITION.

II. EFFECT OF THE CONCENTRATION OF INERT DILUENT – HELIUM AND NITROGEN

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It is shown that when the concentration of helium is increased to 0.7 at the expense of nitrogen in the reacting mixture $CO + N_2O + N_2$ (He), an increase in the gain in the flow of reaction products occurs due to an increase in the vibrational temperature of the asymmetric mode of CO_2.

In [1-4] experimental and theoretical investigations of the gain and emission power in gasdynamic lasers as a function of the helium content in chemically inert mixtures of CO and N_2 are described. The presence of helium in this mixture leads to an increase in the rate of relaxation of the lower laser level of the CO molecules, and to an increase in the rate of cooling of the gas, which is expanding in the nozzle (due to the increase in the adiabatic index γ_{eff}), compared with the corresponding quantities in mixtures not containing helium. Both these factors improve the conditions under which population inversion of the upper and lower laser levels of the CO molecules is achieved. On the other hand, the reduction in the relative concentration of nitrogen when the helium content in the mixture is increased leads to a reduction in the characteristic relaxation time of the upper laser level ($\tau_{001} \sim \xi_{N_2}$ [3]). This makes it difficult to achieve the conditions for obtaining population inversion.

It was experimentally found in [1-3] that the maximum value of the gain at a wavelength $\lambda = 10.6$ µm in triple mixtures of $CO_2 + N_2 + He$ under gasdynamic laser conditions is obtained for a helium concentration $\xi_{He} =$ 0.4-0.5. A change in the helium concentration with respect to the optimum value of ξ_{He} leads to a reduction in the gain. The maximum in the dependence of the gain on ξ_{He} is more pronounced the higher the ratio of the concentration of CO to the concentration of N_2 in the mixture ξ_{CO_2}/ξ_{N_2} [2]. The effect of helium on the oscillatory energy transfer in gasdynamic lasers in chemically reacting mixtures is more complex. In particular, the value of the rate of cooling of the flow determines whether the individual stages of the chemical transformations will take place or will be "frozen," and the conditions under which the chemical energy given to the vibrational degrees of freedom of the molecules is redistributed and relaxes.

Below we describe the results of an experimental investigation of the fundamental characteristics of vibrational energy exchange – the gain K_0, the relative population inversion ΔN, and the vibrational temperatures of CO_2, T_3, T_2 in a CO_2 gasdynamic laser using the products of the reaction that occurs in a mixture of $CO + N_2O$, diluted with nitrogen and helium. The initial composition of the mixtures and the range of variation of the gas temperature in the volume preceding the nozzle T_0 are shown in Table 1. The numbers of the mixtures in the table correspond to the numbers of the curves and points in Figs. 1 and 2. The helium content in mixtures 1-5 increases, taking the values $\xi_{He} = 0.0$, 0.1, 0.3, 0.5, and 0.7. The amount of nitrogen in the reaction products in these mixtures decreases from 0.75 to 0.05. Mixture 6 differs from mixtures 1-5 in that instead of using helium as the deactivator of the lower laser level in the products of the $CO + N_2O$ reaction water vapor $\xi_{H_2O} = 0.025$ is used, which is formed in the volume in front of the nozzle by interaction of hydrogen and nitrous oxide in the initial mixture [6]. The concentration of CO_2 and CO in the reaction products of mixtures 1-6 was the same in all the experiments and was $\xi_{CO} = 0.2$ and $\xi_{CO_2} = 0.05$. The pressure of the gas in the volume preceding the nozzle was maintained constant at $P_0 = 5.2 \pm 0.5$ atm.

The values of the adiabatic indices of the gas mixtures in the "bottleneck" γ_0 given in Table 1 were used to calculate the flow parameter in the critical cross section of the nozzle. To determine the flow parameters

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TABLE 1. Initial Composition of the Mixtures Investigated, the Ranges of Variation of the Gas Temperature in the Volume Preceding the Nozzle T_0, and Values of the Adiabatic Indices γ_0 and γ_{eff}

No.	Initial composition of mixture	T_0, °K	γ_0 (T_0 = 1800—2800 °K)	γ_{eff}
1	$0{,}05\,N_2O + 0{,}25\,CO + 0{,}7\,N_2$	1800—3000	1,291—1,248	1,377
2	$0{,}05\,N_2O + 0{,}25\,CO + 0{,}6\,N_2 + 0{,}1\,He$	1700—2700	1,307—1,294	1,392
3	$0{,}05\,N_2O + 0{,}25\,CO + 0{,}4\,N_2 + 0{,}3\,He$	1700—2800	1,344—1,331	1,426
4	$0{,}05\,N_2O + 0{,}25\,CO + 0{,}2\,N_2 + 0{,}5\,He$	1700—2900	1,391—1,379	1,465
5	$0{,}05\,N_2O + 0{,}25\,CO + 0{,}7\,He$	1700—2700	1,453—1,444	1,513
6	$0{,}075\,N_2O + 0{,}25\,CO + 0{,}65\,N_2 + 0{,}025\,H_2$	1800—2800	1,287—1,274	1,367

in the working cross section, we used values of the adiabatic index γ_{eff} (in Table 1), calculated taking into account the vibrational nonequilibrium of the expanding gas [16]. Because of the considerable difference between the adiabatic index γ_0 for mixtures 1-6 for the same values of the gas temperature in the volume preceding the nozzle T_0, there are different values of the gas temperature in the critical cross section of the nozzle $T_* = 2T_0/(\gamma_0 + 1)$. The difference between the vibrational temperatures of the CO_2 molecules and the translational temperature for gas flow in a nozzle begins to appear close to the critical cross section. Hence, in this work the experimental values of K_0, ΔN, T_3, and T_2 are presented in the form of temperature dependences of the gas in the critical cross section T_*. The temperature dependences of the gain K_0 for mixtures 1-6 in the first working cross section of the flow (the distance from the critical cross section of the nozzle L = 140 mm) are shown in Fig. 1a. Over the whole range of temperatures T_* investigated the gain K_0 increases as the concentration of helium in the mixture increases. In mixture 1 (without helium) absorption of the radiation from the probing laser was observed. The absorption coefficient in this mixture is $K_0 = -0.15$ m^{-1} at T_* = 1500-1700°K, and drops to zero at T_* = 2200-2500°K (curve 1, Fig. 1a). The curves of $K_0(T_*)$ for mixtures 2-5 have a maximum at T_* = 1800-1900°K. The maximum values of K_0 increase in mixtures 2-5 from $K_0^{(2)} = 0.15$ to $K_0^{(5)} = 0.42$ m^{-1}. A feature of the dependence of K_0 on T_* for reaction products in mixture 5 is the sharp increase in the value of K_0 at $T_* \leq 1800$°K. The products of the chemical transformations in mixture 6 contain water vapor in the quantity $\xi_{H_2O} = 0.025$. It is seen that the values of $K_0^{(6)}$ lie between the values of $K_0^{(3)}$ and $K_0^{(4)}$.

At high values of the temperatures in the volume preceding the nozzle $T_0 > 2100$°K ($T_* > 1800$°K), the chemical conversions in the mixtures 1-6 are practically completed before the nozzle diaphragm is opened, and, consequently, the composition of the reaction products flowing out through the nozzle is in thermodynamic equilibrium. Hence, it is justified, for this region of values of T_*, to equate the experimental data obtained for K_0 with the results of measurements of the gain in a gasdynamic laser using chemically inert mixtures of $CO_2 + N_2 + He$ (H_2O) [1, 2, 4, 5, 7, 8]. It should also be taken into account that in the reaction products of mixtures 1-6 part of the nitrogen is replaced by CO. Satisfactory qualitative agreement between the results obtained for K_0 and the data given in [1, 2, 4, 5, 7, 8] is found. From the measured values of K_0 we calculated the relative population inversion of the vibrational levels 001, 100 of the CO_2 molecules: $\Delta N = (N_{001} - N_{100})/N_{CO_2}$, where N_{CO_2} is the overall density of the CO_2 molecules in the flow. When the conservation of helium in the mixture is increased over the whole range of variation of the temperature T_* investigated, an increase is observed in the values of the relative population inversion ΔN. In mixture 1, not containing helium, the values of ΔN are negative. In mixtures 2, 3, and 4, containing ξ_{He} = 0.1, 0.3, and 0.5, respectively, the maximum values of the population inversion are achieved in the range T_* = 1400-1800°K, and are 2.5, 3.2, and 3.3%. The maximum values of the relative population inversion for T_* = 1400-1800°K are obtained for the reaction products of mixture 5 containing the largest amount of helium $\xi_{He} = 0.7$.

The results of measurements of the vibrational temperature T_3 of the asymmetric mode of vibrations of the CO_2 molecules for mixtures 1-6 are shown in Fig. 1b. The dashed line shows the gas temperature in the critical cross section of the nozzle. It is seen that for all mixtures the observed dependence of the temperature T_3 on the gas temperature in the critical cross section of the nozzle is a monotonically increasing function of T_*. In the low-temperature region for $T_* < 1500$°K the value of T_3 differs only slightly from the gas temperature in the critical cross section of the nozzle T_*. When the values of T_* increase the difference between T_* and T_3 increases rapidly. In mixture 1 (without helium) the vibrational temperature T_3 increases

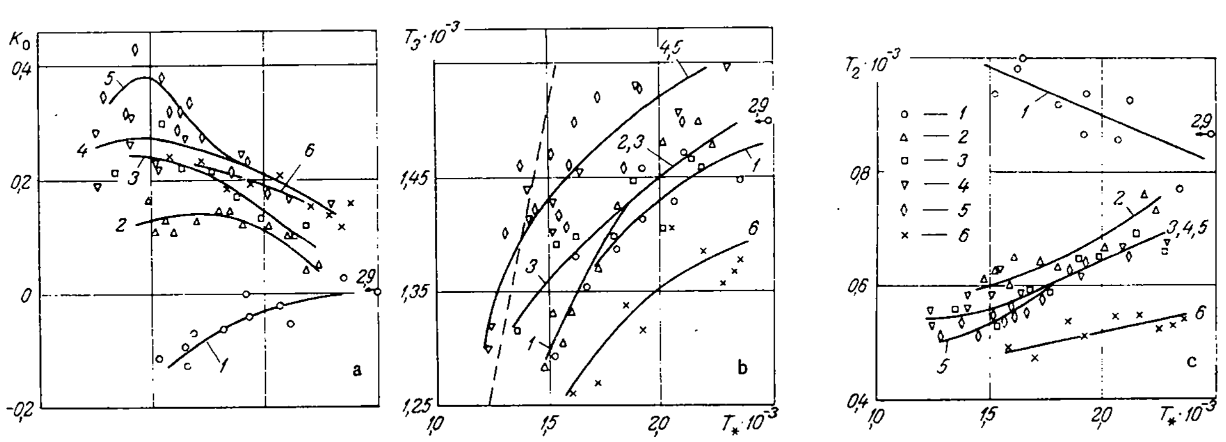

Fig. 1. Curves of the gain K_0 (a) and the vibrational temperatures of the asymmetric T_3 (b) and the joint T_2 (c) modes of CO_2 as a function of the temperature in the critical cross section of the nozzle T_*. The numbers on the points correspond to the numbers of the curves. K_0, m^{-1}; T_3, T_2, and $T_* \cdot 10^{-3}$, °K.

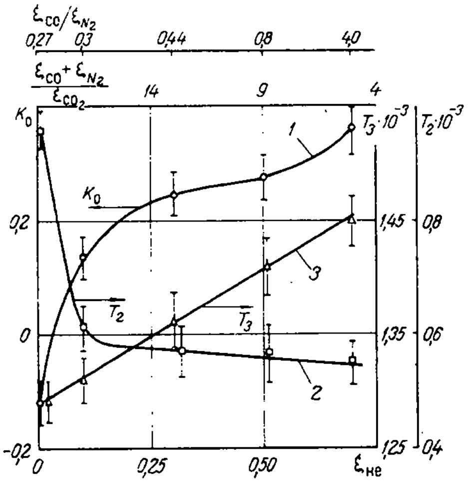

Fig. 2. Dependence of the gain K_0 and the vibrational temperatures of CO_2 (T_3 and T_2) on the helium content in the mixture ξ_{He}, $T_* = 1500 \pm 75$°K; K_0, m^{-1}; and T_2, $T_3 \cdot 10^{-3}$, °K.

from ~1300°K for $T_* = 1500$°K to 1500°K for $T_* = 2900$°K (curve 1, Fig. 1b). The introduction of helium into the mixture in the amount $\xi_{He} = 0.1$ (mixture 2) and $\xi_{He} = 0.3$ (mixture 3) leads to some increase in the vibrational temperature T_3 (curves 2, 3, Fig. 1b). When the helium content in the mixtures is increased further to $\xi_{He} = 0.5$ (mixture 4) and $\xi_{He} = 0.7$ (mixture 5) the vibrational temperature T_3 increases considerably over the whole range of temperature T_* investigated. In this case the vibrational temperatures T_3 for reaction products of mixtures 4 and 5 are the same, within the limits of experimental accuracy. It is essential that for $T_* \leq$ 1400°K the vibrational temperature T_3 in the reaction products of mixtures 4 and 5 exceeds the temperature of the gas T_* in the critical cross section of the nozzle. In the reaction products in mixture 6 containing water vapor in the amount $\xi_{H_2O} = 0.025$, the temperature T_3 of the asymmetric mode of vibrations of the CO_2 molecules is considerably less than the values of $T_3^{(1-3)}$ for reaction products of mixtures 1-5. The values of $T_3^{(6)}$ over the whole range of T_* investigated are ≈ 100°K lower than the values of T_3 (curves 1-3, 6, Fig. 1b).

In Fig. 1c, for mixtures 1-6, we give the values of the temperature of the combined mode of vibrations of the CO_2 molecules (T_2). For reaction products in the mixtures 2-6 the curves of $T_2 = T_2(T_*)$ are increasing functions of the temperature T_*. Mixture 1 has higher values of the vibrational temperature T_2, and the values of T_2 decrease as T_* increases. The absolute values of the temperature T_2 for mixtures with helium are close to one another, varying from ~550°K at $T_* = 1500$°K to ≈ 700°K at $T_* = 2200$°K. The greatest degree of thermalization of the combined mode of vibrations of CO_2 is observed in mixture 6 which contains water vapor. In particular, for $T_* = 2300°K$ the temperature $T_2^{(6)}$ differs from the gas temperature by not more than 20-30%.

For the reaction products in mixtures 1-5, considerable population of the combined mode of vibrations of the CO_2 molecules occurs; the vibrational temperature T_2 in them is more than twice as great as the translational temperature of the gas. The combined mode of vibrations of CO_2 in the reaction products of mixture 1 without helium is least thermalized, particularly at low values of T_*, and also the mixture most enriched with helium, mixture 5, at $T_* = 1500°K$; the temperature T_2 in these mixtures exceeds the temperature of the gas by a factor of more than 3.5.

The gain $K_0^{\prime}$ in the reaction products in mixtures 2-5 in the second cross section of the flow (the distance from the critical cross section of the nozzle L = 350 mm) is less than half the value of the gain in the first section. The dependence of $K_0^{\prime}$ on the temperature T_* for these mixtures is hump shaped with maximum values of $K_0^{\prime}$ at $T_* = 1500$-$1800°K$. As in the first section, the gain in the second section $K_0^{\prime}$ increases as the concentration of helium in the mixture increases. In the reaction products of mixture 6 a considerable, approximately triple, reduction in the gain is observed on going from the first section to the second. This is due to the more rapid relaxation of the vibrational energy of the upper laser level for mixture 6 when water vapor is present compared with mixtures 2-5 containing helium [9, 10]. The greater reduction in the gain in the second section of the flow also facilitates practically complete thermalization of the lower laser level in the reaction products in mixture 6 observed in the first section of the flow.

Hence, the results of the experiments show that the effect on the parameters of the gasdynamic laser of diluting with helium the products of the reaction $CO + N_2O$ differs from that of a gasdynamic laser based on inert mixtures of composition $CO_2 + N_2 + He$. The gain and population inversion increase continually as the helium concentration in the initial reacting mixture is increased to a value $\xi_{He} = 0.7$, whereas in inert mixtures on increase in the helium concentration above the optimum value $\xi_{He} = 0.4$-0.5 leads to a considerable reduction in the gain [2]. This fact is not trivial since when the concentration of helium in the reacting mixtures investigated is increased there is a reduction in the concentration of nitrogen, the temperature in the critical section of the nozzle is reduced, and the relative content of CO is increased, i.e., a situation occurs which brings about a reduction in the gain. The highest increase in the values of K_0 and ΔN when the helium content is increased is observed for mixture 5 ($\xi_{He} = 0.7$) in the temperature range $T_* \leqslant 1800°K$ (the temperature in front of the nozzle $T_0 \leqslant 2200°K$), i.e., under conditions when the chemical changes cannot be completed in the volume in front of the nozzle.

In Fig. 2 the results of measurements of K_0, T_2, and T_3 in the reaction products of mixtures 1-5 are presented in the form of curves of the helium concentration in the mixture (ξ_{He}) for a fixed value of the temperature $T_* = 1500 \pm 75°K$. Here we also show values of the ratio of the concentrations of the other components of the mixture: ξ_{CO}/ξ_{N_2} and $(\xi_{N_2} + \xi_{CO})/\xi_{CO_2}$. As is seen from Fig. 2, the role of helium as a deactivator of the lower laser level of CO_2 predominates at low helium contents in the reacting mixture ($\xi_{He} \leqslant 0.3$). When the helium content is increased ($\xi_{He} > 0.3$) an increase in the gain occurs due to the increase in the vibrational temperature of the asymmetric mode of CO_2 (T_3), the temperature of the lower laser level remaining practically unchanged.

It is essential that when the helium concentration in mixtures 1-5 is increased, the ratio of the concentrations of CO and N_2 are simultaneously changed: $\xi_{CO}/\xi_{N_2} = 0.27$, 0.31, 0.44, 0.80, and 4.0. In [11-15], when the ratio ξ_{CO}/ξ_{N_2} was increased while keeping the helium concentration constant, a reduction in the gain occurred. It has been established in this paper that an increase in the ratio ξ_{CO}/ξ_{N_2} while simultaneously increasing the helium concentration in the mixture leads to a monotonic increase in the gain. The introduction of CO into the $CO_2 + N_2 + He$ (H_2O) mixture leads to an effective relaxation channel for the vibrational energy of the upper laser level

$$CO(1) + CO_2(000) \rightarrow CO(0) + CO_2(110) + 65\ \text{cm}^{-1}.$$

The sharper reduction and lower values of the translational temperature of the gas, which occur when mixtures with a high helium content are expanded, may lead to a reduction in the loss of vibrational energy of the upper laser level in this channel.

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RADIATION OF A PERFORATED CYLINDER

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The generalized zonal method is used to find the energy radiated by a perforated cylinder. The existence of a range of geometric optical parameters is established, wherein the perforated cylinder radiates more energy than a continuous cylinder.

We will consider a cylindrical surface uniformly perforated by orifices. We will find the resultant energy flux (or surface density) radiated by the cylinder at specified temperature, optical properties, and surface geometry.

We make the following assumptions: 1) the cylinder is infinitely long; 2) the unperforated portion of the cylinder is diffuse-gray and homogeneous; 3) the surfaces, inner surface 1 and outer surface 2, are isothermal while $T_1 = T_2 = T > 0$; 4) the medium is diathermal.

We close the surfaces 1, 2 of the perforated cylinder with a coaxially located black ($\varepsilon = 1$) continuous cylindrical surface 3 of arbitrary diameter D_3 and temperature $T_3 = 0°K$. We now apply the generalized zonal method of [1] to this system of surfaces.

For the resultant fluxes from each zone, we obtain the following expressions:

$$Q_{f1} = -\varepsilon_1 E_{13} \gamma \varphi_{13} (1 - \beta) F_0, \tag{1}$$

$$Q_{f2} = -\varepsilon_2 E_{13} \varphi_{23} (1 - \beta_0) F_0, \tag{2}$$

$$Q_{f3} = E_{13} (\varepsilon_1 \gamma \varphi_{31} + \varepsilon_2 \varphi_{32}) F_3, \tag{3}$$

where $\gamma^{-1} = 1 - R_1 \varphi_{11}$; $E_{13} = \sigma_0 T^4$; $\beta = F/F_0$; F is the area of the perforations; F_0 is the geometric area of the cylinder surface.

In Eqs. (1)-(3) the mean angular radiation coefficients (ARC) φ_{ik} can be expressed in terms of the average ARC φ_{11} of the perforated cylinder itself with the aid of the closure and reciprocity equations. Thus, the problem reduces to determination of φ_{11}.

It follows from the physical meaning of the mean angular radiation coefficient that

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